Mineral Resources in Permian Rocks of Southwest Montana

GEOLOGICAL SURVEY PROFESSIONAL PAPER 313-E

This report concerns work done as part of the program of the Department of the Interior for development of the Missouri River basin, and work done partly on behalf of the U.S. Atomic Energy Commission

Swanson—MINERAL RESOURCES IN PERMIAN ROCKS OF SOUTHWEST MONTANA—Geological Survey Professional Paper 313-E

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By ROGER W. SWANSON

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MINERAL RESOURCES IN PERMIAN ROCKS OF SOUTHWEST MONTANA

By Roger W. Swanson

ABSTRACT

Phosphorus is the major resource in the Permian rocks of southwest Montana, but fluorine, uranium, several other elements, and oil shale occur in unusually large concentrations. This report describes their abundance and distribution, giving particular emphasis to the geology of the areas where Permian rocks are preserved. These rocks underlie less than 20 percent of the area (15,000 sq mi) discussed in this report; the report area is generally south of Butte and west of Yellowstone National Park and includes the adjacent parts of Idaho and Wyoming.

The Permian rocks are part of a series of chiefly shallow-water Paleozoic and Mesozoic marine sediments, as much as 9,000 feet thick, that are overlain by a similar thickness of largely continental sediments and volcanic rocks. The series directly overlies the crystalline Precambrian basement rocks in much of the area, here called the southwest Montana positive area, and overlies the late Precambrian Belt Series sediments on the north and west sides of the positive area.

During the Laramide orogeny, blocks of the rigid crust in the positive area were tilted differentially; the overlying strata are draped across the zones of dislocation in steep to overturned asymmetric folds, and shears above the rupture zones extend locally through the overlying strata. Permian strata are preserved in large synclines of this origin. Along the west side of the positive area Permian strata are preserved in a synclinorium about 20 miles wide and about 160 miles long; in it, tight folds and thrust faults are the principal elements. North of the positive area and east of the Boulder batholith is a strongly arcuate zone of folds and faults, convex eastward, that apparently branches from the southwest Montana synclinorium near Dillon and connects by way of Three Forks with the Disturbed Belt of folds and thrusts near the mountain front north of Helena. Post-Laramide uplift by broad warping and by block faulting, volcanism, erosion from highlands, and deposition in lowlands have further complicated the geologic history but helped to establish the outcrop pattern of Permian rocks.

Phosphorus occurs in the Meade Peak and the Retort Phosphatic Shale Members of the Phosphoria Formation as oolitic to pelletal sedimentary apatite that accumulated chiefly near the border zone between the Cordilleran miogeosyncline and the platform to the east. In Montana these members are thickest and contain the most phosphate in the southwestern part of the area. The Meade Peak tongues out in the east- and north-central parts of the area, but the Retort extends over nearly the entire area, tonguing out to the northeast.

Mudstone and phosphorite make up most of the phosphatic shale members and occur together in nearly all proportions; they are thinly interlaminated to moderately thick bedded. Where the members are thickest, interbeds of mudstone are the more common in the phosphate zones, lowering the quality of minable phosphate; consequently, the better grade phosphate deposits are generally east or north of the southwestern part of the area. The best phosphate in the Meade Peak Member is in the Centennial Mountains, and that in the Retort is in the Melrose district. Carbonate rock is common, but not abundant, in these members. Carbonaceous matter is generally present and accounts for the dark color of the rocks; it is less abundant toward the margin of the area. Interbeds of chert and sandstone toward the margin represent intertonguing with other members.

All the phosphate contains fluorine in the approximate F/P_2O_5 ratio of 0.10. The fluorine resources are thus a direct function of the phosphate resources, and both are very large. The Meade Peak and Retort Members contain 10–12 percent P_2O_5, about 4 and 6 percent Al_2O_3, respectively, and nearly 2½ percent Fe_2O_3.

Most of the phosphatic rocks in this area are fairly well lithified, but only locally are they well cemented. The rocks occur in a wide range of structural environments, from undeformed to strongly sheared and mashed. Metamorphism occurred only in the immediate vicinity of the intrusive bodies, chiefly near stocks and larger intrusives but also near small dikes and sills. Hydrothermal effects are present locally but are generally not significant.

Rocks at the surface are variably weathered, some strongly; oxidation and leaching of carbonaceous matter and leaching of carbonate and sulfide minerals, where present, are the main result of weathering. Weathered rocks are lighter colored, more porous and friable, and somewhat richer in phosphate than the fresh rocks. Bluish-white bloom is characteristic of phosphorite fragments at the surface. Weathered rock may respond differently to beneficiation, or treatment, than fresh rock.

The phosphatic strata were measured and sampled at about 50 localities, representing all parts of the area containing Permian rocks. That area is divided into districts, three of which are along the synclinorium and four are in the positive area. The phosphate resources of each district were estimated separately for the two shale members and, within each geologic block in each district, for rock above entry level, rock within 100 feet below entry, and rock in the entire block, using grade cutoffs of 31, 24, and 18 percent P_2O_5 and minimum thicknesses of 3 feet. No phosphate resources were calculated for the

EXPLANATION

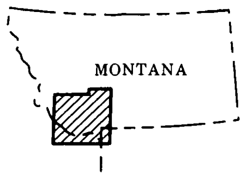
Area underlain by Permian rocks

Outcrop of Permian rocks

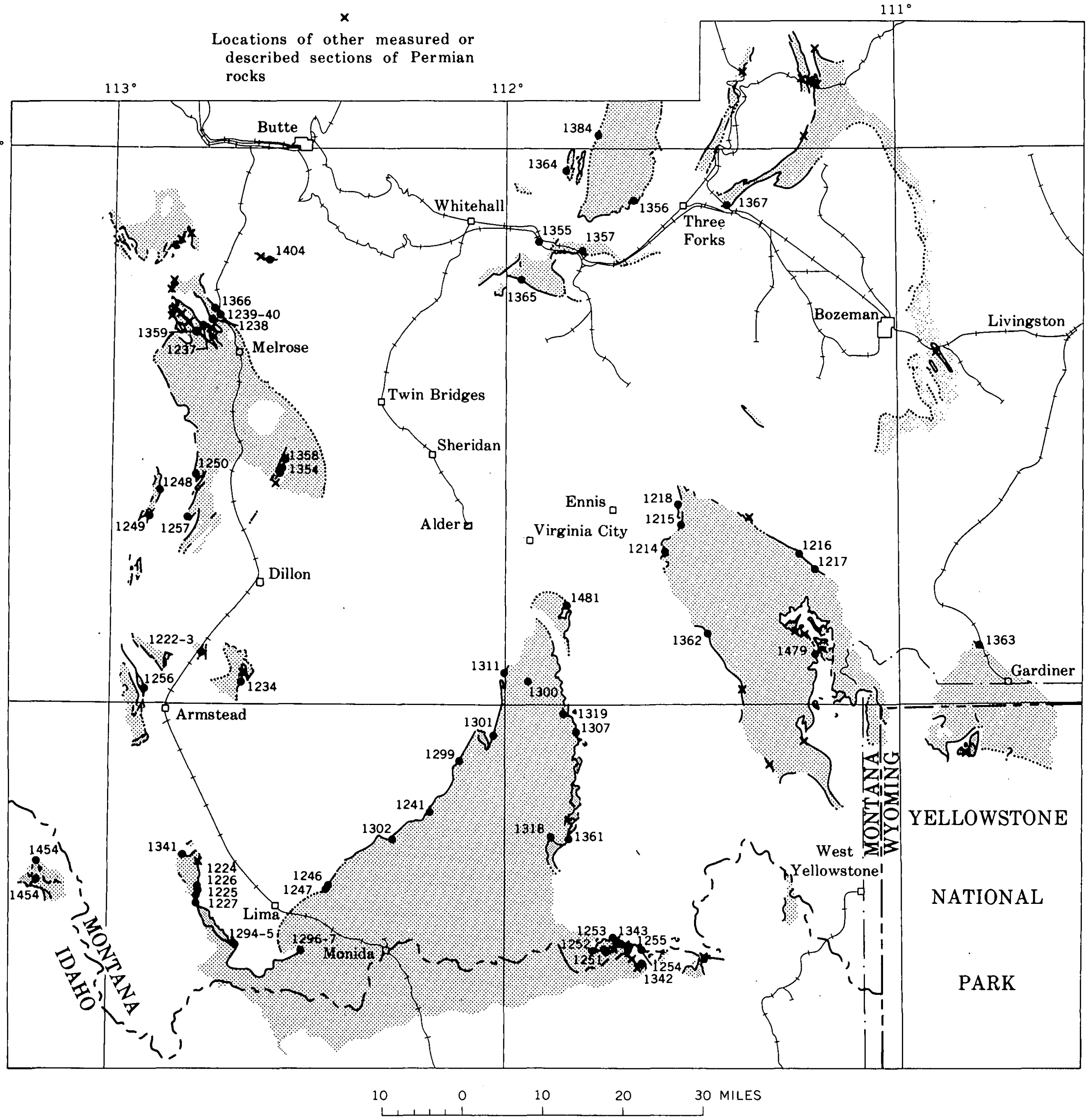
Outcrop location uncertain, Permian rocks covered, or presence uncertain (north and south of Bozeman)

1234 Sample locality and lot number

× Locations of other measured or described sections of Permian rocks



Index map showing area of this report



Permian rocks in the easternmost district or in the vicinity of Three Forks.

The two phosphatic shale members contain more than 10 billion short tons of P_2O_5, 80 percent of which is in the Retort Member. More than 6 billion short tons of rock, nearly equally divided between the two members, occurs in beds containing 24 percent or more P_2O_5. Only 450 million tons—mostly in the Meade Peak Member—occurs in beds containing 31 percent P_2O_5, 50 million tons of which is above, or within 100 feet below, entry level.

More than 400,000 tons of uranium is present in rock containing 24 percent P_2O_5, nearly 25,000 tons of which occurs above, or within 100 feet below, entry level. In rock containing 31 percent P_2O_5, 35,000 tons of uranium is present, 15 percent of which is above, or within 100 feet below, entry level.

Resources of oil shale were not estimated, but they are probably about 1½ billion tons, on the basis of the tonnages of low-grade phosphate in the Dillon and Lima districts where oil shale is known to occur.

Methods of mining and of treatment are major factors to be considered in the evaluation of western phosphate deposits; the methods of mining are governed mainly by geological factors, and those of treatment, by chemical factors. These methods are described briefly with particular reference to conditions in the western phosphate field and to the products that result from treatment. Phosphate rock can be used without treatment, but most phosphate rock from the western field is treated with sulfuric acid or in an electric furnace to produce fertilizers or elemental phosphorus.

INTRODUCTION

The Permian rocks in the Rocky Mountain region of the United States are noteworthy for their unusual content of many elements; phosphorous is the most important of these. All the phosphate contains fluorine as an essential part of the mineral structure, and all of it contains uranium, though only in minor amount. Many other elements, including both metals and rare earths, occur in the phosphatic rocks or associated lithologies in more than normal abundance and may one day prove of economic significance; and some of the phosphatic shales are fairly rich in oil.

Of the elements that occur with the phosphate mineral in the phosphatic shale members of the Phosphoria Formation, those of greatest potential value are uranium, chromium, vanadium, nickel, molybdenum, and rare earths. Gulbrandsen (1960b) showed the approximate content of these and many other elements in 60 representative phosphorite samples from the western phosphate field. They range mostly from a few tenths to a few thousands percent.

A large part of the phosphate in the western phosphate field occurs in western Montana. The Permian phosphate deposits in Montana have been investigated intermittently by the U.S. Geological Survey since 1910, when phosphate was first discovered near Melrose by Gale (1911). Since World War II, all the potential phosphate area of Montana has been studied as part of a larger investigation of the entire western phosphate field (McKelvey, 1949; Swanson, McKelvey, and Sheldon, 1953). This report describes the mineral resources in the Permian rocks in southwest Montana and adjacent parts of Idaho and Wyoming (fig. 169), an area of about 15,000 square miles. The present study was made as a part of the program of the Department of the Interior for development of the Missouri River basin and, in part, on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

Several terms used in this report are defined as follows:

Phosphorus—The chemical element, symbol P.

Phosphate—Chemically, a salt of phosphorus; geologically, a naturally occurring salt of phosphorus, chiefly the calcium phosphates; this report, the sedimentary calcium phosphates (the mineral carbonate-fluorapatite) and the fertilizers made from them.

Phosphate rock—Used mostly in industrial sense for rock that can be mined and sold for direct use or for treatment. Chiefly a commercial term.

Phosphorite—A rock composed dominantly of carbonate-fluorapatite; all rocks containing more than 19.5 percent P_2O_5 (50 percent carbonate-fluorapatite) and those of lesser P_2O_5 content that contain more phosphate mineral than any other rock component. Used in a lithologic sense, a rock term.

Phosphatic—A rock containing more than 7.8 percent P_2O_5 (20 percent carbonate-fluorapatite). Also used in a general sense, as the phosphatic shales.

Usage of these terms is not consistent within industry, and terms as defined are partly synonymous. Phosphate is used here in more of a chemical sense, phosphate rock in an industrial sense for the material mined and treated, and phosphorite in a descriptive sense for a specific kind of rock. Thus, the phosphate

FIGURE 169.—Areas in southwest Montana underlain by Permian rocks. Map was compiled from field data and from following sources: Alexander (1955), Barnes (1954), Cass (1953), Condit and others (1928), Fowler (1955), Freeman and others (1958), Gealy (1953), Guttormsen (1952), Hague and others (1896), J. B. Hadley (written commun., 1957), W. B. Hall (written commun., 1957), Honkala (1949b), Honkala (1953), Karlstrom (1948), Kennedy (1949 and written commun., 1952), Klemme (1949), Klepper (1950), Klepper and others (1957), M. R. Klepper (unpub. map compilation of region about Boulder Batholith), Love and others (1955), Lowell (1949), Lowell (1953), McMannis (1955), Mann (1950), G. T. Moore (1956), Myers (1952), Peale (1896), E. S. Perry (unpub. map information, Three Forks area, Montana), Richards and Pardee (1925), Robinson (1963), Ross and others (1955), Ross and Forrester (1947), Sahinen (1939, 1950), Scholten and others (1955), Skeels (1939), Swanson (1951), Theodosis (1955), and Wilson (1934b).

rock produced by mining contains mostly phosphorite but may also contain mudstone, sandstone, carbonate rock, or chert that occur in thin layers or lenses within the mined sequence, and these rocks may be poorly to richly phosphatic.

A small part of the phosphate rock that is mined in the western field is applied directly to soils without having been treated, but most is treated with sulfuric acid to make a soluble phosphate compound suitable for fertilizer or is reduced to elemental phosphorus in an electric furnace for use in either chemical or fertilizer industries. Many of the associated elements previously mentioned are recoverable as byproducts that result from the treatment of phosphate rock. Other byproducts that result from the treatment include synthetic gypsum, ferrophosphorus, and slag; these may be useful as formed or they may receive further treatment for the recovery of contained elements.

The data upon which this report is largely based were collected from about 50 localities. The analytical data from the samples collected and the bed by bed lithologies of the stratigraphic sections have been published (Swanson, Lowell, and others, 1953; Klepper and others, 1953; Cressman and others, 1953; Swanson, Cressman, and others, 1953; Peterson and others, 1954; Swanson and others, 1956). Most of the analytical data and the full descriptions of the stratigraphic sections were reported by Cressman and Swanson (1964); but the descriptions from two localities and analytical data from one of them are included in this report.

Cressman and Swanson (1964) presented a detailed analysis of the stratigraphy and petrology of the Permian rocks in southwest Montana; that report should be consulted regarding questions of correlation, origin, facies relations, environments of depositions, and sources of sediments. Much of the stratigraphy was summarized by Cressman (1955). The depositional environment of the Permian strata in the western phosphate field and the stratigraphic nomenclature used in these reports were summarized by McKelvey and others (1959). Much of the recent geologic mapping in the area was done by university students for theses; most of the theses have not been published.

Southwest Montana is part of the Northern Rocky Mountains physiographic province (Fenneman, 1946). The area is bounded on the south by the Snake River Plain, which merges to the east with the Yellowstone Plateau of the Middle Rocky Mountains province.

The area contains many less nearly linear mountain ranges that are generally separated, and in part surrounded, by broad basins. Most ranges trend northward, and a rhombic fabric, with north-northeast and northwest trends, is clearly evident in the patterns of both the mountain ranges and the streams of the area. The Centennial Mountains on the south, rising from the north edge of the Snake River Plain, are an exception; they trend west. Many peaks in the area are more than 10,000 feet in altitude. The Continental Divide skirts the west and south boundaries of the report area; however, the divide does not include many peaks higher than 10,000 feet, and it traverses some low areas barely recognizable as drainage divides.

Most of the area is drained by the Jefferson, Madison, and Gallatin Rivers, which join at Three Forks to become the Missouri River. The streams of the area are generally swift, whether they cross broad basins or traverse narrow canyons. The basins range in altitude from about 4,000 feet near Three Forks to about 7,000 feet near the headwaters of the principal streams.

The climate in this area is rather severe—long cold winters and mild short summers. The annual rainfall is locally less than 10 inches in the basins and two to three times as much in the mountains (U.S. Dept. Agriculture, 1941). In the basins, precipitation is greatest in early summer and least in winter, but in the mountains the pattern can be much less regular.

The northern part of the area is traversed by the Northern Pacific and the Chicago, Milwaukee, St. Paul and Pacific Railroads, and the Great Northern Railroad, also within the area, connects Butte with Helena. Butte is connected with Salt Lake City and other points to the south by the Oregon Short Line branch of the Union Pacific Railroad, which crosses the west side of the area. Also, many spur lines from these railroads extend into the area, yet a considerable part of the area is more than 20 airline miles from the nearest rail, and, because of the mountainous terrane, a much larger part is more than 20 miles away by shortest truck route. Much of the phosphate in the most remote parts of the area is of low grade.

Paved highways traverse the northern and western parts of the area and generally follow the rail routes. Other paved roads generally follow major streams or connect the larger towns. Many good graveled roads extend into other parts of the area. Unimproved dirt roads give access to most parts of the basins, and numerous forest trails extend into the mountain areas. The most rugged parts of the area, however, are still inaccessible except on foot or horseback.

The area includes several of the principal cities of Montana—Butte, Bozeman, Livingston, Dillon—and many smaller towns, most of which are serviced by rail. But large parts of the area are many miles from the nearest town and are sparsely populated. Mining is the principal industry of Butte, and there are active mines in several other areas, chiefly near Dillon, Virginia City, and Melrose. Phosphate is mined near Melrose and has been mined in the Centennial Mountains and in the Snowcrest Range. The phosphate from Melrose is treated in the furnaces at Silver Bow, west of Butte, to produce elemental phosphorus. Other phosphate rock is treated at Garrison to make a low-fluorine animal-feed supplement.

STATUS OF LAND OWNERSHIP AND MINERAL RIGHTS

The area discussed in this report is more than 15,000 square miles. About 2,500–3,000 square miles of this area, or less than 20 percent (fig. 169), is known to be underlain by Permian rocks. Most surface exposures of these rocks are in the more rugged, or mountainous, parts, but many of the basin areas are underlain by Permian rocks at depth. Except for some of the basin areas, most of the southwest Montana area underlain by Permian strata is public land, largely in the Beaverhead, Deer Lodge, and Gallatin National Forests, but also in other Federal, State, and railroad lands.

A report by Willey, Cressman, Pierce, and Cheney (1954) shows the ownership of land near the Permian outcrops in a large part of southwest Montana. Also given are a brief description of the classification used and a discussion of those private lands where phosphate or other mineral rights are reserved by the Government.

The first discovery of rock phosphate in Montana was made by Gale (1911) in the Melrose area during the summer of 1910, but the discovery of oolitic phosphate beds in rocks of the same age in southeastern Idaho and adjacent parts of Wyoming and Utah had been made several years earlier (Weeks and Ferrier, 1907). Following the earliest discovery of rock phosphate in the west, both placer and lode claims were filed, in some instances on the same ground, and litigation resulted. In December 1908 (Gale and Richards, 1909, p. 457) the Secretary of the Interior withdrew 4,541,300 acres (about 7,000 sq mi of public land in the area of southeastern Idaho and adjacent States from all claims pending examination and classification of the phosphate resources. Examination was to be carried out by the Geological Survey. Subsequent withdrawals have been made, and the program of classification has continued.

Application of lode and placer laws to the bedded-phosphate deposits was not satisfactory, and the mineral leasing act of February 25, 1920,[1] was passed "to promote the mining of coal, phosphate, oil, oil shale, gas, and sodium on the public domain." Under this law and its amendments, the United States retains the title to such deposits as noted above but may lease specified acreages at certain fees, among which is a royalty on phosphate. Phosphate lands, therefore, may no longer be awarded for mining claims. Applications for leases must be made in the appropriate office of the Bureau of Land Management. Award of lease is made after evaluation of geologic factors by the U.S. Geological Survey, and supervision of the lease is the responsibility of the Conservation Division of the Survey.

EXPOSURE AND SAMPLING OF THE PERMIAN STRATA

The phosphatic shale members of the Phosphoria Formation consist chiefly of strata that are fairly nonresistant to weathering and erosion. Rarely, therefore, are these strata naturally exposed. In some areas, particularly where the members are thin and lie between resistant strata and where rugged topography prevails, the phosphatic shales can be satisfactorily exposed by use of pick and shovel. In much of southwest Montana, however, exposure must be made by bulldozer (fig. 170).

[1] United States Statutes at Large, 66th Congress, 1919–21, v. 41, pt. 1, Public Laws, Statute II, chap. 85, p. 437.

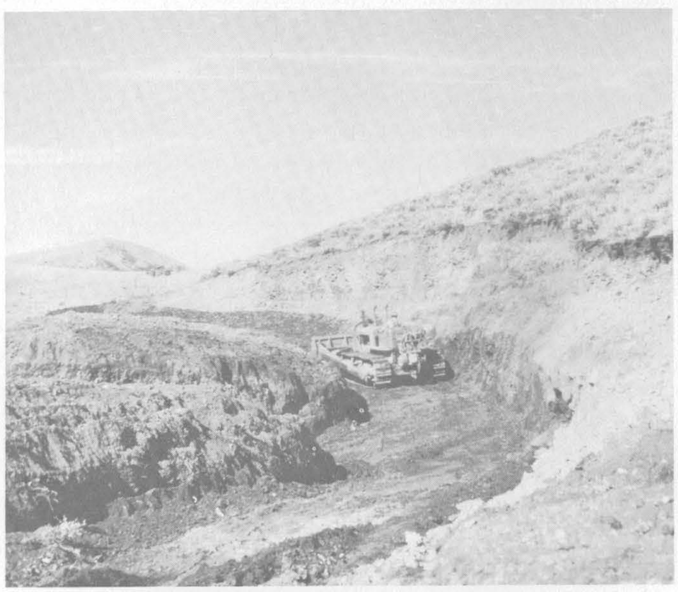


FIGURE 170.—Trench preparation with bulldozer at Little Water Canyon, west of Lima (lot 1341). West along trench. Top of Franson Member of Park City Formation in foreground. Tosi Chert Member of Phosporia Formation behind bulldozer. Fault by bulldozer cuts out upper part of Retort Member and lower part of Tosi Chert Member. Note thick mantle that effectively conceals soft phosphatic shale.

Almost all bulldozer trenches prepared for this study were cut to a depth of more than 5 feet to reach unaltered rock that had not been affected by slumping or other creep; some trenches had to be cut to depths of 25 feet or more. For example, the top of the exhaust stack of the bulldozer in figure 170 is about 9 feet above the trench floor. Some trenches were cut so deep that benches or steps had to be left on the high side for safety.

Some of the stratigraphic information on the Melrose district was obtained from mine openings. Because these openings have generally been made only in the more phosphatic parts of the shale member, data on the full thickness of the member were often not obtainable. Generally, rock samples from mine exposures are fresher than those from surface exposures.

Channel samples were collected from each lithologic unit whose thickness was not less than 0.5 foot nor more than 5 feet. Surfaces were smoothed, or planed, and swept clean before channeling to insure uniformity and avoid contamination. Channels were of fairly uniform width and depth (5–8 × 2–4 in.), and the samples generally averaged 12–15 pounds, although thick units generally yielded larger samples. Most samples were cut with geologic pick, but some hard rocks required use of moil or cold chisel and heavy hammer. Samples were collected in heavy canvas sacks that were double tied and triple labeled to insure against loss or misidentification.

All samples were analyzed for P_2O_5, acid insoluble, and equivalent uranium (eU), and many, chiefly those richer in phosphate, for Al_2O_3, Fe_2O_3, loss on ignition, F, and chemical uranium. Analyses for organic matter and spectrographic analyses for many major and minor elements were made on samples obtained across a member, or across the entire sequence, at selected localities, and oil content was determined for samples of the Retort Member from the type locality (lot 1234). Analytical data obtained from the samples, and petrographic descriptions of the strata they represent, are included in a preceding chapter of this professional paper (Cressman and Swanson, 1964).

ACKNOWLEDGMENTS

More than 25 geologists and assistants have participated in measuring and sampling the stratigraphic sections used in this study, and their help is greatfully acknowledged. (See Cressman and Swanson, 1964.) The contributions to this study made by V. E. McKelvey, under whose guidance the studies in the western phosphate field were organized and conducted, and by E. R. Cressman are also gratefully acknowledged. The author appreciates the many suggestions by, and discussions with, other colleagues engaged in various aspects of the western phosphate studies, particularly M. R. Klepper, A. E. Weissenborn, F. C. Armstrong, W. B. Myers, G. C. Kennedy, R. P. Sheldon, R. A. Gulbrandsen, and T. M. Cheney.

GEOLOGIC HISTORY

The rocks of southwest Montant represent most of the geologic eras and include a wide variety of igneous, metamorphic, and sedimentary types. Crystalline Precambrian basement rocks are exposed in a large part of the area and are unconformably overlain by a thick sequence of strata of the late Precambrian Belt Series, which are present only along the north and west sides of the area.

Paleozoic and lower Mesozoic strata, which once covered the entire area, are dominantly shallow-water-marine varieties and range in thickness from 3,500 to 9,000 feet or more. They are overlain by at least as great a thickness of upper Mesozoic mixed marine and continental deposits that, upward, include progressively more volcanic material.

Severe deformation during the Laramide orogeny was accompanied by extensive uplift, erosion, and continental deposition, and by intrusion of large granitic bodies. Later events were chiefly periodically renewed fault-block and regional uplift, extensive erosion, continental deposition, and volcanism.

The following discussion summarizes the principal geologic events that affected the report area. Emphasis is given to those events that most directly affected the Permian rocks; details of Permian stratigraphy are discussed in a preceding chapter (Cressman and Swanson, 1964).

REGIONAL STRATIGRAPHY

Precambrian rocks crop out extensively in southwest Montana and represent two major series—older, crystalline rocks and younger, Belt sedimentary rocks. The older rocks include a large variety of metamorphic and igneous types and form the basement complex of the entire area. Ancient tectonic elements within the older rocks have exerted major controls on the depositional and techonic history of the region. (See Thom, 1923; Chamberlin, 1945; Sloss, 1950.) These rocks directly underlie Paleozoic strata in most of Wyoming and the adjacent part of Montana (Wyoming shelf of Sloss, 1950) and also in much of northern Montana; the southernmost exposure of the latter is near Neihart. A northwesterly extension of the Wyoming shelf makes up more than half the report area and is here called the southwest Montana positive area (fig. 171). It extends west to about the 113th meridian and north

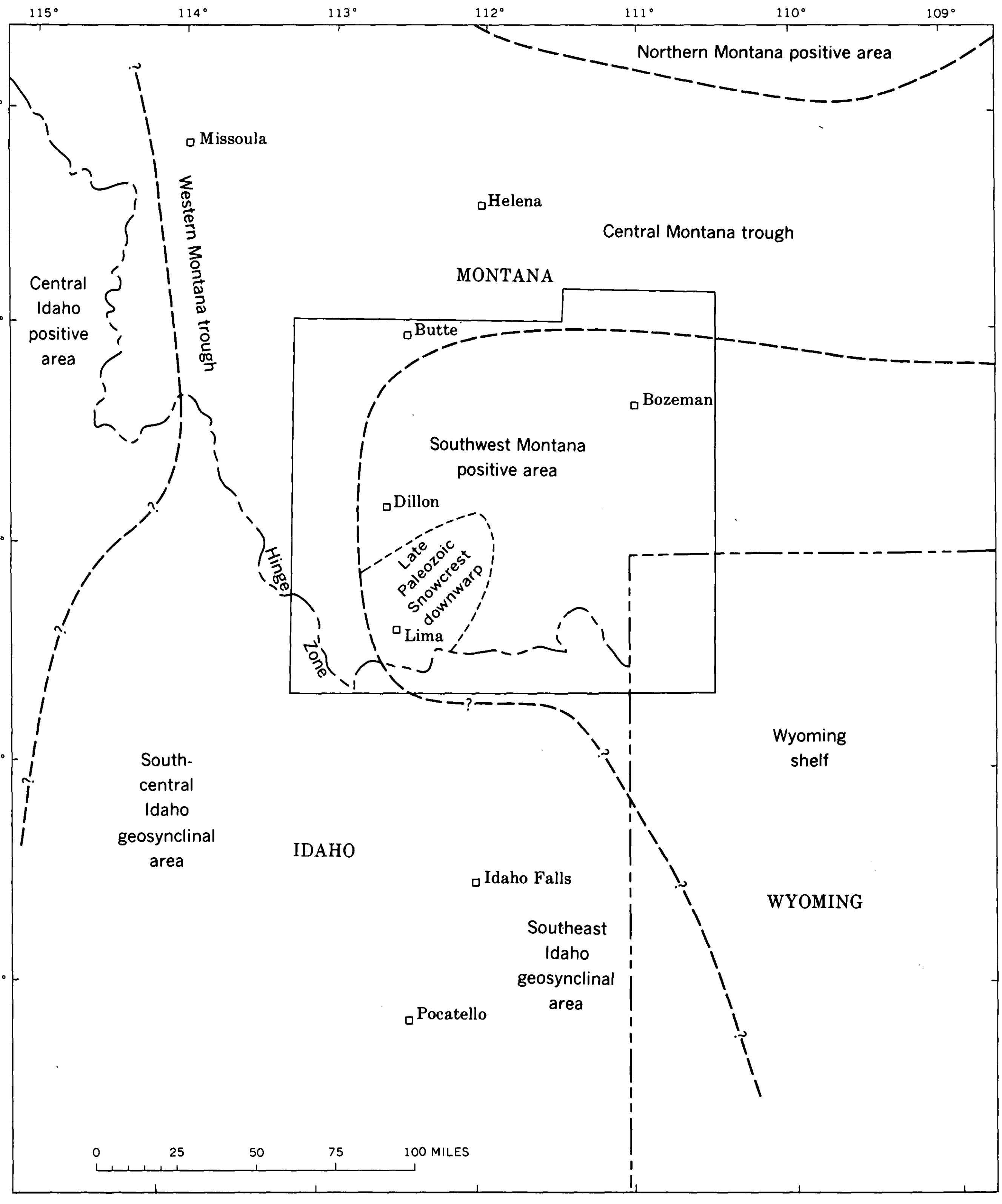


FIGURE 171.—Major tectonic elements of the Paleozoic Era in southwest Montana and adjacent areas. Prepared from data compiled by Mansfield (1927), Ross (1934, 1958b) and Scholten, Keenmon, and Kupsch (1955).

to about lat 45°50′ N., and it is fairly straight sided. The south boundary of the positive area is not known, but it is believed to be just south of the Idaho State line near the north boundary of the Snake River Plain.

A thick sequence of strata of the late Precambrian Belt Series was deposited in western Montana and in an easterly embayment into central Montana. On the south side of the embayment the strata include very coarse conglomerates (La Hood Formation of Alexander, 1955) that apparently accumulated against a fault scarp. (See McMannis, 1963.) Elsewhere the strata are dominantly fine-grained clastic sediments that are weakly metamorphosed to quartzite and argillite and some impure limestones.

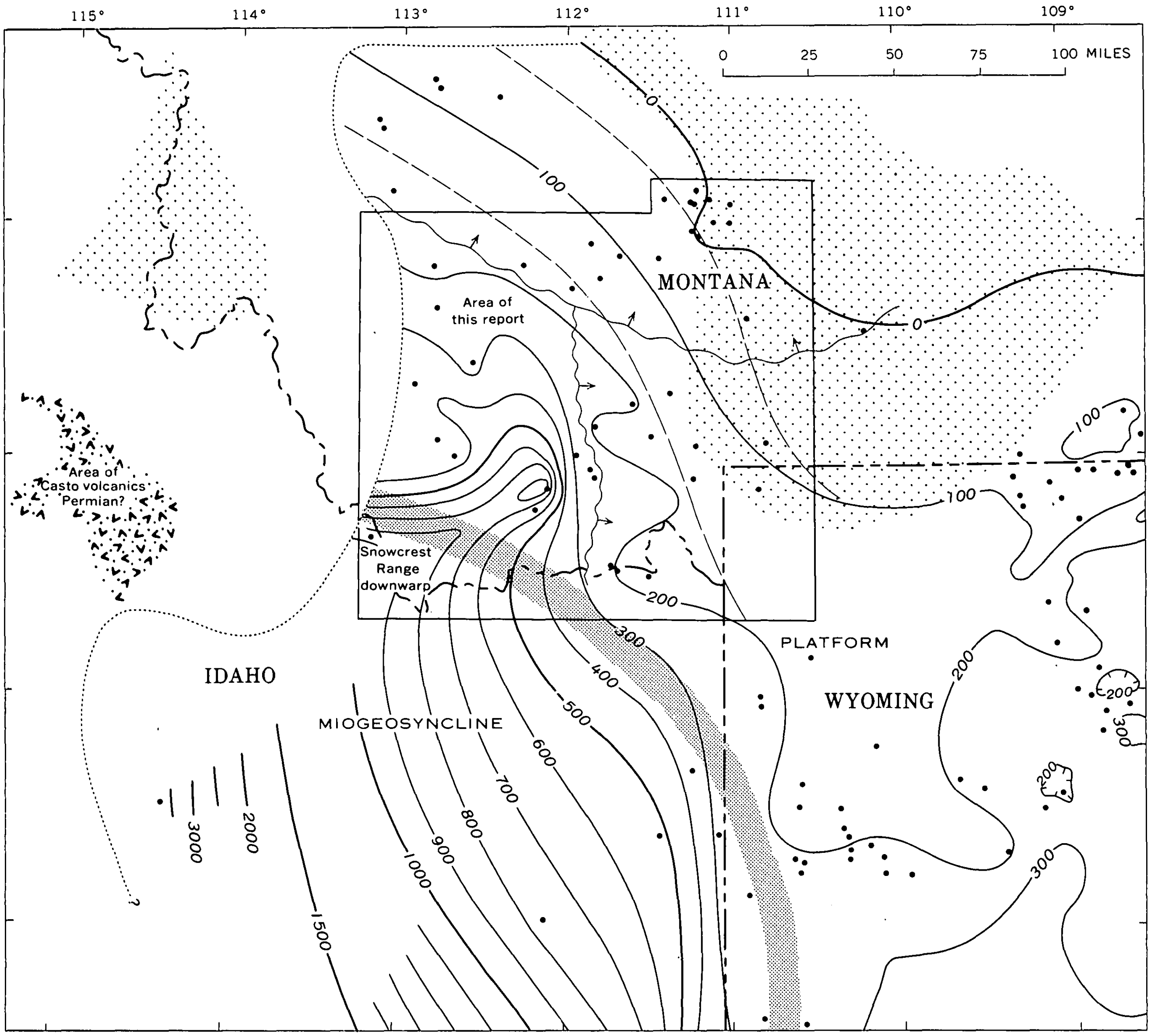
McMannis (1963) measured 18,000 feet of Belt strata in the Highland Mountains near the west (open) end of the embayment, just north of the crystalline area of southwest Montana that supplied the coarse arkosic sediments. He measured more than 10,000 feet in the Bridger Range. Ross (1959, p. 17) indicated a total thickness of 21,600 feet at "Helena and vicinity including Belt and Little Belt Mountains" in the central part of the embayment. In the main part of the geosyncline, Belt strata are much thicker; they are nearly 46,000 feet thick at "Missoula and vicinity including Philipsburg quadrangle" and 45,000 feet thick near Libby, at the northwest corner of the State (Ross, 1959, p. 17). The base of the Belt is not exposed, and, therefore, the full thickness is not known anywhere west of the mountain front in northern Montana or west of about the 113th meridian in southern Montana. The west border of the southwest Montana positive area is in a zone of tight folds and thrust faults. Neither the thickness of the Belt strata near this margin nor the relation of the Belt to the crystallines is very well known, but Myers (1952) measured more than 10,000 feet of Belt strata in the Pioneer Mountains northwest of Dillon, all in thrust plates, and, in the Tendoy Mountains west of Lima, both crystalline rocks and Belt strata occur in thrust plates.

Although the southwest Montana positive area was a highland that supplied coarse debris to the Belt seaway, it was reduced to fairly low relief before deposition of the Middle Cambrian Flatland Sandstone. Locally, much of the Belt sediment was also eroded before Cambrian deposition (Klepper and others, 1957; McMannis, 1963; Maxwell, 1959; Poulter, 1956); however, Ross (1958a) questioned the existence of a major sub-Cambrian unconformity.

Chiefly platform facies sediments accumulated over this region during the Paleozoic Era; sandstone is dominant at the base and near the top and carbonate rock and shale in the rest of the Paleozoic section. Thickness ranges from about 3,000 feet at the east, near Yellowstone National Park, to a known maximum of about 7,000 feet at the west side of the report area. Thick miogeosynclinal sediments accumulated in nearby southeastern and south-central Idaho (fig. 171). The boundary between the rocks of this area and those of southeastern Idaho is covered, and its character unknown, but the boundary with the south-central Idaho area has been described as a hinge zone (Sloss and Moritz, 1951; Scholten and others, 1955; Scholten, 1957; Ross, 1958b). Ross believed that "the area of the Idaho Batholith [central Idaho] has been a positive block since Precambrian time" and that "any invasion by marine waters during the Paleozoic was local and brief, except perhaps along the western border." This concept corresponds to the seaway-distribution maps of Schuchert (1955), but not with the maps of Eardley (1951), Kay (1951), or Sloss (1950), which show the main Paleozoic geosyncline as crossing that area. All post-Belt strata have been removed from central Idaho. A shallow depositional trough extended northward between the positive blocks of central Idaho and of southwest Montana and connected the south-central Idaho geosynclinal area with the central Montana trough.

Most stratigraphic units in this report area are fairly thin, widespread, and uniform in character. Many diastems in the record show no evidence of deposition or erosion and therefore reflect stability; others, however, indicate much uplift and erosion. In Mississippian time, much local downwarping occurred in the area now occupied by the Snowcrest Range (fig. 171) and persisted through the Pennsylvanian and much of the Permian. The downwarp apparently did not exist earlier (according to data noted by Gealy, 1953; Hanson, 1952; Scholten and others, 1955; Sloss, 1950; and Sloss and Moritz, 1951), and the area may have been mildly positive then. Mississippian to Permian strata are about 6,000 feet thick in the downwarp area, more than twice as thick as in adjoining areas to the east and to the north. Exposures of these strata are limited to a narrow band along the axis of the Snowcrest Range, and in part of this band these strata are buried by continental deposits; hence, most boundaries of the downwarp cannot be defined clearly, but at the 45th parallel the east edge is between the Gravelly and Snowcrest Ranges.

This downwarp was one of the major active elements during accumulation of the Permian strata in southwest Montana (fig. 172). As post-Retort Member strata in this area range mainly from 100 to 140 feet



EXPLANATION

Probable land areas during part of Permian time, a composite taken from Cressman and Swanson (1964, pl. 25)

Approximate boundary of area containing Permian strata

Permian strata partly stripped by pre-Dinwoody (Triassic) erosion

Permian strata partly stripped by pre-Ellis (Jurassic) erosion

Where disconformably overlain by Triassic or Jurassic strata

Presumed original thickness (before Triassic erosion)

Presumed original thickness (before Triassic and Jurassic erosion)

Approximate boundary between miogeosynclinal and platform facies

Control point

500

600

Contour showing thickness, in feet; contour intervals 100 and 500 feet

FIGURE 172.—Permian rocks in southwest Montana and adjacent area. Wyoming adapted largely from Sheldon (1963). Includes, also, data from Bostwick (1955), Condit and others (1928), Ketterer and Swirczynski (1952), McKee and others (1959), McKelvey and others (1959), Ross and Forrester (1947), Scott (1935), and Tourtelot (1952).

in thickness, except where thinned toward the east and northeast by post-Permian erosion, most of the variations shown in figure 172 formed earlier. Details of stratigraphic relations are given by Cressman and Swanson (1964).

Platform conditions persisted into the Mesozoic, which is represented by as much as 2,000 feet of marine Triassic and Jurassic strata. The Triassic strata unconformably overlie the Permian in the eastern part of the area. A widespread unconformity also occurs beneath the Jurassic rocks (McKee and others, 1956; Peterson, 1957), transecting the Permian near Three Forks and successively older formations northward onto the Sweetgrass arch. Possibly as much as 1,000 feet of strata was removed by this erosion, including 50 feet to perhaps 100 feet of Permian strata near Three Forks.

Continental and marine conditions alternated in Late Jurassic and Cretaceous time, during which clastic debris was shed chiefly from the rising and expanding central-Idaho positive area. Volcanic debris, largely from the Boulder batholith area, is increasingly abundant upward in the section; locally the Upper Cretaceous rocks are 10,000 feet or more thick.

LARAMIDE OROGENY

Tectonic forces of the Laramide orogeny, which began late in Cretaceous time and continued into early Tertiary, brought to a close the long period of sedimentation in this region. Both simple and complex patterns of folds and faults evolved and characterize the areas critical to this study. Intrusive and extrusive igneous activity was widespread, and the region was uplifted and eroded extensively during the orogeny.

Within the southwest Montana positive area (fig. 173) a fairly simple structure pattern formed that involved chiefly the differential uplift and tilting of large blocks of the rigid crust. Faults in that area are mostly steep and reflect vertical movements along major shears controlled by ancient tectonic elements. The weakly competent sedimentary formations that overlie the crystalline rocks draped across the zones of dislocation, thus yielding a pattern of strongly asymmetric folds that have gentle dips over the tops of the blocks and steep to overturned dips above the shear zones. Some of the shear zones extended up through the sedimentary sequence as normal faults or as steep reverse faults.

Along the west side of the positive area, in the region of the western Montana trough of Paleozoic time (fig. 171), a pattern of tight folds and faults reflects a synclinorium (fig. 173) that averages about 20 miles wide and that extends about 160 miles north from the southwest corner of Montana almost to Drummond. The complex structure of the synclinorium includes folds overturned to the east, extensive thrust faults that are in part imbricate, and numerous cross faults of large and small displacement. Structural foreshortening may be more than 10 miles, and rocks from Precambrian through Cretaceous age are complexly associated. The synclinorium is bounded on the west chiefly by a large area now composed dominantly of Belt strata. In the southernmost part, however, the area to the west contains thick geosynclinal Palezoic strata, and the west boundary is less readily defined. The synclinorium terminates abruptly on the north near the Clark Fork River at the "Lewis and Clark line" (fig. 173) of Billingsley and Locke (1941). Structure patterns north of that line are very different from those to the south.

The Boulder batholith invaded the western part of the central Montana trough of Paleozoic time. East of the batholith the structure pattern shows many folds and faults in a belt that trends generally northward. Structure in this eastern belt is generally less complex than that to the west in the main synclinorium, but some overthrusting has occurred. To the north, this belt, or branch, swings slightly westward and, north of Helena, apparently connects with the Disturbed Belt (Dobbin and Erdmann, 1955; Robinson, 1959), which constitutes the mountain-front structural complex of northern Montana and which includes much overthrusting. To the south, the belt swings westward from Three Forks and includes the Jefferson Canyon structural complex, which extends from nearly 20 miles east of Whitehall to the Jefferson valley about 8 miles south and a little west of Whitehall. This complex is at the north edge of the southwest Montana positive area and most probably has been controlled partly by it. From there, the zone apparently trends southwest across the northwest corner of the positive area and joins the structural complex of the synclinorium near Dillon. Because the Whitehall to Dillon interval is largely covered, details of that part of the gross structure are not clear.

POST-LARAMIDE HISTORY

Thick conglomerates and other continental sediments accumulated in basin areas formed during the Laramide orogeny (Lowell and Klepper, 1953), some early enough to be folded and thrust faulted by late episodes of the orogeny. Later, the region underwent a complex history of uplift and erosion, the former by both broad warping and local block faulting. Quiet to explosive volcanic activity has been both widespread and frequent and has included basaltic to rhyolitic

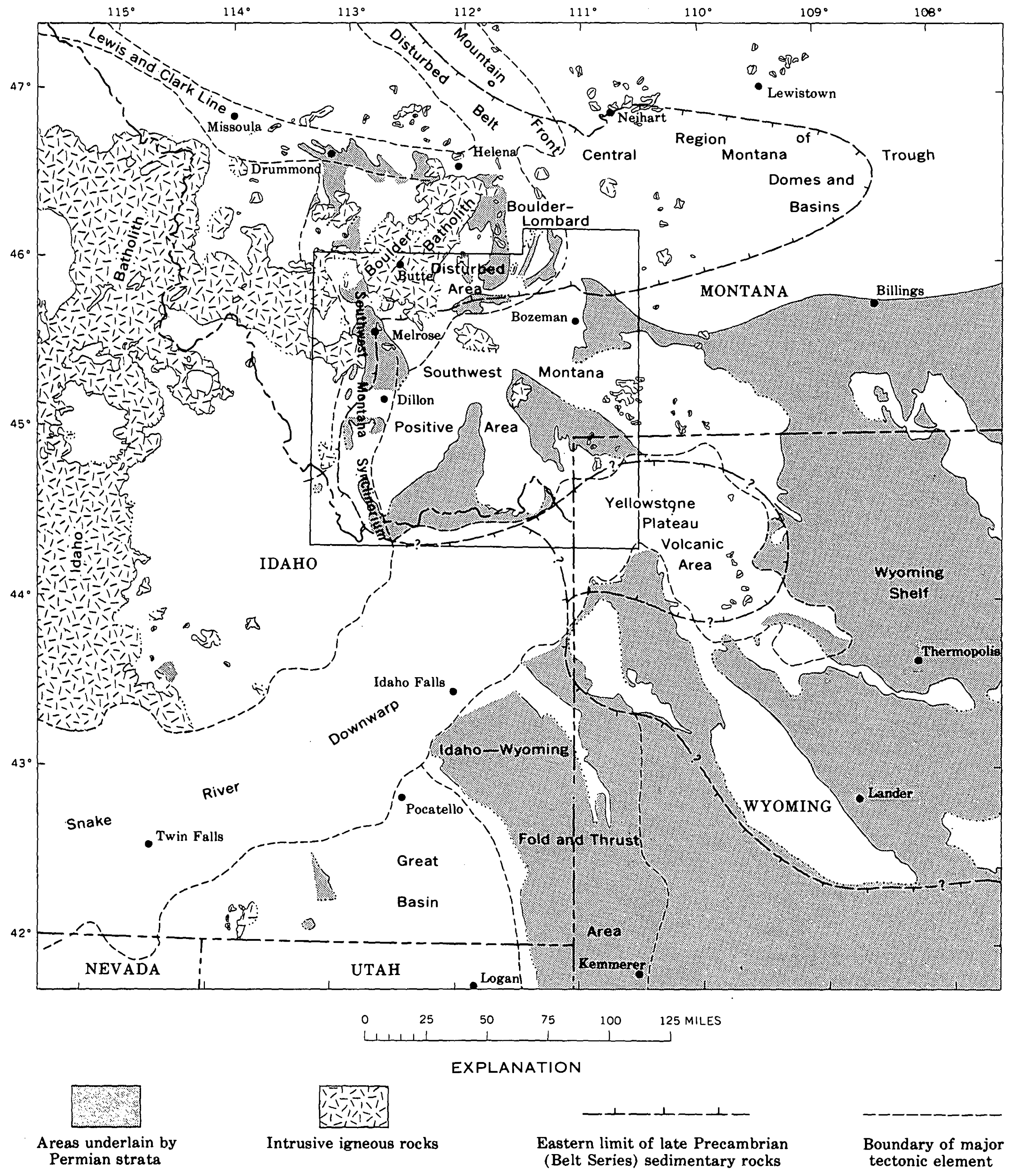


FIGURE 173.—Distribution of Permian rocks, major tectonic elements, and intrusive igneous rocks in southwest Montana and adjacent area. Includes data from Billingsley and Locke (1941), Bostwick (1955), Dobbin and Erdmann (1955), Love and others (1955), Merewether (1960), Ross and others (1955), Ross and Forrester (1947), and Sloss (1950).

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rocks. Some structural and lava-blocked basins received thick continental deposits; streams on such deposits were later superposed on buried bedrock divides. Elsewhere, antecedent streams cross mountain masses that have been uplifted many thousand feet. Short but deep canyons have resulted. Regional planation in the Eocene and Pliocene alternated with canyon-cutting stages. Mountain glaciation during the Pleistocene modified nearly all the ranges, some very extensively. Uplift by block faulting is still active, as indicated by widespread fault scarps (Pardee, 1950) and by many historical earthquakes.

OCCURRENCE AND CHARACTER OF PHOSPHATE IN MONTANA

The phosphate deposits in the western phosphate field represent concentrations of sedimentary apatite that formed near the border zone between the Cordilleran miogeosyncline and the platform to the east (McKelvey, Swanson, and Sheldon, 1953). The phosphorites and phosphatic mudstones are parts of the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation (McKelvey and others, 1959). Cressman and Swanson (1964) fully described the stratigraphy of these members; therefore, only major features of the stratigraphy, lithology, and lithofacies trends, and other aspects of the geology significant in prospecting and mining are summarized here.

STRATIGRAPHIC AND AREAL DISTRIBUTION

The Permian rocks of southwest Montana attain a maximum thickness of more than 800 feet near Lima and in the Snowcrest Range (fig. 172). They thin northward and eastward, by overlap, by shoreward thinning and pinchout, and by post-Permian removal, and they are generally less than 200 feet thick east of the Gravelly Range and north of Melrose. Most of these rocks represent platform facies with tongues of geosynclinal facies. They include chiefly phosphatic shale and chert assigned to the Meade Park, Rex, Retort, and Tosi Members of the Phosphoria Formation, carbonate rock assigned to the Grandeur and Franson Members of the Park City Formation, and sandstone assigned to the lower and upper members of the Shedhorn Sandstone (McKelvey and others, 1959). The members of these formations intertongue regionally, and individual lithologies intertongue locally in a complex manner. Strata representing all three formations are found throughout most of the area of this report. (See Cressman and Swanson, 1964, for stratigraphic correlation diagrams.) Nearly all the phosphate in the Permian rocks of this region occurs in the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation.

The Meade Peak Member is present only in the southern and western parts of the area, lensing out in the Gravelly Range, on the east, and near McCarthy Mountain and in the Pioneer Mountains, on the north and northwest. Its maximum thickness—nearly 30 feet—occurs to the southwest near Lima (Cressman and Swanson, 1964, fig. 117). That area contains the greatest total phosphate—more than 300 feet-percent (thickness × percentage of P_2O_5) of P_2O_5—but most of the area contains less than 200 feet-percent of P_2O_5 (fig. 174*A*).

The Meade Peak Member contains a minable thickness of phosphate rock only in the area south of the 45th parallel and at the localities sampled near the Big Hole River (fig. 169, lots 1354, 1358), but the Big Hole deposit is apparently a lenticular bed of very limited areal extent. In the southern part of the area, the best phosphate and the only zones of minable grade 3 feet thick or more occur at or near the base of the member. Eastward the phosphate rock tends to thicken and to improve in quality by thinning or pinchout of shaly partings, but the member also thins in that direction. Farther east—at the easternmost localities where the member is known—the member is thin, and phosphorite constitutes almost the entire thickness. Much of this eastward thinning is due to the combined effects of facies change and intertonguing with other lithologies.

The Retort Member extends over nearly all of the report area. It is thickest in the western part of the area, reaching a maximum thickness of 85 feet at Big Sheep Creek (lot 1225), west of Lima, and it is 83 feet thick at Hogback Mountain (lot 1299) in the Snowcrest Range. It thins gradually northward and irregularly eastward (Cressman and Swanson, 1964, fig. 123) and it tongues out to the northeast near Three Forks. The total phosphate in the Retort Member in southwest Montana (fig. 174*B*) is more than 800 feet-percent of P_2O_5 at Hogback Mountain, in the Snowcrest Range, and exceeds 500 feet-percent in areas northwest and southwest of that locality. Most of the area west of the 112th meridian contains more than 200 feet-percent of P_2O_5.

Most phosphate in the Retort Member in southwest Montana occurs in thin beds of phosphorite. Much of the phosphorite is very argillaceous and is interbedded with partings or thicker beds of very low grade shale; therefore, the quality of beds of minable thickness is generally poor. Nevertheless, rock that is of minable thickness and that contains more than 18 percent P_2O_5

occurs at nearly every sampled locality except those within 35 miles of Three Forks (pl. 26). Few localities south of Melrose, however, include as much as 3 feet of rock containing more than 24 percent P_2O_5.

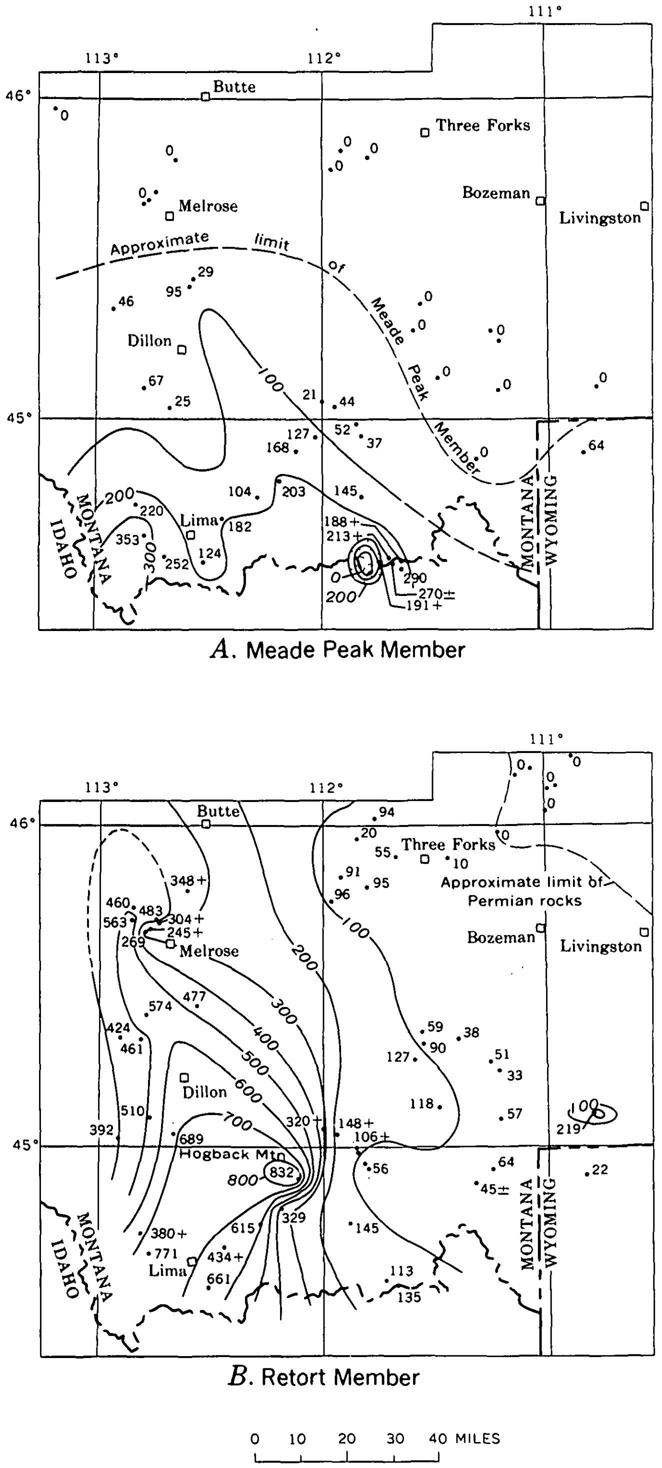

FIGURE 174.—Total phosphate in the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation, southwest Montana. Contour values are in feet of thickness multiplied by the percentage of P_2O_5. *A*, Meade Peak Member; *B*, Retort Member.

The phosphate in the Retort Member is unevenly distributed toward the southwest, where the richest beds of phosphate generally occur in zones near the base, middle, or top; one or two of these zones may be of very low grade or may be unrecognizable at an individual locality. Northward, however, individual beds of phosphorite are generally both thicker and of higher grade, and the low-grade partings are generally thinner and more phosphatic; thus, the zones of minable grade are both richer and thicker. The richest and thickest phosphate occurs in the northwesternmost part of the area (Melrose district), where the furnace-grade rock (24 percent P_2O_5) is as much as 12 feet thick. The upper part of the member there is the most phosphatic part.

AREAL VARIATIONS IN LITHOLOGY AND COMPOSITION

The phosphatic shale members are composed mostly of mixtures of phosphorite and mudstone, which occur together in nearly all proportions. Carbonate rock is common though not abundant. Carbonaceous matter is nearly everywhere present, though nowhere is it the principal constituent of a bed and it is the principal cause of the dark color of typical phosphatic shale. Toward the margins of the area, interbeds of chert and (or) of sandstone represent intertonguing with other stratigraphic members. In places the boundaries between members are gradational and arbitrary.

In contrast to many formations or members of formations in the Rocky Mountain region, the phosphatic shale members of the Phosphoria Formation are compound stratigraphic units of somewhat unusual character and composition. The large number of sections measured during this study, the chemical reports from the many samples, and the detailed field notes, substantiated by rock chips for laboratory study from all measured strata, made possible the extensive analysis of the stratigraphy of these rocks (Cressman and Swanson, 1964). Nevertheless, many questions remain unanswerable, and many answers must be qualified. This is illustrated by McKelvey's statement on the interpretation of chemical analyses of Phosphoria rocks (McKelvey, Davidson, and others, 1953 p. 3, 4):

> Nearly all the phosphate is in carbonate-fluorapatite, which has a composition of about $9CaO{\cdot}3P_2O_5{\cdot}CaF_2{\cdot}CO_2{\cdot}H_2O$. The percentage of P_2O_5 multiplied by 2.56, therefore, gives the approximate percentage of the phosphate mineral. The percentage of tricalcium phosphate, $3CaO{\cdot}P_2O_5$, or bone phosphate of lime (B.P.L.) as it is called in the phosphate industry, may be calculated by multiplying the percentage of P_2O_5 by 2.18.
>
> Acid-insoluble content may be determined by a variety of procedures that yield widely different results. In the analyses reported here, the acid-insoluble content represents that portion of the rock not soluble in aqua regia and not ignitable or

volatile at about 1,000°C. The acid-insoluble fraction consists principally of silica, but it generally also includes 10–30 percent of the total iron oxide, alumina, and titania and a generally negligible percentage of phosphate, magnesia, lime, and several minor metals such as zirconium. Mineralogically it may be taken as an approximate index of the total amount of detrital minerals in the rock; the fact that some of the detritals may have been partially dissolved by the acid treatment is counter-balanced by the fact that many rocks contain some secondary chert. Attention is called to the fact that the acid-insoluble residue determined in this fashion includes little if any carbonaceous matter.

That portion of the rock not in carbonate-fluorapatite or acid insoluble, that is, A. I. $+(P_2O_5 \times 2.56)$, includes the CaO and CO_2 not in fluorapatite as well as nearly all the MgO, Na_2O, K_2O, SO_3, organic matter, and minor metals such as vanadium, chromium, nickel, zinc, etc. (even some of the zirconium is in acid-soluble form); it also includes all the Fe_2O_3, Al_2O_3, and TiO_2 that would be reported in separate analyses for these constituents (only soluble iron, alumina, and titania are generally reported). Mineralogically this portion of the rock consists mainly of calcite and dolomite; pyrite, marcasite, and other sulfides; limonite, hematite, and other iron oxides; iron sulfates and gypsum; and organic matter. The minerals containing the soluble alumina, alkalis, and minor metals are as yet poorly defined, but they seem to be mainly of the hydromica type.

Loss on ignition includes chiefly carbonate CO_2, organic matter, and water. It may also include some sulfur, depending upon the minerals present in the rock and the temperature reached during ignition. Loss on ignition may be taken as a rough measure of the organic-matter content if the rock contans no carbonates and little or no clay or if CO_2 and water have been determined and can be substracted from the loss on ignition.

An accurate total of all constituents is extremely difficult to obtain, even when all the constituents present, and this may include 30 or 40, are determined. This is partly because the accurate determination of many constituents in phosphate rock is extremely difficult and partly because the state of oxidation of many of the elements is not known. Thus, iron is generally reported as Fe_2O_3 but it may actually be present as FeO, FeS_2, etc.; vanadium is reported as V_2O_5 but may be present as V_2O_3; and sulfur is reported as SO_3 but is known to be present as organic, sulfide, and sulfate compounds. The same uncertainty applies to several other elements, particularly metals.

The mineralogy and chemistry of the marine phosphates have been the subject of much investigation. Kazakov (1937) showed that carbonate-fluorapatite precipitates from marine waters containing fluorine, and Gruner and McConnell (1937; summarized by McConnell in 1938) presented evidence that carbonate-fluorapatite (francolite from Poland and Germany) is a structurally distinct species. Altschuler, Cisney, and Barlow (1952) demonstrated that marine phosphorites are composed of carbonate-fluorapatite and that this material is a distinct variety. Altschuler, Clarke, and Young (1958) and Gulbrandsen (1960a) presented good summaries of the general problem of the mineralogy and of the numerous substitutions of both anions and cations that occur.

Most apatite from the Phosphoria Formation is so fine grained that it appears to be isotropic in thin section. This variety of apatite has commonly been referred to as collophane. Generally, the apatite from the Phosphoria contains such a mixture of brown to black organic matter, clay, and quartz (as well as other constituents common to marine muds) that reliable optical characteristics and chemical analyses cannot be determined. Locally the apatite has recrystallized to an anisotropic variety referred to by some geologists as francolite. (See Lowell, 1952.) Many phosphate shell fragments also appear to be composed of this variety.

The apatite in the phosphatic rocks in Montana occurs mostly as oolitic to pelletal grains that are of very fine to medium-sand size, but nodules are locally common, and in some places organic remains—chiefly fragments of shells, fish scales, bones, and teeth — constitute a major part of some beds. The character and distribution of the various types were described in more detail by Cressman and Swanson (1964). In summary, the phosphorite to the west (basinward) is composed of compound nodules in a matrix of structureless pellets; phosphorite in the central area is composed almost entirely of pellets; and phosphorite to the east (shoreward) is made up of oolites, nodules, and organic remains. Distribution of these types varies from one bed to another, especially from the Meade Peak Member to the Retort Member. For example, in the Centennial Mountains the Meade Peak phosphorite is coarsely oolitic and light colored and contains abundant skeletal remains and numerous nodules, whereas the Retort phosphorite is finely pelletal and black. The shoreward facies of phosphorite generally contain smaller amounts of carbonaceous matter and are consequently lighter colored.

Theoretically, fluorapatite $(Ca_{10}F_2(PO_4)_6)$ has an F/P_2O_5 ratio of 0.089, but the sedimentary apatites generally contain an excess of fluorine. In the 46 Montana samples analyzed for fluorine during this investigation, the total range in ratio was from 0.081 to 0.546, but most samples ranged from 0.085 to 0.115 (fig. 175). Most of the exceptions to this small range were found in samples containing 6 percent or less P_2O_5, where minor errors in analysis or minor secondary fluorite would exert maximum influence on the ratio. In fact, the ratios for two of these samples were so high that they probably reflected either analytical error or the presence of free fluorite. The average ratio for the other 44 samples (table 1) was 0.102, or 0.101 when the samples were weighted for thickness. The

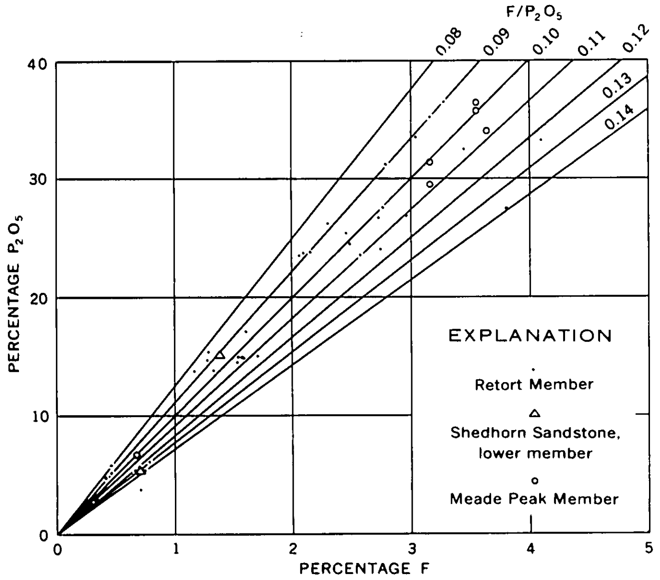

FIGURE 175.—F/P_2O_5 ratio found in samples from the Phosphoria interval, southwest Montana.

ratio for the Meade Peak Member (0.104) was higher than that for the Retort Member (0.098) when the samples were weighted for thickness. Because only seven analyses for fluorine were made of Meade Peak samples, this comparison may not be significant.

The phosphate mineral represents only about 80 percent of acid-grade phosphorite (31 percent P_2O_5) and correspondingly smaller proportions of lower grade rocks. Other rock constituents include chiefly finely divided quartz, chalcedony, mica, clay minerals, common to fairly abundant carbonaceous matter, locally common carbonate minerals, iron in the form of pyrite or limonite (depending largely on the degree of weathering), and minor amounts of many other constituents. Gypsum, formed by weathering, is common in some samples. More than P_2O_5 and acid insoluble content were determined for some samples, but for most samples both the identity and the quantity of the materials composing the rock had to be inferred from these two reports and from the field notes and the supplemental laboratory studies or rock chips.

The distribution of P_2O_5 and of acid insoluble material in both the Meade Peak and Retort Members in southwest Montana shows a close reciprocal relationship. This relationship is to be expected, for these constituents represent the dominant components of the members throughout most of the area. The sum of phosphate mineral (calculated as percent P_2O_5 times 2.56) plus acid insoluble content is generally more than 80 percent in the Meade Peak Member and between 65 and 85 percent in the Retort Member (fig. 176). The percentages decrease generally from north-

TABLE 1.—*Summary of F/P_2O_5 ratio in samples from the Phosphoria interval, southwest Montana*

Formation or Member	Number of samples	Total thickness (ft)	Total value: Thickness × percent P_2O_5	Total value: Thickness × percent F	[1] F/P_2O_5
Retort Member	37	42.8	835.93	83.248	0.100
Do	[2] 35	41.0	828.85	81.294	.098
Lower Shedhorn Sandstone	2	11.4	82.90	9.591	.116
Meade Peak Member	7	18.3	473.11	49.044	.104
Total	[2] 44	70.7	1,384.86	139.929	0.101

[1] Weighted for thicknesses of sampled intervals.
[2] The two samples omitted had such high ratios that analytical error or free fluorite was probably responsible. The samples were Nos. 288 and 290 of lot 1239, both low in P_2O_5, with ratios of 0.550 and 0.187, respectively.

east to southwest in both members, and are smallest (58 and 63 percent, respectively) at Big Sheep Creek west of Lima. Other components in the members are chiefly carbonate in the Meade Peak and carbonaceous matter, clays, and carbonate in the Retort. (See Cressman and Swanson, 1964, for further details on the stratigraphy of the Meade Peak and Retort Members.)

The average P_2O_5 content in both members is 10–12 percent, but the Meade Peak is much thinner and is considerably less extensive than the Retort. Both members are the most phosphatic in an arcuate zone extending west, and then northwest, from Yellowstone National Park, and their average grade is progressively lower toward the southwest and the northeast. Both members thin markedly (or pinch out) and increase in P_2O_5 content toward the northeast; the mudstones commonly grade in that direction into thin-bedded chert layers that are included in the Rex and Tosi Members.

The clastic material associated with the phosphorite is chiefly fine quartz sand near the east and north margins of the phosphatic shale members, especially in the beds near the base or the top of a member. Quartz silt is the principal diluent in the members within these marginal areas, as well as throughout the members farther west and southwest, but mica silt and clay are common. Still farther west, the rocks contain a larger percentage of clay.

The iron and aluminum contents of phosphate rock are important factors in both the furnace- and the acid-treatment processes, which are described later in this report. The number of samples analyzed for these constituents was sufficient to furnish a fair idea of the general distribution of the iron and aluminum but not to establish reliable patterns of regional distribution.

Of the 222 samples analyzed for Al_2O_3 and Fe_2O_3, 170 represent all samples at two localities—Sheep Creek and Jack Creek (lots 1234 and 1218; the Franson Member of Park City Formation was not sampled at Jack Creek)—and all samples from the base of the Meade

Peak to the base of the Retort at Big Sheep Creek (lot 1225). The values for the individual samples, by locality and by member, and the weighted average content of these components, by formation and member, as well as a notation of the thicknesses of strata for which data are available, are shown in figure 177.

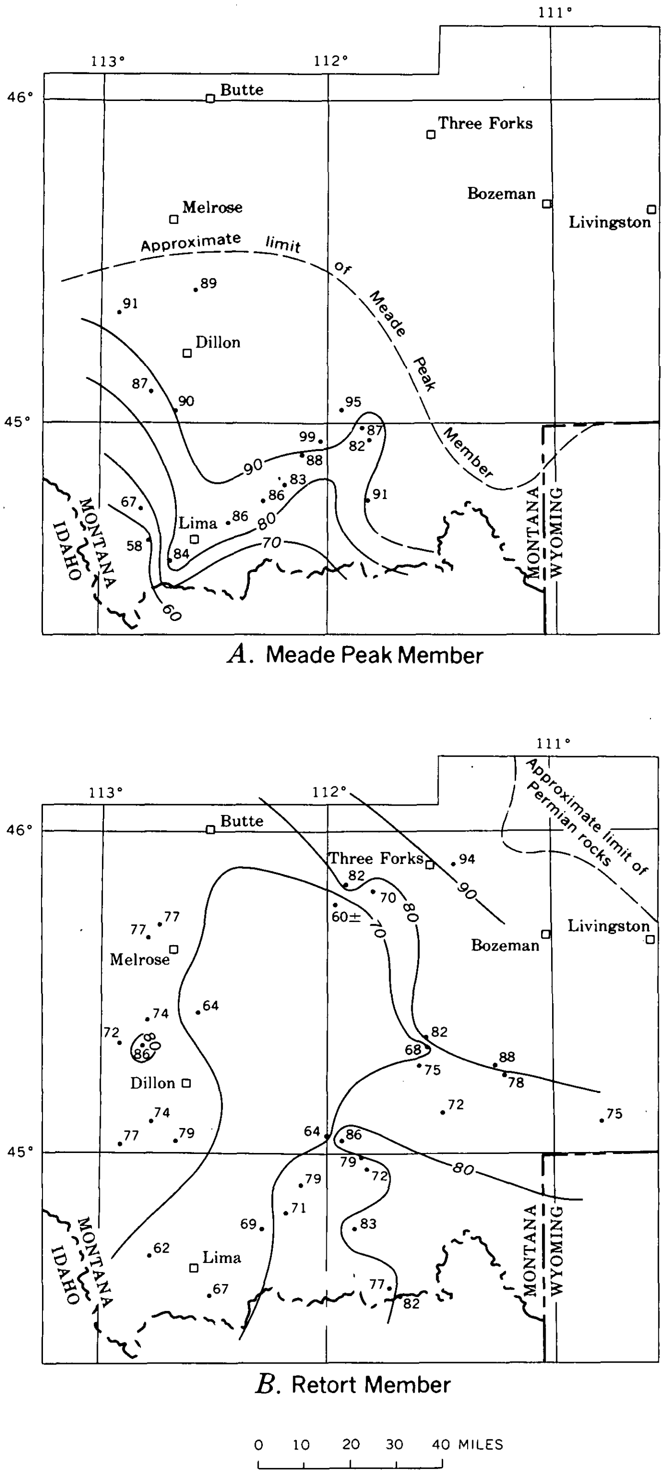

FIGURE 176.—Distribution of combined apatite ($P_2O_5 \times 2.56$) and acid insoluble material in the Meade Peak and Retort Phosphatic Shale Members of Phosphoria Formation, southwest Montana. Contour values in percent. *A*, Meade Peak Member; *B*, Retort Member.

All the high-alumina samples (those containing more than 6 percent Al_2O_3) are from shaly beds. The Retort Member contains more than 6 percent Al_2O_3 (weighted average), and the Grandeur, Meade Peak, and Tosi Members contain nearly 4 percent if the shaly beds most closely related to them are included. Most samples from other members contain less than 4 percent Al_2O_3; the average of all samples from those members is less than 2 percent. More than two-thirds of the phosphatic shale member samples containing less than 6 percent Al_2O_3 contain more than 18 percent P_2O_5; all samples containing more than 31 percent P_2O_5 for which data are available contain less than 4 percent Al_2O_3. Most of the alumina is probably in clay minerals. The Retort Member at its type locality south of Dillon (lot 1234) contains 8.5 percent Al_2O_3, an unusually high amount. If all the Al_2O_3 at this locality were in the form of illite,[2] it would represent 26 percent or more of the total member, and if it were muscovite, it would represent 22 percent or more of the member.

Alumina is most abundant in the shaly rocks, but iron is most abundant in the cherty rocks. The Rex and Tosi Chert Members average 3.74 percent Fe_2O_3, and most cherty beds of the other members contain more iron than the adjoining beds. The average Fe_2O_3 content of all analyzed strata from other than the two chert members is 2.4 percent, and the average values for all the members except the Rex and Tosi are similar (fig. 177). Although iron probably occurs chiefly as limonite in the moderately weathered sections sampled, much of it probably occurred as pyrite before weathering, for thin sections show numerous tiny opaque cubes and other euhedral forms that are pseudomorphs of limonite after pyrite.

Carbonate minerals and carbonaceous matter are the only other rock-forming constituents in the phosphatic shale members, and both are major factors in the commercial treatment of phosphate rock. (See description of methods of treatment.) The ranges in absolute and relative quantities of these constituents are rather wide in southwest Montana, and the two phosphatic shale members have many dissimilarities. Figures 119, 125, and 126 in Cressman and Swanson (1964) present the general areal distribution of these constituents, and the preceding descriptions of the two members indicate their stratigraphic distributions as well.

[2] Illite is a general term proposed, not as a mineral name for a specific clay but for the micalike clay minerals (Grim, 1953, p. 35; Grim, Bray, and Bradley, 1937), which contain 20–32 percent Al_2O_3 (Grim, 1953, p. 372).

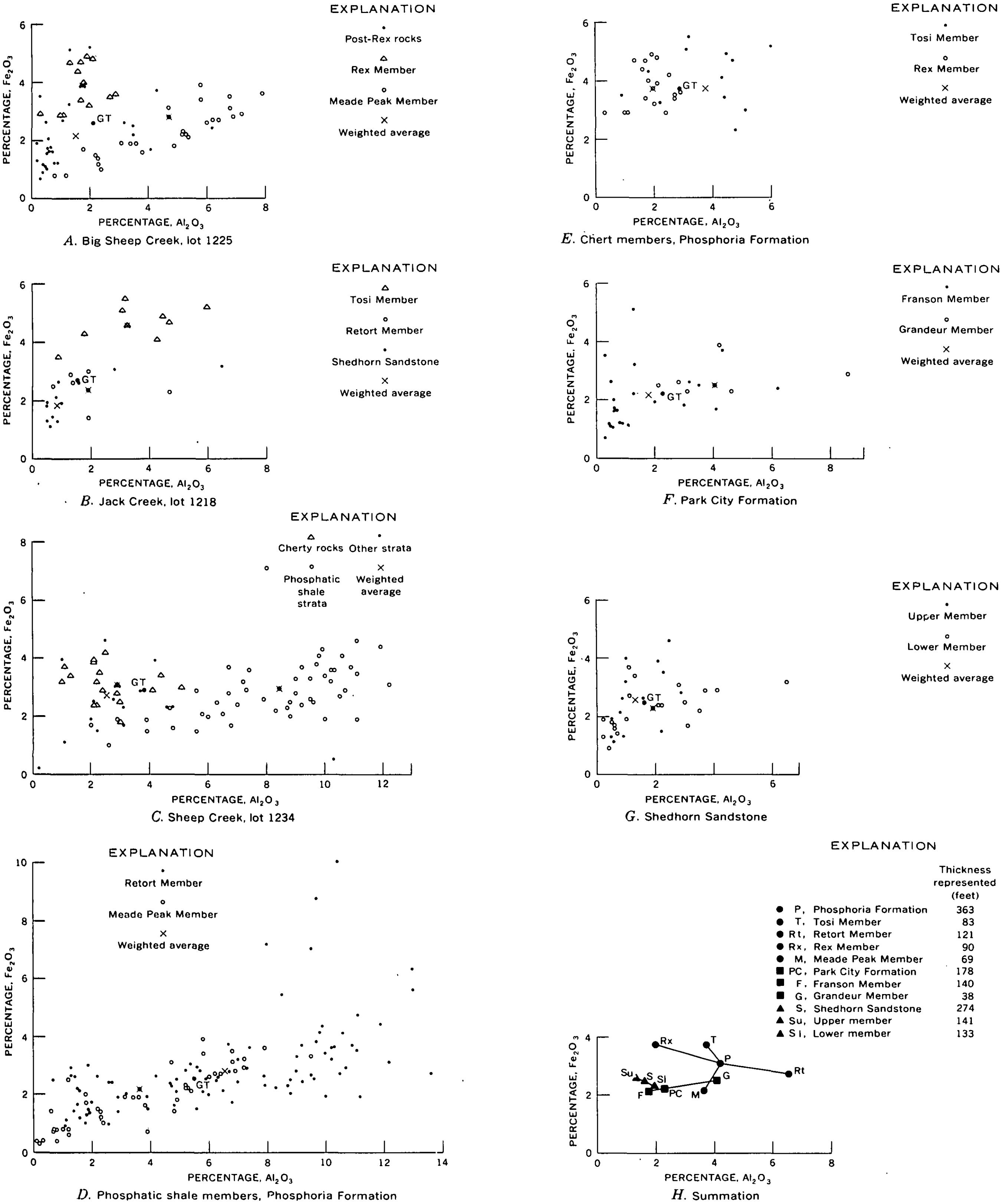

FIGURE 177.—Comparison on Al_2O_3 and Fe_2O_3 contents of samples from Permian rocks of southwest Montana according to locality and to formation and member. Average values weighted for thickness. GT, grand total.

Carbonate occurs as beds of impure dolomite and calcite (limestone) and as a minor constituent of other rocks. In the Meade Peak Member, limestone is more abundant than dolomite, but in the Retort Member, dolomite is more abundant. The carbonate rock in the Retort Member (Cressman and Swanson, 1964, fig. 125) is much more widespread than that in the Meade Peak, and individual beds probably have greater lateral extent. The carbonate tends to be coarser and dominantly limestone toward the east, or shoreward, margin of the field, and to be finer and dolomitic toward the west and southwest.

The generally low content of carbonaceous matter makes the Meade Peak phosphorite particularly attractive for commercial treatment by acid processes. In part, this low content may be attributed to removal by weathering processes; however, even in the areas of least intense weathering, the Meade Peak strata are consistently lighter colored than those of the Retort Member.

Both the areal and the stratigraphic distributions of carbonaceous matter in the Retort Member are irregular (Cressman and Swanson, 1964, fig. 126); even adjacent beds may differ greatly in contents of organic matter. The condition of the carbonaceous matter also appears to be widely variable. For example, at Sheep Creek (lot 1234) some beds contain 20 gallons or more of oil per ton; at Dalys Spur (lots 1222, 1223), a few miles to the west, shale chips that have apparently lain on the dump for nearly 60 years will burn freely when ignited with a match. Other oil-rich shales were found by Condit (1919) farther south. Elsewhere, however, seemingly comparable shales will not burn.

In the area of oil shales south of Dillon and near Lima, the entire Retort Member contains more than 8 percent carbonaceous matter (Cressman and Swanson, 1964, fig. 126) and some beds in this area contain nearly 10 percent oil. In thin section most of the carbonaceous matter is black and appears to cloud the rock, but under high magnification, tiny spherules can be seen; the spherules are amber colored and may be droplets of oil.

In some parts of the Melrose district at the north, the carbonaceous matter appears to have been converted to fixed carbon by heat from the Boulder batholith. This is particularly noticeable at Mount Humbug (lot 1404), in a roof pendant of this intrusive.

Near the margins of the Retort area, where the member is much thinner, the rocks are generally lighter colored, ranging from gray to brown, although locally they are dark almost to the pinchout. Locally, small spots of glassy black material resembling tar or gilsonite occur in or near the Retort rocks.

Thickness of bedding is primarily a result of depositional environment, but the apparent thickness of bedding may vary with the degree of weathering. Thus, the deeper and fresher the rock, the less conspicuous the bedding. Thickness of bedding also differs geographically. For example, in this area the bedding in the deeper water facies to the southwest is generally thinner than that in the shallower water facies to the east. Much of this variance in thickness in the area is due to partings of mudstone in the phosphorite. In the area of deeper water facies, the quality of the phosphate rock is generally low because of the abundance of such mudstone partings. In some places layers of phosphorite and mudstone, averaging about one-sixteenth inch thick, alternate; however, some layers of phosphorite are only about one pellet thick. The areas of finer clastics are also generally the areas of thinner bedding. Thick beds tend to break into larger pieces during mining, which is favorable to some types of treatment, whereas the thin beds can be more easily crushed, ground, and washed.

The characteristics of the footwall and hanging-wall rocks may be controlling factors in the minability of phosphate rock. Hard thick-bedded wallrocks generally reduce the cost of mining, particularly if the phosphorite is separated from them by thin partings that allow the rock to break clean. Soft footwall rocks tend to break during mining, and soft hanging-wall rocks tend to cave; thus, both tend to dilute and spoil the phosphorite. Because most of the phosphate rock is only slightly above cutoff grade, dilution necessarily must be kept very low.

The thin-bedded argillaceous phosphorites in the areas where the Retort Member is thick are likely to have weak rocks in both the hanging wall and the footwall. Where the shale members are thin, the beds adjoining the phosphorites are more commonly the hard thick-bedded types that form hard mining walls.

STRUCTURE AND METAMORPHISM

Some of the postdepositional events in geologic history that may have affected the quality of phosphorite in the area are lithification by compaction and by cementation, folding and faulting, and alteration by igneous activity or hydrothermal solutions. Lithification may have been diagenetic or it may have been much later; however, as it generally accompanies the other events noted, it is included here. The changes caused by these events may be very local or they may be widespread; they may affect the minability of the rock, its beneficiation, and its treatment; and they may be subtle but major factors in an evaluation.

Lithification starts with compaction of the sediments on the sea floor and is involved in almost all subsequent events that affect the deposit. Loss of porosity almost always occurs by (1) redistribution of fine materials to spaces between coarse grains, (2) deposition of locally or remotely derived mineral matter in pores, (3) recrystallization (together with local crushing) of matter already present to form interlocking texture, and (4) replacement of material already present by new mineral matter.

Most structural features are related to folding and faulting that occurred during the Laramide orogeny. These features differ widely in character but are best considered in correlation with the southwest Montana positive area and synclinorium. (See the section "Geologic History" of this report.) In the positive area, major folds are widely spaced and are generally asymmetric, having a long gently dipping limb and a steep limb. Minor thrusts, strong local shear zones, and cross faults are common to the steep limb. On the gentle limb, minor folds are uncommon, and fault zones are widely spaced and generally have small vertical displacement. However, the small stratigraphic throw on faults across the strike of gently dipping beds must involve much larger horizontal displacement, which could seriously disrupt a mining plan. In the positive area, the weak shale zones are thin, and the wallrocks are generally hard and, thus, favorable to mining.

In the synclinorium, typical folds are fairly tight, rather closely spaced, and generally of small amplitude; many are overturned. Moderately dipping to low-angle thrust faults are common, and displacements range from several thousand feet to several miles. Cross faults are common, resulting in many small offsets; zones of shearing and mashing spoil much phosphate rock or make it difficult to mine owing to weakened wallrocks.

In southwest Montana, igneous intrusives, consisting chiefly of quartz monzonite, include the Boulder, Tobacco Root, and Pioneer Mountains batholiths, as well as stocklike bodies north of Melrose, at McCarthy Mountain north of Dillon, and in the Beaverhead Range northwest of Lima. Some igneous rocks intrude upper Paleozoic strata and are locally in contact with rocks of Permian age. Also, many small intrusives, chiefly sills or dikes of porphyritic andesite, were intruded into or near Permian strata at these and other localities.

The contact effects of intrusive rocks on Permian strata in southwest Montana were described by Cressman and Swanson (1964, p. 319). Little study has been made of the contact effects, however, and they are not well known. Narrow dikes and sills probably had little effect, other than local disruption, on phosphate deposits. The larger bodies of igneous rock, having more latent heat, caused more readily apparent effects. Lowell (1955) described bleaching, destruction of texture, minor recrystallization, and some migration of apatite near an apophysis from a small stock. E. S. Perry (oral commun., 1950) reported that phosphorite at the south border of this same stock is recrystallized to apatite grains that are fairly clear. The material he described was not examined by the author. The carbonaceous matter in the roof pendant at Mount Humbug (lot 1404) apparently has been converted to fixed carbon. (See more detailed description by Cressman and Swanson, 1964, p. 320.) Rooney (1956, p. 37) reported that the quartzites in the Mount Fleecer and Highland Mountains areas are largely recrystallized into a mosaic structure, in which former grain boundaries are largely lost.

Hydrothermal solutions probably have affected the phosphatic sequence locally. In the valley of Warm Springs Creek north of Garrison at lot 1402, 40 miles north of Butte, the present warm springs are rich in carbonate, as indicated by the travertine terraces in the valley bottom. But the nearby Quadrant and Shedhorn Sandstones are highly silicified and abnormally hard and vitreous; the phosphorite is also harder than normal and contains numerous veinlets and spots of purple fluorite. All features at this locality except the travertine terraces are believed to be related directly to an earlier phase of the hydrothermal activity. Very probably the fluorite was derived by leaching of phosphorite at depth.

Fluorite crystals line vugs in the chert of the upper Shedhorn Sandstone in the Madison Range east of Lone Mountain and may be the result of hydrothermal activity. Rooney (1956) found montmorillonite and kaolinite to be the dominant clay minerals in Permian strata of the Melrose area; he suggested that these minerals are mainly a result of hydrothermal alteration related to the Boulder batholith. Except for those just described, very few hydrothermal effects have been observed in the Permian strata of Montana.

INFLUENCE OF WEATHERING

Weathering, primarily that in the Cenozoic, has also locally affected the quality and character of the Permian phosphate deposits. Mansfield (1927, p. 213) recorded a progressive decrease in P_2O_5 content away from the outcrop at the Waterloo mine in southeastern Idaho, and he ascribed this principally to weathering.

Weathering has also affected the quality and character of many of the phosphate deposits of southwest

Montana. Extensive uplift and erosion, deep weathering, widespread volcanic activity, and abundant continental deposition combined in various ways to produce a complex pattern of rock units. Thus, during middle Tertiary time, volcanic debris and commonly associated continental deposits covered the very slightly to moderately weathered bedrock in areas of sharp to moderate relief, but in base-leveled areas this debris concealed much more deeply weathered bedrock. The present distribution of Permian strata is generally very difficult to predict in areas of second- or third-cycle uplift, where extensive deposits of Cenozoic age are also present. In these areas the effects of weathering are also very difficult to predict.

No simple set of guidelines has been found for judging the nature and extent of phosphorite weathering in such an inherently complex area. Nevertheless certain basic guides can be recognized, and these, when considered together with the local geologic history, should prove helpful in evaluating the weathering effects on individual phosphate deposits.

The principal chemical changes due to weathering of phosphorite and associated rocks are oxidation and leaching of carbonaceous matter and sulfide minerals and leaching of carbonate minerals and some minor metals. Quantitatively, only weathering of the carbonaceous matter and carbonates is significant, and loss of these constituents results in a net increase in the P_2O_5 content. McKelvey (McKelvey, Swanson, and Sheldon, 1953) estimated, from the changes apparently due to moderate weathering at Conda, Idaho, that this increase at the surface may be as much as 1–2 percent of P_2O_5. Intense weathering, as at Laketown, Utah, would undoubtedly represent a significantly larger increase, but the absence of exposed unaltered rock near areas of deeply weathered rock prevents reliable determination of maximum enrichment; however, enrichment may be more than 5 percent. Very finely disseminated pyrite, present in small amounts in most phosphatic strata, is oxidized fairly readily to form limonite and gypsum. These minerals, which commonly can be seen in exposures of moderately weathered rock, are gradually leached out. Some redistribution of both phosphate and silica apparently takes place during weathering, but movement of these materials that occurs during diagenetic cycles is very difficult to distinguish from that which occurs during weathering cycles. Prolonged weathering of impure carbonate rock results in mudstone. Where such beds occur in a minable phosphate zone, as in the mines near Melrose (C. P. Zergiebel, oral commun., 1951), they materially affect the minability and the treatment of the phosphate rock.

Physically, weathering causes the rocks to be lighter colored owing principally to loss of organic matter. It also makes some rocks porous and thinner owing to loss of soluble constituents, and less blocky to friable owing principally to the loss of cement. During the oxidation and gradual removal of iron, the rock commonly is stained bright yellow to red.

Soft, shaly zones slump fairly readily and can cause significant downhill creep in the frost zone, as at Greenstone Gulch (lot 1250; Cressman and Swanson, 1964, fig. 88), where the sequence of beds in the first few feet below the grass roots has crept downhill several yards but has remained nearly intact. Differential slumping and heaving due to the effects of solution and of frost action may cause notable thickening and thinning of strata in the immediate subsoil zone; thus at many places rocks that are well below the base of the soil zone must be exposed to make reliable any studies of thickness, composition, and character of the strata. Also, the soft shale zones tend to weather and erode more readily than adjoining strata and thus form swales or flats on which talus and rubble tend to accumulate, or cause adjacent harder rocks to slump because of undercutting. This porous mantle protects the soft, shaly rocks from runoff erosion and affords ready and prolonged access for surface and ground water, thereby promoting increased chemical weathering even in areas of limited rainfall.

A bluish-white bloom is characteristic of weathered phosphorite (Gardner, 1944, p. 15). This bloom forms only on fragments at or near the surface. The phosphorite in trenches, though weathered a lighter color (brownish black to brown, instead of very dark gray to black), does not exhibit any bloom. The bloom does form fairly readily, however, for it occurs on most phosphorite fragments at the surface, even in very rugged areas where erosion is rapid, and it is most pronounced on fragments on the surface of old prospect dumps, as at Dalys Spur (lot 1222), where the Retort Member was prospected for coal about 50 years ago. Although some primary color variation is present in the fresh rocks, the intensity of bloom formation, nevertheless, is a general indication of the intensity of weathering—that is, the more intense the weathering of the rock, the heavier and whiter the bloom on the rock surface, and the lighter the color through the interior of the rock. Factors such as composition, permeability, structure, and relation to topography undoubtedly influence the rate of bloom formation, and not all phosphorite in an area will have the same amount and color tone of bloom, but phosphorite from the same member will generally show comparable bloom in a given area of similar geologic history.

Because of the number of variables that have influenced the depth of weathering, each deposit (and commonly the individual parts of a deposit) should be considered separately in relation to both regional and local geologic history. Problems of mining that may be governed in part by the degree of weathering are—

1. The overall mine layout, such as location of main haulageways in more competent rocks of the hanging wall or footwall instead of in shale zones where they may be difficult to maintain.
2. The method of breaking and removing the ore. Weathered rock tends to break finer and thereby cause packing in the stopes and chutes, and it may require more nodulization before furnace treatment.
3. The kinds of equipment to be used and their manner of use to obtain maximum recovery but avoid excessive dilution from wallrocks.

Also, beneficiation procedures may be strongly influenced by the nature and degree of weathering because of changes in both composition and physical character. Finally, details of ore refining—such as the oxidizing of organic matter before acid treatment or the nodulizing of the material before charging to the furnace—should be considered according to the degree of weathering of the ore.

The primary characteristics of the rocks and the effects of structure and weathering are widely variable throughout southwest Montana. These influence the quality of rock that might be mined. Note, however, that weathered rocks at the surface will differ in both chemical and physical properties from those at depth that are relatively fresh. Careful consideration of the differences in physical and chemical properties of the rock is essential to the success of a large-scale phosphate mining and treatment enterprise.

PHOSPHATE RESOURCES

Many reports, such as those by Mansfield (1942) and McKelvey (1949), call attention to the large reserve of phosphate in the western phosphate field, but all these were based on very limited information about the deposits. The recent investigations by the U.S. Geological Survey, of which this study is a part, have been much more extensive and have made possible a more comprehensive analysis of that reserve. A preliminary estimate for the western field (McKelvey, Cathcart, and others, 1953) noted an "inferred reserve minable under present conditions" of about 3 billion long tons and an "additional inferred resource minable under changed conditions" of 20 billion long tons; however, no breakdown of these figures was given. A large part of this phosphate reserve occurs in southwest Montana. A summary of the phosphate resources in southwest Montana was published earlier (Swanson, 1960, p. 66); these resources are described here in detail by districts and with respect to their relation to the geology of the region.

TREATMENT OF DATA

The western phosphate deposits exhibit a wide range in quality and thickness of phosphorite, in stratigraphic relations of phosphorite, in geologic structure, and in physiographic setting. Nevertheless, where the phosphatic and enclosing rocks are exposed at the surface or can be exposed readily by some form of excavation, detailed geologic mapping, careful field examination and sampling, and laboratory testing will usually lead to a reasonably accurate definition of the deposits. Study of these rocks at land surface and underground has demonstrated the great lateral continuity of most of the strata, including thin layers that can be identified positively because of special characteristics, such as composition or texture. Within limits, therefore, known characteristics at surface exposures can be projected for a considerable distance along strike or downdip with good assurance of continuity. However, chemical and physical differences are known to occur laterally, and data must be projected with due caution.

The investigation of which this study is a part involved extensive sampling, measurement, and description of the Permian strata; principal emphasis was given to the phosphatic shale members. The sampling program followed carefully prescribed procedures to insure obtaining fairly uniform data that would allow detailed lithologic and chemical interpretation. Thus, each lithologic unit 0.5–5 feet thick was sampled, measured, and described separately in the field. Locally, thinner or thicker intervals were sampled where conditions required. At lot 1241, where the Retort Member was found to be low in phosphate content and where the samples had to be back-packed out, fewer samples were taken in order to reduce the sample load. The data for this locality undoubtedly reflect the true gross character of the strata but detailed comparisons with adjoining areas cannot be made as readily as elsewhere, and some "phosphate zones" (as used in this report) may not be recognizable. In contrast, the marked alternation of thin lithologic units, which is characteristic of the Retort Member over much of the region, is reflected by the large number of thin sampled units sampled at lot 1256, where many of the units are less than 0.5 foot thick.

The sampling data combined with topographic and geologic information from areas that contain Permian rocks make it possible to estimate the quantity of phosphate present in the various parts of the western phosphate field. This report includes such estimates for southwest Montana.

Despite the detail of the investigation, many data essential to evaluation are lacking, for the geology of much of the area has been mapped in reconnaissance only. Also, at the time this report was prepared, the topography of much of the area had not been mapped in detail. Many of the sample localities are too widely spaced for detailed correlation, and some strata are too lenticular for good correlation, even where the sample localities were closely spaced. Much of the geologic history of the region is not well known, especially that of the Cenozoic Era.

Where the geologic structure is particularly complex, even the most detailed geologic mapping may be inadequate for use in resource appraisal. For the most part, however, the data are believed to be one of satisfactory quality for use in estimating the phosphate resources in southwest Montana. Much of the phosphate noted is not amenable to immediate, or even foreseeable, mining, but the tables do indicate those areas worthy of detailed investigation by industry, and they supply information that may be useful for long-term planning on a regional or a national scale.

All the phosphate contains uranium, which is described separately by districts. Other resources associated with the phosphate in this area include fluorine, synthetic gypsum, oil shale, and minor amounts of many metals. These are described briefly but no separate quantitative estimates are made of them.

DEFINITION OF TERMS

It is customary in describing quantitative aspects of a mineral deposit to apply standard classification terms, such as "reserves" or "resources." Lasky (1949, p. 36), in considering the problems of a national mineral appraisal, defined reserves and resources as follows:

> Ore (mineral) reserves include those mineral deposits that are known to exist—or for the existence of which there is at least some evidence—and that have aspects of usability with a practical limit of time and within a specified set of economic and technologic conditions.
>
> Mineral resources include all the material in the ground, discovered or undiscovered, usable at present or not, rich or lean, considered within the context of all factors, quantitative and qualitative, that may influence its conversion into a "reserve," and within the context of all factors that enter into prediction or opinion as to possible future usability.

The distinctions between reserves and potential future sources have been outlined by the U.S. Geological Survey and the U.S. Bureau of Mines (President's Materials Policy Commission, 1952) as follows:

> ***the term "mineral reserves" refers only to the material that in some degree has been inventoried in terms of commercial enterprise***[and] can be mined, processed, and marketed without financial loss under the economic and technologic conditions prevailing at the time of the inquiry. *** It does not contain material of submarginal grade which, with improved economic conditions, may become a reserve, nor does it include off-quality material which cannot be treated satisfactorily under current technologic practices. ***.
>
> The use of materials classed as "marginal and submarginal" primarily awaits more favorable prices, whereas utilization of most of the material classed as "potential future sources" must await new—in some cases revolutionary—technologies as well. *** It is recognized, however, that in certain instances these materials contain some of the greatest potentialities for future sources of supply even though they cannot be tapped economically by existing mining and metallurgical methods.

Many of the factors that control whether a given phosphate deposit can be mined, processed, and marketed are beyond the scope of this investigation, and they are temporal in that they probably vary fairly widely with changes in the national economy. Because temporal factors are involved in the term reserves, the phosphate deposits described in this report are now appropriately considered to be resources, even though some are known to be minable under present conditions. The term "deposits" might have been used instead of "reserves" or "resources," but such use would only add another term to the many already used in classification of phosphate deposits. Also, the term "deposits" has many other connotations that are unrelated to the classification of phosphate.

Were the phosphate in this country of limited supply, the distinction between reserves and resources would be a major consideration. The abundance of this commodity, however, precludes the need for such distinction, which in turn obviates the need for rigid definition of class limits. In the following discussion, as well as in the descriptions of individual districts and deposits, therefore, the phosphate believed to be present (on the basis of sample-locality data and of interpretation of geologic structure) is classed under the general category of resources. The classification used in this report should, nonetheless, serve many of the interests of those who wish information on reserves.

The reserves in many mineral deposits are classified by the U.S. Geological Survey and the U.S. Bureau of Mines as measured, indicated, or inferred (Lasky, 1947, p. 185). On the basis of that classification, most phosphate reported here would be called inferred, for the distance between sample localities is generally too great and the geologic mapping is too general for higher classification.

In this study the resources of phosphate and uranium were calculated for individual geologic blocks, such as synclines or large fault blocks. These blocks are generally large and include larger areas than would be held by a single company.

In the estimation of resources, cutoffs for grade, thickness, and depth of mining must be established. To establish, in advance, every cutoff that might eventually be desired would be impossible, and to attempt to compute resources in terms of all potential combinations of grade, thickness, depth, and other limitations that might one day be applied would be impracticable. Accordingly, certain basic combinations were selected, and essential factors of the calculations were recorded so that interpolation to other cutoffs can be made if desired. By presentation of bed-area data (area in the plane of the bedding or stratification), the recomputation of resources to different cutoffs should be greatly simplified.

Phosphate rock in much of southwest Montana occurs at one horizon, or at two that are widely separated, and assay boundaries are commonly abrupt. Interpolation to other specifications must be done with caution, therefore, to avoid unrealistic mining programs.

Two types of phosphate rock are being treated in the western phosphate field: high-grade rock containing more than 31 percent P_2O_5, for manufacture of fertilizer by the sulfuric acid process; and medium-grade rock containing about 24 percent P_2O_5, for reduction to elemental phosphorous by electric furnace. These two standard cutoffs are adhered to in the resource calculations. A third cutoff, at 18 percent P_2O_5, is used to account for that lower grade rock which can be beneficiated. Also, the total content of P_2O_5 in each geologic block was calculated. Resources for each of the two phosphatic shale members were computed separately. In addition, calculations were made of bed area, and of tonnage for (1) that phosphate rock above entry level, (2) that within 100 feet vertically below entry level (from which the calculation for greater depths would generally be a simple matter of multication), and (3) that of the entire geologic block.

As not all phosphatic rock currently mined meets these grade limitations, some beneficiation is necessary. The success of beneficiation depends upon many factors that are widely variable throughout the region, however, so the grade cutoffs were strictly adhered to in making the estimates recorded in this report.

RULES FOR COMPUTATION

So that the computation of all phosphate resources of the western phosphate field may be consistent and the results thus comparable, a set of basic rules governing the calculation of grade and of thickness has been established. The rules are as follows:

1. Grade cutoffs are 18, 24, and 31 percent P_2O_5 for low grade, and high grade, respectively. Also, total phosphate content in each phosphatic shale member is calculated.
2. Each phosphate zone must be at least 3.0 feet thick, except as noted in rule 6.
3. The top and bottom beds of a zone must be above grade cutoff except as noted in rule 6.
4. No zone may contain a sequence of beds more than 3.0 feet thick; all contain less than the below grade cutoff.
5. No bed may be used more than once for any one grade cutoff, but the same bed may be used for different cutoff calculations.
6. A bed below minimum thickness may be combined with adjacent rock that is below cutoff grade to define a minimum 3-foot zone, providing the combined thickness averages cutoff grade or more. If the adjacent bed is sampled, that grade is used; if not, an average grade for that type of rock is used, or the added thickness is considered to be barren.
7. Tonnages (short tons) are computed for rock above entry level (lowest level of access to phosphatic strata, determined from topographic map), for rock within the first 100 feet below entry level, and for rock in the total geologic block.
8. Tonnage factors for high-grade, medium-grade, and low-grade rock are 11.0, 11.5, and 12.0 cubic feet per ton, respectively.
9. Computed tonnages are rounded to the nearest 5 of the second significant figure (second figure from left).
10. No block shall be recorded as containing less than 50,000 tons. Any tonnage above entry level of less than 50,000 tons is added to that in the first 100 feet below entry level.
11. No tonnages are computed for areas containing less than 3 feet of 18 percent P_2O_5 rock.

With one exception these rules leave no room for interpretation or choice. To some extent the rules may even be considered unrealistic, for instance, the rule stating the minimum mining widths for low-grade rock; but enough basic data from which the resources were calculated are presented that the reader can reinterpret readily to other specifications.

Whether a bed is thick enough to mine at any given locality is determined largely by factors that are not considered in this report because many of them vary with changes in economic conditions. Farther north in Montana, at the Luke and the Graveley mines (Armstrong and McKay, 1949), the phosphate bed has been mined underground where it is only 3 feet thick. Therefore, a 3-foot minimum thickness has been applied to all grade cutoffs, even though it may not be currently realistic for low-grade rock.

The exception made in rule 6 is intended primarily to call attention to the richer zones that are slightly less than 3 feet thick. This exception may be defended logically by stating that the treatment of the rock would be nearly the same whether the low-grade material mined came from the center or from a wall of the ore body. In some places, however, a considerably different mining method would have to be used, for the surrounding rock might not break cleanly or might include chert or quartzite, which is difficult to mine; also, a different method of treatment might have to be used.

Of perhaps greater concern, however, is the specific application of the rule to definition of grade and thickness of a zone. The question is, should just enough of the wallrock be included to attain a 3-foot-thick zone, or should the entire adjacent bed be included? Neither approach has been followed exclusively in this study. Where the entire adjacent bed is rich enough that it could be included without lowering grade below cutoff, the entire bed was included. Where the adjacent bed is thick or of very low grade and where the phosphate rock is rich enough to satisfy a full 3 feet above cutoff, just enough of the adjacent bed was included to attain a 3-foot minimum thickness. For such places, to avoid the possible difficulties due to inhomogeniety in the phosphate content of the rock so added, normally no phosphate was ascribed to the added rock in determining the average grade for the zone.

Few determinations of the specific gravity of phosphorite in the western phosphate field were made during this investigation; however, Mansfield (1927, p. 209–210) noted that the specific gravities determined for high-grade phosphate rock from southeastern Idaho range from 2.85 to 2.95. That of the phosphate mineral itself is probably a little more than 3.0, and that of quartz, the principal impurity in much western phosphate rock, about 2.6. The ranges in contents and ratios of other impurities, such as carbonaceous matter, clay, and carbonates, are rather large, as is also the range in porosity of the rock from place to place. The specific gravity of any of the western phosphate rock is therefore impossible to predict accurately. However, on the basis of available data and of discussions with representatives of industry, the tonnage factors used (which reflect specific gravities 2.92, 2.79, and 2.67 (fig. 178)) are believed to be fairly accurate for the stated cutoff grades.

METHODS USED IN ESTIMATING RESOURCES

Estimates of ore reserves are based on weight and volume. The weights of various grades of western phosphorate rock, as reflected in the tonnage factors used in this investigation, are noted in rule 8 above and in the succeeding discussion. The calculation of volume (length × breadth × thickness) is complicated, because the phosphate-bearing strata have been complexly folded and faulted. The configuration of these strata, which lie buried beneath other rock units, must first be determined, therefore, and then the bed area can be determined. The best means of portraying this configuration is by use of structure-contour maps. Such maps have been prepared for all areas containing Permian rocks in southwest Montana except those that lie within a radius of 35 miles of Three Forks; the latter areas have insufficient phosphate to meet the requirement of rule 11.

All available topographic and geologic data were used in the preparation of these structure maps. The geologic data consist primarily of published reports and maps, student theses, and unpublished maps prepared by geologists of the U.S. Geological Survey. These data were supplemented by field observations made during the course of these investigations, principally in conjunction with the sampling program. In a few areas, for which only scanty data are available,

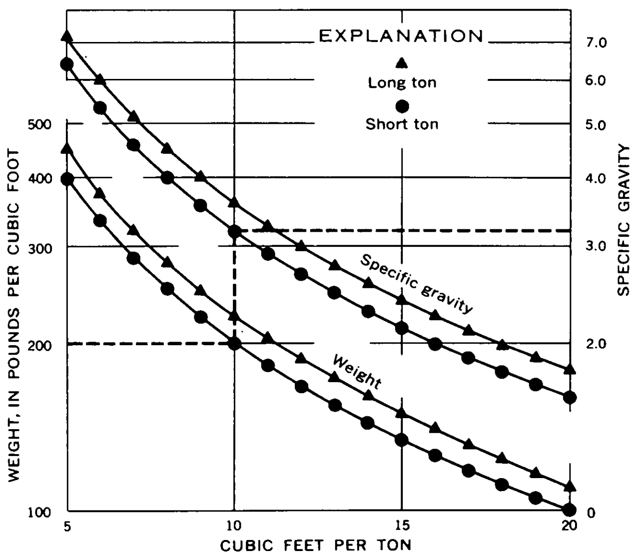

FIGURE 178.—Tonnage factor and specific-gravity chart, showing relation between cubic feet per ton, weight per cubic foot, and specific gravity for both long and short tons.

particularly areas of extensive cover, only a calculated guess as to the location of the Permian strata could be noted. The district structure maps (pls. 27, 28) therefore represent syntheses of large amounts of geologic data gathered by a great many geologists, most of whose study objectives did not pertain directly to phosphate-resource estimates.

The stratigraphic continuity in grade and thickness of phosphorite is known to range from fairly uniform over wide areas to lenticular. Sample localities that are 6 to 10 miles apart may be too widely spaced to permit the correlation of individual beds, or even of some sequences of beds, from one locality to the next. Nevertheless, on the basis of overall correlation, there is good reason to believe that the phosphate zones (3 ft thick or more about cut-off grade) at most sample localities are representative of the areas about those localities and, therefore, that it is justifiable to use data from those localities in the calculation of resources for the surrounding areas. Where data from two or more localities may be applied, averages of these data were used in the calculations.

Lenticular deposits cause the greatest amount of uncertainty. Some lenses are predictable on the basis of the lithologic type or the texture of associated strata, and added factors can be applied in making a resource estimate. But some lenses are not recognizable from data collected at widely spaced intervals, and estimates made on the basis of such data may be in error. These errors are likely to be both positive and negative, such as those caused by extending known beds too far and by failing to identify other beds, and are thus believed to be somewhat compensatory.

The 1,000-foot structure-contour interval used on the district maps is small enough in most areas to fairly clearly show the configuration of the strata, though it is not entirely satisfactory for use in areas of either very gentle or very complex folds. Only in the areas of complex folds, however, would a smaller contour be more useful for making resource calculations. In these areas, larger scale maps would also be preferable. The map scale employed (1 inch = 2 miles) is suitable for presentation of most data needed for preparing the estimates of major geologic blocks, but this scale would be wholly inadequate for planning mining operations. Most calculations for the resources noted in this report were made from larger scale maps.

A principal function of the structure-contour lines is to aid in the computation of bed area. Bed area varies with respect to horizontal area as the secant of the angle of dip; thus, bed area is 10 percent greater than horizontal area at a dip of 25°, 30 percent greater at 40°, and 100 percent greater at 60°. Bed area is therefore considerably larger than horizontal area in all parts of a structure except those of gentle dip. The cosecant of the angle of dip is used in determining the bed area for the first 100 feet below entry level. For example, at a dip of 30°, the bed area is 100 percent greater than the vertical area.

The spacing of structure contours is a direct function of the angle of dip of the plane being contoured, so the bed area can be obtained by determining the angle of dip from the contour spacing and then multiplying the horizontal area by the secant of that angle. A slope scaler devised by the author is particularly useful for this purpose, and an adaptation of it for use on the structure-contour maps of this report is shown in figure 179.

The slope scaler is designed to measure, on a map of the same scale, the slope angle between any two points of known difference in altitude. It utilizes a series of diverging lines that are equally spaced along lines normal to one of them, the "base line"; the spacing of the diverging lines in the direction of the normal lines is equal to the cotangent of the slope angle at the map scale and the vertical interval used. The adaptation used here is for vertical intervals of 1,000 feet for dips of more than 25° and 200 feet for dips of 5°–25° at a map scale of 1 inch = 2 miles. In its use, the scaler should always be oriented with the "base line" parallel to the structure contours (dip-value lines parallel to direction of slope).

The Permian rocks of southwest Montana are extensively folded and faulted. At about half the sample localities the strata dip 45° or more, and at about 10 percent of the localities the beds are overturned. The relatively soft phosphatic shales have probably been thinned on the limbs of many of the folds, as indicated at some localities by extensive shearing of the strata

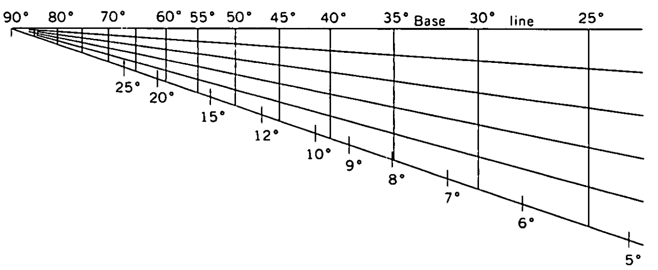

FIGURE 179.—Slope scaler—a device to measure the angle ofdip from contours—for use on the structure conteur maps of this report (scale: 1 in. equals 2 mi, or 1:125,000). Spacing of diverging lines on scaler represents spacing of 1,000-foot structure contours at dip angles noted along "base line" (top line of scaler, for angles >25°; five spaces or intervals represent 1,000 feet at dips noted along bottom line, 5° to 25°). To use scaler, measure spacing between adjacent contours on map with dividers, then slide dividers along scaler until the points lie on adjacent lines, always measuring normal to contours on map and to base line on scaler; read dip (by interpolation as necessary) from figures along "base line." For widely spaced contours, use top and bottom lines on scaler for 1,000-foot interval, then read dip from figures along bottom line. A transparency of the scaler superposed on the map speeds and simplifies use.

and by some near-bedding-plane faults. At a few localities some strata are repeated by small shears, but there is very little indication as to the amount of thinning (or thickening) of individual layers — particularly those of phosphorite, which are generally more competent than the shales with which they are interbedded — that has occurred as a consequence of structural environment. Some changes in thickness of phosphate zones are probably due to folding. Because the phosphorite occurs in widely diverse stratigraphic and structural environments, no attempt was made to reinterpret the measured thicknesses of the phosphatic shale members or their contained phosphate zones. In some places readily recognized shears and abnormal thicknesses appear to be related to these environments. The strata at a few localities, such as lots 1248, 1301, and 1311, are known to be greatly affected by structure, chiefly by elimination of strata along near-bedding-plane shears. The data from these localities must be used with particular caution, and the data from nearby localities governed the author's interpretation of these sections.

Much of the phosphate rock in the western field has been spoiled for mining by structural complexities, such as fine breakage and consequent mixing with low-grade material, breakage into blocks too small to mine, elimination of beds along flat shears, and intense shearing of adjacent strata. Where deemed advisable on the basis of the geologic setting of the deposits, a rough spoilage factor was applied to the resource calculations. Determination of an accurate spoilage factor is impossible owing to the small amount of data available. In computation, this factor is applied to small units in the geologic block, such as sections of land area, but not to the block as a whole, and the total tonnage for the block is then rounded (rule 9, p. 683).

PHOSPHATE DEPOSITS IN SOUTHWEST MONTANA

The Permian rocks in southwest Montana occur in three principal tectonic environments. In the southwest Montana positive area, they are preserved in large asymmetric synclines formed by large faulted and tilted blocks of the underlying rigid crust. In the southwest Montana synclinorium, along the west side of the positive area, the Permian rocks have been tightly folded and thrust faulted. In the central Montana trough, on the north side of the positive area, these rocks are in geologic structures that are generally intermediate in complexity, relative to the other two areas. The central Montana trough contains no phosphate deposits thick enough or rich enough to warrant the estimation of resources. The other two areas are divided into districts that represent the principal areas underlain by Permian rocks; these districts are described separately in the pages that follow.

This study was conducted by a large number of geologists whose diverse backgrounds have led to some variation in their method of recording field data. However, rather extensive precautions were used throughout this study to maintain consistency and to prevent mechanical errors as much as possible. Therefore, the data from which this report was prepared are believed to be reasonably accurate. Despite all precautions, however, some phosphate zones that meet the specifications of grade and thickness as herein defined may not have been identified. Also, if the zones that were identified were to be resampled, some might not meet the necessary specifications at the same locality or at a new one nearby.

MELROSE DISTRICT

General features

The Melrose district is about 20 miles southwest of Butte and comprises 16 townships (pl. 27*A*), most of which contain phosphate-bearing strata of Permian age. The district ranks second in phosphate production in Montana.

Richards and Pardee (1925, p. 4), whose statement was prepared for the south-central part of the district but applies equally well to the whole area, described the Melrose district as follows: "It is characteristically made up of broad, well-rounded mountain masses separated by V-shaped canyons, except where these canyons have been locally widened by glacial action and the long-continued erosional activity of trunk streams." The Big Hole River is the major drainage and crosses from west to southeast. In places it flows through sharp canyons across major geologic structures, where it has been superposed from an old erosion surface (Richards and Pardee, 1925). The river enters the southern part of the old valley called the Divide Trench by Pardee (1950, p. 388), which is several miles wide and apparently was filled to a considerable depth with Tertiary sediments. Total relief in the district is about 4,500 feet; the lowest point, at an altitude of about 5,000 feet, is along the Big Hole River south of Melrose. Most of the phosphate deposits in the district are below an altitude of 7,500 feet.

Access to the district is by two paved highways, U.S. 91, which follows the Divide Trench through Divide and Melrose, and State 43, which extends from Divide westward through the canyon of the Big Hole River. Numerous small dirt roads give access to most of the district during much of the year, and many trails are accessible only in the summer. The region is also serviced by the Oregon Short Line branch of the Union

Pacific Railroad, which is generally parallel to Highway 91 between Butte and Salt Lake City.

The only phosphate mining in this district is done by the Victor Chemical Works of the Stauffer Chemical Co. at several mines mainly along or near Canyon Creek a few miles northwest of Melrose. The ore is treated at the company furnaces near Silver Bow, a few miles west of Butte.

Geologic setting

The Melrose district includes part of the complex synclinorium that bounds the southwest Montana positive area on the west. The district is adjacent to the northwest corner of this positive area and includes the southwest corner of the Boulder batholith, the largest pluton of quartz monzonite in Montana. On the west the district is bordered by a broad area of Precambrian Belt strata, pre-Permian Paleozoic strata, and intrusive monzonite.

In the central part of the Melrose district, the synclinorium is structurally higher than to the north and to the south. The cross arch that is thus formed is approximately alined with the north boundary of the positive area. Most of this cross arch is underlain by Mississippian and older rocks and the small Mount Fleecer quartz monzonite stock. However, several synclines that strike into the cross arch from the north and from the south contain rocks as young as Upper Cretaceous. Thus, the structural and erosional history has produced repeated bands of outcrop of Permian and adjoining formations. North and south of this cross arch, the Permian rocks are buried deep within the central part of the synclinorium.

The strata in the Melrose district have not only been complexly folded and faulted but, also, have been invaded by several pluglike bodies of quartz monzonite, most probably cupolas or satellites of the Boulder batholith. Numerous andesitic sills probably also are related to the batholith (Lowell, 1955). Most of the folds are asymmetric and are overturned to the northeast. The major faults are chiefly reverse faults and tend to parallel the folds; some dip to the southwest at a low angle and have thrust displacements of several thousand feet. Numerous cross faults of generally small displacement add to the complexity of the structure.

The closely folded strata have been planed off by erosion, with removal of rocks as old as Mississippian from the axial parts of plunging anticlines. The repetition of outcrop of Permian rocks so created has greatly facilitated exploration. Deep valleys that cut across the folds make possible more thorough exploitation of the phosphate, with entry levels low on the limbs of folds. Much of the phosphate reserve lies above entry level, and all mining in this district has been above that level.

Stratigraphy

Underlying the Permian section is the vitreous orthoquartzite of the Quadrant Formation. Theodosis (1955) reported that the Quadrant ranges in thickness from 220 to 450 feet in the central part of the area and that "weathered friable sandstone in the uppermost part" marks an old erosion surface, which was suggested to occur regionally by Sloss and Moritz (1951). Presumably, the wide range in thickness largely reflects this erosion. Near the Big Hole River at the west edge of the area, Guttormsen (1952) estimated the thickness to be 800 feet; about 8 miles to the northeast, near Mount Fleecer, Moore (1956) measured only 371 feet.

The unconformity also appears to be reflected in the Park City Formation (Permian), which ranges from 34 to 187 feet in thickness, as measured by Peterson and Gosman (Peterson, Gosman, and Swanson, 1954, lots 1359, 1366), Theodosis (1955), W. E. Fowler (1955), and Rooney (1956). The thinnest sections were measured at Mount Fleecer and in the Highland Mountains to the north and to the northeast, respectively, and the thickest, near Trusty Lake on the west side of the area. The section is dominantly dolomite, much of which is cherty or sandy. Theodosis (1955, p. 46) reported that siltstone and sandstone are dominant in the east-central part of the area and that "siliceous-chert-dolomitic limestone, dense (lithographic) to fragmental limestone and thin-bedded silty shale" are dominant to the west. He also stated that the "variation in facies" suggests "deposition in an environment transitional between a miogeosynclinal and platform facies." These observations closely correspond to the relationships that can be inferred from the distribution of Precambrian rock types just described, for the Park City appears to reflect accumulation near the outer edge of the platform.

The Retort Member of the Phosphoria Formation is about 25 feet thick throughout most of the Melrose district; however, Lowell (1955, p. 720) reported 30 feet at a locality in the Highland Mountains, and Rooney (1956, p. 86) reported 45 feet, apparently at the same locality. Most Retort beds in this district are phosphatic and range from thin-bedded phosphatic shale to fairly thick bedded phosphorite; the poorly phosphatic beds are generally siltstone or dolomite. The entire member is generally dark brown to black. Most of the phosphate is pelletal, but oolites are common, and some phosphate occurs as matrix or cement.

The interval of Permian rocks above the Retort Member — formerly referred to as the E member by

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Swanson, McKelvey, and Sheldon (1953)—is a little more than 100 feet thick in the Melrose district and is dominated by quartzitic sandstone (the upper member of the Shedhorn Sandstone). Chert of the Tosi Member of the Phosphoria is common but thin at the base of the sandstone. Much of the lower part of the interval is cherty, and locally chert is common in the upper part (Rooney, 1956, p. 77). The upper member of the Shedhorn and the Tosi are intergradational and are not readily separated in many sections.

The Shedhorn Sandstone is overlain with apparent conformity by greenish- to yellowish-gray shale of the Dinwoody Formation of Triassic age.

Phosphate

The Melrose district is one of the richest phosphate areas in southwest Montana, both in average phosphate content of the rock (pl. 26) and in reserves. In most areas farther south that contain more total phosphate per unit area (fig. 174*B*), the phosphate is distributed through a much greater thickness of strata, and the average grade of the Retort Member is accordingly much lower. For example, the entire member contains 18-20 percent P_2O_5 near Melrose but only 11½ percent at the type locality south of Dillon, and even lower percentages at most localities farther south. In the Melrose district the upper part of the member generally contains the richest beds, and several beds at each locality contain more than 31 percent P_2O_5. These beds are generally separated by layers of low-grade mudstone or of carbonate rock that reduce the average grade. Nevertheless, the upper ⅓–½ of the member generally contains more than 24 percent P_2O_5. The lower half of the member is composed of low-grade phosphatic shales containing less than 16 percent P_2O_5.

The individual parts of the Melrose district, chiefly single structural units, are discussed below. The phosphate resources in each of the geologic blocks of the district (fig. 180) and the total for each block are given in table 2.

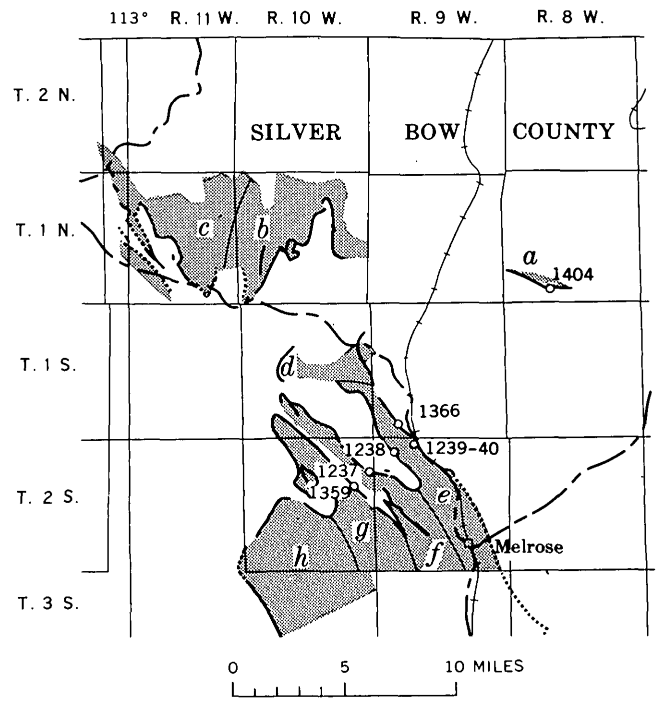
NORTHERN MELROSE DISTRICT

HIGHLAND MOUNTAINS AREA

The Highland Mountains area is in the northeast corner of the Melrose district about midway between Butte and Melrose and is accessible by a dirt road that leaves U.S. Highway 91 near Beaudines, about 8 miles north of Divide.

The geology of the Highland Mountains was first mapped in general reconnaissance by Weed (1912); it was later mapped in more detail by Sahinen (1950), who showed the phosphate area as part of a large roof pendant in the Boulder batholith (pl. 27*A*). The area containing the phosphate deposits was remapped by Cass (1953).

Lowell (1955) measured two sections in the NE¼ sec. 32, T. 1 N., R. 8 W. He found, respectively, 43 and 40 feet of carbonate rock (Park City Formation) that was recrystallized to marble and separated from quartzite of the underlying Quadrant Formation by a 75-foot-thick andesite porphyry sill; 30.5 and 27.5 feet of Retort Member containing two andesite porphyry sills about 8 feet thick, now deeply weathered; and 140 feet of quartzite of the upper member of the Shedhorn Sandstone. Rooney (1956, p. 96) later measured what was apparently the western of the two sections measured by Lowell and recorded 45 feet of Retort Member. Rooney's section of the Retort is fairly similar to Lowell's, but he recorded the interval between the uppermost sill and the overlying quartzite as 18 feet thick, as contrasted to the 5- or 6-foot thickness recorded by Lowell. Both authors noted that the upper part of this interval is covered. Neither author record-



EXPLANATION

Outcrop of Permian rocks
Dotted where outcrop is concealed or where location is uncertain

FIGURE 180.—Index to resource blocks in the Melrose district. Area for which resource calculations were made is shaded. *a*, Highland Mountains area; *b*, Mount Fleecer-Jerry Creek area; *c*, Wise River-Johnson Creek area; *d*, Quartz Hill syncline; *e*, Big Hole syncline; *f*, Cattle Gulch syncline; *g*, Trusty Lake syncline; *h*, Trapper Creek syncline. Circle and number indicate sample locality and lot number.

TABLE 2.—*Phosphate resources in the Retort Phosphatic Shale Member of the Phosphoria Formation, Melrose district*

[Phosphate resources given in millions of short tons]

Resource block	Bed area [1]			Average member thickness (ft)	Average grade (percent P_2O_5)	Total tons P_2O_5 in block	Rock containing >31 percent P_2O_5					Rock containing >24 percent P_2O_5					Rock containing >18 percent P_2O_5				
									Tonnage					Tonnage					Tonnage		
	Above entry level	First 100 ft. below entry	Total block				Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)
Highland Mountains area	4.5	1.8	22	30.0	16.0	8.5	4.0	33.0	1.5	0.5	[illegible]	11.0	28.0	3.5	1.5	15	15.0	25.0	4.5	2.0	20
Mount Fleecer-Jerry Creek area	14.9	9.8	513	30.0	16.0	200.0	3.4	31.0	4.0	3.0	150	7.0	26.0	8.0	5.0	300	10.0	25.0	10.0	7.5	400
Wise River-Johnson Creek area	9.9	9.1	522	30.0	16.0	200.0	3.4	31.0	2.5	2.0	150	7.0	26.0	5.0	4.5	300	10.0	25.0	7.0	7.0	400
Quartz Hill syncline	15.3	2.5	162	22.5	19.5	60.0						8.0	25.0	9.5	1.5	100	19.0	22.0	20.0	3.5	250
Big Hole syncline	46.3	7.2	360	22.7	18.0	100.0						8.7	25.0	30.0	5.0	250	15.8	18.7	45.0	7.5	400
Cattle Gulch syncline	78.5	13.1	337	20.0	15.8	100.0						4.1	24.6	25.0	4.5	100	12.9	20.0	60.0	10.0	300
Trusty Lake syncline	105.5	9.5	406	20.0	15.9	100.0						3.6	25.0	35.0	3.5	100	12.9	20.0	100.0	10.0	400
Trapper Creek syncline	50.7	4.7	639	17.0	15.0	150.0											6.0	20.0	20.0	2.0	300
Totals and averages	325.6	57.7	2,961	23.4	16.2	918.5	3.4	31.0	8.0	5.5	306	6.8	25.5	116.0	25.5	1,165	11.1	21.7	266.5	49.5	2,470

[1] Area in the plane of the bedding, in millions of square feet.

ed the quality of the phosphate, but Lowell's sections specifically indicate that the central part of the member is more phosphatic with 8 feet of phosphate rock at one locality and 16 feet at the other. At lot 1404 (pls. 26, 27A; description of strata and analyses below), apparently a different trench from the two described by Lowell, a partial section includes almost 11 feet that contains nearly 30 percent P_2O_5. This section is underlain by a weathered porphyry sill; the overlying strata were not exposed.

Mount Humbug, Mont., lot 1404

[Upper part of Retort Member measured and sampled in bulldozer trench near top of Mount Humbug in E½ sec. 32, T. 1 N. R. 8 W., Silver Bow County, Mont., by R. W. Swanson in August 1954. Beds occur in roof pendant of Boulder batholith and strike N. 70° W. and dip 40° NE.]

Bed	Thickness (ft.)	Description
Rt–15	0.5?	Siltstone, medium-hard, thin-bedded, light-olive-gray to yellowish-gray (5*Y* 5/2–7/2); not well exposed.
14	.4	Mudstone and phosphorite; 0.3 foot medium-hard medium-dark-gray (*N* 4/0) mudstone underlain by 0.1 foot interlaminated medium-hard dark-gray (*N* 3/0) mudstone and phosphorite.
13	1.1	Phosphorite, hard, medium to coarsely oolitic, dark-gray (*N* 3/0); locally porous as though cement or matrix leached from around oolites, many of which have hollow centers. Irregular basal contact.
12	.7	Phosphorite and argillaceous phosphorite; 0.45 foot hard medium coarsely pelletal dark-gray (*N* 3/0) phosphorite overlain by 0.2 foot soft dark-gray argillaceous phosphorite and underlain by 0.05 foot medium-hard yellowish-gray (5*Y* 7/2) siltstone.
11	2.2	Phosphorite, medium coarsely pelletal, hard, dark-gray (*N* 3/0); soft friable zone 0.7 foot below top.
10	.4	Phosphorite, soft to friable, finely pelletal, dark-gray (*N* 3/0); 0.05 foot mudstone layer in middle.
9	.95	Phosphorite and phosphatic mudstone; hard, finely to coarsely pelletal dark-gray (*N* 3/0) phosphorite overlain by 0.15 foot hard, finely pelletal dark-gray phosphatic mudstone.
8	1.0	Phosphorite, argillaceous, hard, medium coarsely to coarsely pelletal, laminated to massive, dark-gray (3/0).
7	.95	Phosphorite, hard, medium coarsely to coarsely pelletal, thick bedded, locally laminated, dark-gray (*N* 3/0).
6	.85	Phosphorite, soft friable to medium hard, medium coarsely pelletal, poorly bedded, dark-gray to grayish-black (*N* 3/0–*N* 2/0). Unusually dirty to handle, generally very porous, and locally tiny crystals between pellets.
5	.95	Phosphorite, argillaceous, hard, finely to coarsely pelletal, thin-bedded to laminated, dark-gray (*N* 3/0).
4	.9	Phosphorite, argillaceous, hard, medium coarsely pelletal, thick-bedded, dark-gray to grayish-black (*N* 3/0–2/0).

Mount Humbug, Mont., lot 1404—Continued

Bed	Thickness (ft.)	Description
Rt–3	0.85	Phosphorite, argillaceous, medium hard, finely pelletal, laminated to thin bedded, grayish black (*N* 2/0).
2	.7	Mudstone, phosphatic, medium-hard; pellets very fine and indistinct, thin bedded to laminated, grayish black (*N* 2/0); upper part appears clayey, is soft and sheared, and looks graphitic.
1	2.0	Mudstone, phosphatic, soft to medium hard; scattered very fine pellets, thin to thick bedded, grayish black (*N* 2/0); appears graphitic; many small cleavage or crystal-face flashes.
-------	(?)	Deeply weathered soft andesite(?) porphyry sill of undetermined thickness.

Chemical analyses and uranium content of rocks at Mount Humbug, Mont.

Bed	Sample	Chemical analyses (percent)		Uranium content (percent)	
		P_2O_5	Acid insoluble	eU	U
Rt–14	7541–RWS	5.40	61.9	0.004	0.003
13	7540–RWS	32.8	13.9	.007	.007
12	7539–RWS	26.1	23.3	.005	.005
11	7538–RWS	35.8	4.97	.005	.005
10	7537–RWS	26.6	17.0	.003	.002
9	7536–RWS	27.2	22.1	.005	.006
8	7535–RWS	22 3	33.9	005	.005
7	7534–RWS	34.0	8.10	.006	.007
6	7533–RWS	29.5	17.0	.002	.003
5	7532–RWS	25.5	24.3	.007	.007
4	7531–RWS	26.6	21.8	.007	.007
3	7530–RWS	26.2	22.8	.007	.007
2	7529–RWS	11.9	39.6	.004	.005
1	7528–RWS	8.90	44.3	.004	.004

Sahinen (1950, p. 20) referred to "two zones of phosphatic shale, each about 65 feet thick, separated by dark bluish-grey crystalline dolomitic limestone about 75 feet thick" and overlain by about 300 feet of quartzite. He did not find the lower zone exposed, but two grab samples from it, collected 92 feet apart, contained 29.5 and 29.2 percent P_2O_5. Cass (1953) also believed that a lower phosphatic shale is present in this area, but Lowell (1955, p. 720–721) reported an exposure of "unaltered porphyritic andesite" at this horizon in one of his trenches and believed that the entire interval between the quartzite of the Quadrant Formation and the marble of the Park City Formation is occupied by this andesite in the form of a sill 75 feet thick. If this is true, and because other evidence suggests a northward pinchout of the Meade Peak Member of the Phosphoria Formation nearly 25 miles to the south near McCarthy Mountain, the grab samples reported by Sahinen probably represent float from the Retort Member; the float would have moved down hill only about 100 feet, a reasonable distance. The grab samples collected by Sahinen are not described, but the question could probably be clarified by an examination of the phosphorite from his lower zone, for phosphorite from the Meade Peak and Retort Members is distinct enough to be differentiated at any one locality.

That part of the roof pendant containing Permian strata is about 1 mile wide and 3 miles long. The beds in it strike about N. 65° W. and dip about 35° NE. The pendant includes rocks from the upper part of the Madison Group (Mississippian) to the upper part (?) of the Kootenai Formation (Cretaceous). The beds near the intrusive contacts are metamorphosed. A pre-intrusion fault separates that part of the roof pendant containing the phosphate deposits from an area of older strata to the east that are capped by the Quadrant Formation. At the west end of the pendant, a probable fault (covered by alluvium) separates the northwest-trending strata from a northern prong of Cretaceous strata that strike northeast. (See geologic map by Sahinen, 1950.)

Lowell (1955) found that the phosphatic shale of the Retort Member in contact with the thin sills showed some bleaching, some recrystallization of apatite, and partial replacement of both apatite and matrix by quartz, but these effects were not widespread. Rooney (1956) noted numerous quartz and calcite veinlets. As mentioned previously (p. 678), some of the carbonaceous matter in this area appears to have been converted to fixed carbon by heat from the Boulder batholith.

Though the size and shape of the roof pendant in plan are fairly well known, little information is available on its configuration at depth. The surface of the Permian strata appears in outcrop to have a relief of about 1,200 feet, ranging in altitude from about 6,800 feet near Tucker Creek at the west end to about 8,000 feet on the north side of Mount Humbug near the east end (interpreted from an old topographic map that was used by Weed, 1912). If one assumes that the batholith contact dips 45° toward the Retort outcrop, the dimensions of the phosphate area in the plane of the strata are about 1,800 feet downdip by 12,000 feet along strike, or a bed area of about 22 million square feet.

This is the basis upon which the total phosphate in this area, before reduction for spoilage, is computed (table 2). The phosphatic strata close to the intrusive body are probably more highly metamorphosed, however, and may be unsuitable for mining.

MOUNT FLEECER–JOHNSON CREEK AREA

Most of the northern Melrose district is west of Mount Fleecer (pl. 27*A*), and includes that part of the synclinorium north of the cross arch. This area includes five townships within Tps. 1 and 2 N., Rs. 10, 11, and 12 W., although almost all outcrops of Permian strata are within two of these (T. 1 N., Rs. 10 and 11 W.). Altitudes in this area range from about 5,600 feet at the Big Hole River, in the south-central part of the area, to 9,465 feet on Mount Fleecer, less than 5 miles to the northeast.

The geology of most of the area was mapped by G. T. Moore (1956), who not only described the complex structure involved but also mapped a several-mile long outcrop of Permian strata that was not previously known. Moore showed that the area contains primarily upper Paleozoic and Mesozoic formations that have been folded and faulted, overthrust by fairly extensive plates of Precambrian and lower Paleozoic strata, and invaded by quartz monzonitic rocks that are either part of or closely related to the Boulder batholith. The fold axes trend generally north to northwest, and the folds are broken by both parallel and cross faults.

The Mount Fleecer anticline in the central part of the synclinorium, just west of Mount Fleecer, plunges northward, and its axial part is occupied by the northern part of the Mount Fleecer stock of quartz monzonite. The eastern part of the original synclinorium is occupied in large part by the Boulder batholith. The southwestern part of the area north of the cross arch is characterized by closely spaced folds overturned to the east and by many faults, and it includes most of the several miles of the Permian outcrop belt that was first recognized and mapped by G. T. Moore (1956). In the northwestern part of the area, the east edge of a large thrust plate of Belt rocks overlies steeply dipping formations of Paleozoic age that have been upfaulted against the Cretaceous rocks in the heart of the synclinorium. Moore suggested that the stock of quartz monzonite in that area, which he called the Granulated stock, may have been emplaced along the thrust fault. The small Libby Creek stock is in an area of Upper Cretaceous strata midway between the Granulated stock and the Boulder batholith, to the east.

G. T. Moore (1956, p. 30) measured a section of the Permian strata about 1 mile north of Mount Fleecer that consists of 43 feet of carbonate, chert, and sandstone beneath the Retort Member and 102 feet of sandstone and some chert above it, and has covered zones at the top and bottom. At this locality he measured 20.3 feet of Retort Member, but on the west limb of the anticline about 1½ miles west of Mount Fleecer (p. 81) he measured 31.25 feet of Retort Member. Data on the quality of the phosphate are available only for the thicker section: a 7-foot zone near the top of the member contains nearly 26 percent P_2O_5 (more than 31 percent P_2O_5 in the lower half of the zone), and a 3-foot zone 4 feet lower contains almost 24 percent P_2O_5;

the bottom 14 feet is low-grade shale. The entire member averages about 16½ percent P_2O_5. The difference in thickness between the two sections is not accounted for, but it may be due more to structural complication—that is, either loss of section by shearing on the eastern limb or repetition of some beds on the western limb — than to a difference in the original thickness of the strata.

The east limb of the Mount Fleecer anticline (pl. 27*A*) lies between the main mass of the Boulder batholith and the Mount Fleecer stock (Ross and others, 1955; Moore, G. T., 1956). The batholith transects the axis of the anticline about 2½ miles north of the place where the Permian strata cross this axis, and the stock transects the Permian strata on the east limb about 2½ miles south of that point. The Permian strata crop out nearly 1 mile west of the batholith, and they dip about 45° toward it.

The subsurface configuration of the intrusive contact where it transects the east limb is unknown; however, in outcrop the contact of the stock does tend to follow the approximate base of the Quadrant for some distance (Moore, G. T., 1956, pl. 1; Lowell, 1955, fig. 5). Myers (1952, and oral commun., 1952) noted that similar relations occur along the east side of the Pioneer Mountains pluton. G. T. Moore (1956, p. 79) suggested that the Permian strata might be transected by the intrusive at as little as 300 feet downdip (assuming a plane surface of contact between the nearest outcrop points of the stock and the batholith). But if the two contacts dip toward each other — which seems more probable — the point of transection might be as much as 2,000 feet in depth, or nearly 3,000 feet downdip.

The rock near the intrusive contact probably contains andesitic sills, as suggested by G. T. Moore (1956), and it may be otherwise so altered as to be unfavorable for ore treatment. Lowell (1955, p. 725–730) discussed the contact effects of sills on the east limb and described bleaching, partial recrystallization, destruction of original texture, and some migration of phosphate in a narrow zone near the contact. The effects near the contact of the main intrusive with the limb are probably more intense, but there is no information to suggest a wide aureole of alteration that would be deleterious to phosphate.

In estimating the phosphate resources for the east limb of the Mount Fleecer anticline, an average width (downdip) of 1,250 feet was used. About 25 percent of the phosphate was assumed to have been spoiled by igneous contact effects, invasion by sills, and faulting. For computation purposes, the east limit of the block was placed at the town line between Rs. 9 and 10 W. The tonnages are combined with those for the Mount Fleecer–Jerry Creek area in table 2.

The southwest quarter of T. 1 N., R. 9 W., contains extensive outcrops of Cretaceous rocks in a southeasterly extension of the remnant of sedimentary rocks between the Mount Fleecer stock and the Boulder batholith. These rocks are identified as the Kootenai Formation on the State geologic map (Ross and others, 1955), but the detailed maps of Theodosis (1955) and G. T. Moore (1956) of the areas immediately to the south and the west suggest that the rocks are post-Kootenai. The Divide Trench (Pardee, 1950), which crosses southward through the east side of the Melrose district, and which is between the stock and the batholith in this township, is filled with Cenozoic deposits that blanket the central part of the township. The nature of the bedrock beneath them is unknown. However, in T. 1 S., R. 9 W., this trench, part of which is occupied by the Big Hole River near Divide, appears to be underlain chiefly by Paleozoic formations in the eastern, central, and southern parts, and by Mesozoic strata in the northern part. (See map by Theodosis, 1955.) The Mesozoic strata occur in a synclinal structure that plunges northward into the southwest quarter of T. 1 N., R. 9 W. The formations on the east flank of this syncline were once continuous with the northeast-dipping formations in the Highland Mountains roof pendant previously described (p. 688–691); these two rock masses are the remnants of the two flanks of an anticlinal structure that plunged northwestward off the northwest corner of the southwest Montana positive area. The southwest corner of the Boulder batholith engulfed the axial part of the north end of this anticline and most of the adjoining syncline farther north.

Most of the Permian rocks in the syncline in T. 1 N., R. 9 W., may have been engulfed by the Boulder batholith and by the Mount Fleecer stock beneath both the area of Cretaceous outcrop and the area covered by Cenozoic deposits. Any phosphate deposits there would be too deeply buried to be of economic interest. Because of the many uncertainties in the geology, no estimate of the amount of phosphate in T. 1 N., R. 9 W., was made.

The southern part of the area west of the axis of the Mount Fleecer anticline in T. 1 N., Rs. 10 and 11 W., is complexly folded and faulted. The Permian rocks are repeated on the successive flanks of several crenulated and faulted anticlines and synclines whose axes strike N. 20° E. to N. 30° W.

The folded area is bounded on the west by an overthrust plate of Belt rocks. The northwest-striking folds on the west side of the folded area appear to have formed in response to this overthrust, and the strata have been dragged and crumpled beneath it. These folds, in turn, are bounded on the northeast by a lesser thrust. A very irregular fault, trending nearly due east, transects the south ends of the folds east of the lesser thrust. This irregular fault was interpreted by G. T. Moore (1956) as a transverse fault, presumably steep. Interpretation of it as a minor thrust appears to be equally logical, however, particularly inasmuch as the fold axes on the two sides not only are offset but differ in number and in amount of offset, and much of the change in strike of the fold axes from northwest to north occurs at this fault zone.

The folds of this area plunge north into a broad synclinal area in T. 2 N., Rs. 10 and 11 W., that is underlain by Cretaceous rocks. G. T. Moore (1956) traced the axes of these folds for several miles into the area. The area is bounded on the east by the Boulder batholith and the Mount Fleecer stock and anticline, and on the west by a north-trending sequence of steeply dipping Paleozoic formations that are upfaulted against Cretaceous strata and that have been overridden from the west by the large thrust plate of Belt rocks. The central part of the syncline was invaded by the Libby Creek stock, which has an areal extent of about 4 square miles.

The steep fault on the west side of the syncline in T. 2 N., R. 11 W., was interpreted by Moore to be nearly vertical because of its fairly straight course. But the topographic relief along the fault is only about 1,000 feet and the local offset in alinement is as much as 1,200 fee. Thus the fault does not have a very plane surface, and it may be a reverse fault. To the south in sec. 2, T. 1 N., R. 11 W., it disappears beneath the southeast corner of the thrust plate of Belt rocks, and no trace of it was found just a quarter of a mile south of that thrust plate in the area of gently dipping Upper Cretaceous strata. Thus, in the short distance of about 1,000 feet along the strike of the Paleozoic sequence, there is a stratigraphic discontinuity of more than 7,000 feet and a dip and strike discontinuity of nearly 90°. To fulfill the requirements of the large displacement on the north-trending fault, this discontinuity would necessarily indicate the presence of a west-trending cross fault that is believed to be concealed beneath the thrust plate of Belt rocks. The cross fault probably represents the tear which terminates the south end of a thrust block that is, in turn, bounded on the east by a steep reverse fault. Most of this thrust block was subsequently covered by a thrust plate of Belt rocks. In the tectonic history of the area, therefore, this steep reverse fault and its associated tear probably represent an early stage of the compression that was culminated by the large overthrust. The amount of lateral displacement that might have accompanied the tear and the steep reverse faults is not known, but on the basis of the distribution of strata and of the structures in the area, it would appear to have been fairly large, perhaps 3 miles.

Except where engulfed by the monzonite, this entire synclinal area between the steep reverse fault and the Boulder batholith is probably underlain by Permian strata. Loss of strata due to the intrusion of monzonite might be large, however, for the Mount Fleecer, Libby, and Granulated stocks are probably cupolas of the Boulder batholith. Monzonite may thus occur at a fairly shallow depth in the syncline. Inasmuch as any phosphate in this area is deeply buried — probably at least 2,000–3,000 feet beneath the surface in most of the area — no resources were estimated for T. 2 N., Rs. 10 and 11 W.

In the complexly folded and faulted area near the major thrust (west side of T. 1 N., R. 11 W.), much phosphate rock has probably been spoiled by mashing and shearing, so a large spoilage factor must be applied when making an estimate of the phosphate resources. Furthermore, lack of data on this area makes thickness and grade estimates of phosphate rock very uncertain. The Permian rocks at depth in the northwest flank of the Mount Fleecer anticline may have been partly engulfed by the monzonite of the Mount Fleecer stock, or they may have been metamorphosed near the stock and thus rendered unsuitable for treatment. However, the general tendencies of the intrusive to assimilate the carbonate of the Carboniferous, stop at the base of the Quadrant, and not assimilate the highly siliceous rocks at the top of the Paleozoic column suggest that most of the phosphate on the northwest flank of this anticline probably was not affected by intrusive activity except for invasion by small andesitic sills.

Observations by Richards and Pardee (1925), as well as by the many geologists who have worked in this region in recent years, indicate that one or more periods of deep weathering occurred in middle Tertiary time. During this weathering, subdued topography formed and various types of continental deposits accumulated. Subsequent uplift, caused partly by block faulting (Pardee, 1950), caused the superposition of drainage on the complex bedrock structure.

Undoubtedly, this and subsequent weathering have enriched the near-surface phosphorite by leaching carbonate and by oxidizing the organic matter and sulfide. Thus, the rock has also been made more friable and, thereby, more easily mined and beneficiated. The andesitic sills that were intruded into, or near, the Retort Member are now soft montmorillonitic clay that preserves only faint relicts of the original texture. (See Lowell, 1955; Moore, G. T., 1956.) The condition of these sills reflects the intensity of alteration, much of which was probably caused by middle Tertiary weathering related to development of the old erosion surfaces. In general the weathering effects may be expected to decrease with depth. Rooney (1956) believed that the montmorillonitic clay in the Retort Member of this district (and presumably that in the sills) was formed by hydrothermal alteration associated with the period of igneous intrusion. (See discussion on p. 696.) Such alteration should be expected to persist to greater depth than that due to weathering. Although the effects of hydrothermal alteration should not be discounted, weathering seems to have caused greater alteration.

Because of the lack of a suitable topographic base map and because of the complexity of the structure in the northern part of the Melrose district, detailed estimates of the phosphate resources could not be made. Estimates are given (table 2) for two blocks of approximately equal area in T. 1 N., Rs. 10 and 11 W., that are separated by the anticlinal axis crossing the town line between the ranges. The blocks are the Mount Fleecer–Jerry Creek area on the east and the Wise River—Johnson Creek area on the west.

SOUTHERN MELROSE DISTRICT

The southern part of the Melrose district comprises four townships (Tps. 1 and 2 S., Rs. 9 and 10 W.; pl. 27*A*) that contain the best phosphate deposits in this part of Montana. Phosphate was first found in the area by Gale (1911) in 1910, and the four townships were mapped by Richards in 1912. This work, including observations by Pardee in 1911 and 1923, was reported by Richards and Pardee (1925). An exploration tunnel was driven into the Retort phosphatic shale after World War II and has since been developed into the Maiden Rock mine by the Victor Chemical Works of the Stauffer Chemical Co. Theodosis (1955) remapped the four townships at a larger scale and in more detail. W. E. Fowler (1955) remapped parts of the area in even greater detail to attain better definition of the phosphate reserve. Peirce (1952) and Rooney (1956) made special studies of the Permian rocks.

These townships include the synclinorium south of the cross-arch. The area contains a series of asymmetric southeast-plunging folds in which Carboniferous rocks are exposed in the anticlines and Permian to Cretaceous formations are preserved in the synclines. The northeast flanks of the anticlines are generally overturned and sheared. Some low-angle thrusting has moved Madison Limestone over younger strata.

The area was eroded to a surface of moderate to low relief during the Tertiary; parts of the area were covered by continental deposits, most of which have since been eroded away. Much of the drainage pattern was established on those deposits, and was superposed on the bedrock structure during subsequent uplift and erosion. Part of the uplift appears to have been caused by block faults, as indicated chiefly by the Divide Trench (Pardee, 1950).

The southwest corner of the Boulder batholith is in the northeast corner of this area, and the southern part of the Mount Fleecer stock is near the northwest corner (pl. 27*A*). Quartz monzonite is also present in several smaller intrusives. The largest of these, about 1 square mile in surface area, is near the center of T. 2 S., R. 9 W.; small intrusives occur near the north edge of this township in sec. 4, near the east edge of T. 2 S., R. 10 W., in sec. 13, and in the western part of T. 1 S., R. 10 W. (Theodosis, 1955, pl. 1). Several sills of andesitic rock, reportedly found in surface and subsurface exposures, are also probable offshoots from the larger intrusives. In addition, the northeast flank of the large Pioneer Mountains pluton is only a short distance southwest of the area. All these intrusive bodies are probably connected at depth; therefore, a large part of this area is believed to be underlain by quartz monzonite. The thickness of the sedimentary plate above the intrusive is very difficult to estimate, but it seems probable that the phosphate deposits are well above intrusive rock in most of the area and that they were not altered very much by the intrusives.

The resources in the central part of the Melrose district are here considered relative to five synclinal structures (fig. 180)—the Quartz Hill, Big Hole, Cattle Gulch, Trusty Lake, and Trapper Creek synclines (table 2). The Quartz Hill syncline on the north and the Big Hole syncline on the east were originally part of the same structure. Although they are still joined, they have had different histories and are discussed separately. All but the Quartz Hill syncline join in the southern part of this area and apparently die out farther south.

QUARTZ HILL SYNCLINE

The Quartz Hill syncline (fig. 180, area *d*), which includes about 5 square miles, is on the south side of the Mount Fleecer stock. It is terminated on the south by a combined tear and thrust fault that brought Madison Limestone of Mississippian age against rocks as young as Late Cretaceous.

The east and west sides of the syncline are rather sharply upturned, and the Permian strata dip about 45°–50°. The width of the syncline between Permian outcrops is about 3½ miles, but the length is only 1½ miles between the stock and the thrust plate. The Retort Member is presumed to be at an altitude of 3,000–4,000 feet in the central part of the structure; however, it reaches an altitude of nearly 7,000 feet of the southwest corner of the syncline, and an altitude of about 6,000 feet on the east side. It projects perhaps as much as 1,500 feet beneath the thrust plate on the south, and beneath the thrust the beds are probably sharply upturned or overturned. That part of the south boundary adjacent to the west limb of the Big Hole syncline is a large tear fault. On the southeast side of the fault, the beds were folded upward in front of the thrust of Madison Limestone, whereas on the northwest side they were sheared off and overridden by the thrust.

The quartz monzonite of the region was probably emplaced after the main folding stage of the Laramide orogeny, for it transects the fold structures. The thrust stage followed the initial folding, probably after a long period of time. The structural features associated with the Quartz Hill syncline suggest that the thrusting occurred after the intrusion and consolidation of the stock; these features also suggest that the Mount Fleecer stock acted as a buttress, past which the strata on the south side were squeezed eastward into tighter folds and were sheared. The strata in the moatlike Quartz Hill syncline near the south side of the stock were apparently protected by the stock and were bridged by the thrust plate of older, more massive rocks that rode past the side of the stock and across this part of the synclinal structure.

In their outcrop areas the Permian rocks of the Quartz Hill syncline probably have not been badly crushed or sheared, except near the boundary of the thrust plate and, locally, near small cross faults. The Permian rocks near the intrusive have undoubtedly been somewhat altered and also intruded by minor apophyses. These effects are probably restricted to a narrow zone no more than a few hundred feet wide.

No data on the thickness and the quality of phosphate rock in the east limb are available, but data are available for exposures a few miles to the south. (See the section on "Big Hole Syncline.") In the west limb, an average of about 8 feet of furnace-grade rock, or nearly 20 feet of 18 percent P_2O_5 rock, is present (Theodosis, 1955; Fowler, W. E., 1955; Rooney, 1956). The resources above or near entry level are small, for the strike length of the strata is short and the relief is moderate. No tonnage is calculated for the aureole within 1,000 feet of the presumed contact with the Mount Fleecer stock. The location of that contact at its intersection with the Permian was obtained by projecting the contact 45° outward from the contact at the surface.

BIG HOLE SYNCLINE

The Big Hole syncline is on the northeast side of the southern Melrose district and connects at the northeast with the Quartz Hill syncline. It contains the Maiden Rock, Canyon Creek, and La Marche Gulch mines of the Victor Chemical Works. The part of the syncline within the district is about 10 miles long. The southernmost 4 miles of the syncline contains no outcrops of the phosphatic strata, for the Permian rocks on the northeast limb are buried beneath Tertiary deposits, and those on the southwest limb do not reach the surface. At the northwest end of the syncline, the Permian strata in the two limbs are half a mile apart, but they are 1 mile apart near Canyon Creek. Near the south end of the syncline, the width from the buried outcrop on the east to the axis of the plunging anticline on the west is 1½–2 miles.

The syncline strikes N. 30°–35° W. and is asymmetric. In the overturned southwest limb, dips are as low as 35° and in northeast limb dips are about 45°. The Permian rocks in the trough apparently lie at altitudes of a little more than 4,000 feet near the northwest end and a little less than 2,000 feet near Melrose to the southeast. Their outcrops range from an altitude of 5,250 feet at the Big Hole River (and perhaps less beneath the Tertiary cover to the southeast) to nearly 7,500 feet in the overturned limb near the northwest end. The overturned limb is complicated by bedding-plane shearing and some faulting, and both limbs are broken locally by numerous small cross faults. Near the north end, Theodosis (1955) mapped a strong shear zone near the axis of the syncline and another on the east flank beneath the Permian. To the northwest, these two zones apparently join at the town line and cross the syncline diagonally; they probably also join the tear fault that terminates the southwest limb (described above). The zones appear to represent moderately high angle reverse faulting that is part of the general system of thrusting. At the north these zones have been selected as the arbitrary boundary between the Quartz Hill and Big Hole synclines.

Near the south end of the Permian outcrop zone a small stock of quartz monzonite was intruded near the center of the syncline. The stock is probably not much more than 1 square mile in outcrop area, and its east and south sides are covered by valley fill. The several small sills that occur in the central part of the northeast limb are probably related to both this stock and a small plug east of the Maiden Rock mine.

In the general area where Canyon Creek crosses the Big Hole syncline, the phosphatic part of the Retort Member was sampled in both limbs of the structure. (See pl. 26, lots 1238, 1239, 1240, and 1366.) The rocks include both surface and underground exposures. Also, both limbs have been mined south of Canyon Creek, and subsurface exploration work has been done north of the creek, on the southwest limb. The thickness of furnace-grade phosphate rock is generally 6–12 feet, and the low-grade phosphate rock is 15–18 feet thick.

Much of the phosphate above entry level in the middle third of the northeast limb (south of the Big Hole River) has been mined from the Maiden Rock mine, but the total amount of rock mined is unknown. All mining has apparently been above the entry level, and the mine portal is about 50–75 feet above the river. A similar situation exists at the Canyon Creek mine on the southwest limb. Because the tonnage mined is unknown and is changing continually, and because this tonnage would be small in relation to the total tonnage in the structure (even though it might represent a large percentage of the total tonnage above entry level), no attempt has been made to deduct the amount of rock mined from the total estimate.

The rocks in faulted zones are probably strongly sheared, so the spoilage factor for some parts of the structure probably is fairly large. Furthermore, this area appears to have been rather deeply weathered beneath the Tertiary erosion surface described by Richards and Pardee (1925). The highly altered condition of andesitic sills appears to be chiefly the result of deep weathering. Lowell (1955, p. 730) stated that a 5-foot-thick clay zone in the Mount Fleecer area "undoubtedly represents" a "deeply weathered" sill. In discussing a highly altered sill exposed in the Maiden Rock mine, however, Lowell (1955, p. 733) seemed to infer that the alteration was late-stage-magmatic —"following emplacement the dike rock was altered to clay minerals." Rooney (1956, p. 58–60) examined the shaly beds of the Retort Member at several localities and found an abundance of montmorillonite. He considered the rocks to be slightly weathered, for they retain their black color; he attributed the montmorillonite primarily to hydrothermal alteration. However, the carbonaceous matter in this area seems to have been converted to fixed carbon by heat from the intrusives. (See p. 678; Lowell, 1955, p. 725; and Cressman and Swanson, 1964, p. 320.) The carbonaceous matter would not readily oxidize, therefore, and darkness of color would not be a reliable index of the degree of weathering. Evidence seems to indicate that weathering was both extensive and deep in this area, and it may have been a major factor in the formation of montmorillonite. In those areas that were subjected to both igneous activity and subsequent deep weathering, the causes of clay alteration are difficult to identify. But the overall evidence indicates that the weathering of the phosphatic and associated rocks in the near surface was widespread and, locally, may have been fairly deep.

The approximate area of the small monzonite plug where it cuts the Permian strata was determined by assuming the outward dip at the top of the intrusive to be 45°. By including an alteration aureole about 1,000 feet wide, the area presumably spoiled by intrusion would be a little more than 2 square miles.

CATTLE GULCH SYNCLINE

The Cattle Gulch syncline, adjacent to the Big Hole syncline on the southwest, is a long narrow structure that trends N. 45° W. The northeast limb dips about 45°, and the southwest limb is overturned and is largely cut out by a thrust fault that is nearly parallel to the syncline. The northeast limb of the adjacent Trusty Lake syncline forms the upper plate of this thrust. On the southeast, a bifurcation of the anticlinal axis between the two synclines forms a small shallow syncline between them; it was called the Dry Gulch syncline by Peirce (1952). Estimate of the phosphate in this small syncline is given together with that of the Cattle Gulch structure.

The thrust fault on the southwest side of the Cattle Gulch syncline was described by Theodosis (1955) as dipping about 60° SW. near the northwest end but flattening with depth. Southeastward, the fault trace is increasingly irregular and apparently the fault dips more gently. Near the town line between Rs. 9 and 10 W., the fault splits; the lower, or northeastern, segment underlies the Dry Gulch syncline and reaches the surface near the crest of the overturned limb of the Cattle Gulch syncline. This branch apparently dies out about 3 miles southeast of the split. The upper segment crosses into the northeast limb of the Trusty Lake syncline and appears to die out there, but a prominent shear and thrust zone farther southeast (and in line) may be the continuation of this same fault. The thrust also appears to bifurcate at the northwest end of the Cattle Gulch syncline, and the smaller, lower segment crosses the end of the fold, offsetting the axis where the Permian rocks cross the trough of the structure in outcrop. This thrust fault and the large fault bounding the Quartz Hill syncline on the south presumably connect in the western part of T. 1 S., R. 10 W., where both the upper and lower plates are composed of Madison Limestone. The faults could not be readily traced through this formation; accordingly, they were not mapped, although breccia zones were indicated by Theodosis (1955).

Numerous small cross faults offset the Permian strata on the limbs of the folds. A small plug of quartz monzonite occurs near the intersection of the thrust segments in the east-central part of T. 2 S., R. 10 W. It is not known to invade the Permian rocks of the Cattle Gulch syncline, though it might do so beneath the thrust plate. Tertiary volcanics cover a significant part of the syncline in the northeastern part of this township.

As defined by the Permian rocks, the trough of the Cattle Gulch syncline crops out at an altitude of 7,700 feet at the northwest, and the limbs nearby rise to about 8,300 feet. The syncline plunges southeastward, rather steeply in the northwestern part, and gently in the central part, where thrusts and drag folds complicate the structure of the southwest limb. In the southern part of T. 2 S., R. 9 W., near its apparent junction with the Big Hole syncline, the trough of the east, or main, branch of the Cattle Gulch syncline is at less than 2,000 feet altitude. The west, or Dry Gulch, branch crops out at an altitude of about 6,000 feet in the western part of T. 2 S., R. 9 W., and it plunges southward to less than 4,000 feet at the south side of this township.

Most of the data on the phosphate in the Cattle Gulch syncline were interpolated from localities in the adjoining Big Hole and Trusty Lake synclines, but some are from lot 1237 on the northeast limb of the syncline near the town line of Rs. 9 and 10 W. These data indicate the presence of a somewhat smaller thickness of minable rock of the two lower grades in the Cattle Gulch syncline than in the Big Hole structure. The data also appear to indicate a slight drop in both thickness and grade toward the southeast.

Shearing along the major thrust fault and along bedding planes in the drag folds and extensive breakage and dilution near the numerous cross faults have probably caused spoilage of much of the potential reserve in this syncline. The shallow Dry Gulch structure appears to be the most attractive area of potential stripping deposits; however, much of the phosphorite is covered by chert and quartzite that would make strip mining difficult.

TRUSTY LAKE SYNCLINE

The Trusty Lake syncline parallels the Cattle Gulch structure and is almost as long. The northwest end of the fold is nearly symmetric, but elsewhere the fold is asymmetric with a steeply dipping to overturned southwest limb complicated by thrust faults and drag folds. Dips on the northeast limb average about 45°, but they are generally steeper near the town line between Rs. 9 and 10 W., where the upper segment of the thrust fault that bounds the Cattle Gulch syncline cuts across the intervening anticline into this structure. A very small plug of quartz monzonite crops out in this area but apparently does not extend very far into the syncline.

In the north-central part of T. 2 S., R. 10 W., the southwest limb is drag folded, and the width of the syncline, which is almost doubled, is about 2 miles. Sheared beds and some reverse and cross faults further complicate the structure. A little farther south, in the center of the township, the southwest limb is offset eastward about 1 mile on a large fault (apparently a combined thrust and tear fault) that joins on the east with the north end of another thrust fault. The Permian strata near this junction are overturned, and the net offset of the southwest limb is about 4,000 feet. Although this structure bears many resemblances to the fault zone to the north that terminates the Quartz Hill syncline, it is much smaller. The thrust zone on the east side of the syncline, and chiefly south of Trapper Creek, in the southwestern part of T. 2 S., R. 9 W., is believed to be related to the Cattle Gulch thrust, as previously noted.

The Permian rocks in the trough of the syncline crop out at an altitude of about 7,200 feet at the northwest end but reach 1,000 feet higher on the two limbs within 1 mile, beyond which the altitudes of outcrops decrease southeastward. The structure is crossed at an altitude of about 6,000 feet by Canyon and Trapper Creeks, which emerge from canyons to the west. At its southeast end the trough is believed to be lower than 2,000 feet in altitude.

The Retort Member has been sampled at several places in the Trusty Lake syncline: namely, lot 1359 and localities reported by Theodosis (1955) and by W. E. Fowler (1955). The grade and the thickness of the phosphate seem to diminish southeastward. Some deposits that could be strip mined are believed to be present, as on the southwest side of the drag fold just north of Canyon Creek, but these deposits were not examined by the author.

TRAPPER CREEK SYNCLINE

South of the Trusty Lake syncline is a synclinal basin that is drained by Trapper Creek; it is here called the Trapper Creek syncline. This syncline forms a broad structural basin that is open on the east and bounded on the north and west (Theodosis, 1955; Karlstrom, 1948) by upturned Paleozoic strata. The southern part of the structure has not been mapped in detail, but on the basis of interpretation from the Montana geologic map (Ross and others, 1955), the Trapper Creek syncline seems to be bounded on the south by a small cross arch in the north-central part of T. 3 S., R. 10 W., that strikes a little north of east (See pl 27*B*). At the west side the Madison Limestone has been thrust across upturned Permian and Triassic strata. Toward the center of the basin, Theodosis (1955) mapped a small klippe of Madison, Amsden, and Quadrant strata. This klippe was mapped by Richards and Pardee (1925) as a much larger thrust plate of Quadrant, and it is similarly shown on the State map; but Theodosis showed outcrops (indicated by dip and strike symbols) of Colorado Group rocks within the area of the large thrust plate in the southern part of T. 2 S., R. 10 W.

On the north and northwest sides of the syncline, Theodosis (1955) showed Permian rocks dipping 40°–50°, and the dips on the southwest are assumed to be comparable. Theodosis also showed some cross faults and shears on the north side. Except for these details, little is known about the structure.

From stratigraphic and analytical data on the adjoining areas to the northeast, this area is assumed to contain 6 feet of phosphatic shale containing more than 18 percent P_2O_5. Some of the area on the north and northwest, north of Trapper Creek, may have strippable deposits on the slopes nearly parallel to bedding.

DILLON DISTRICT

General features

South of the Melrose district the synclinorium widens to almost 25 miles, in the area north of Dillon, and swings in a broad arc that is convex to the east. Included in the Dillon district is that part of the synclinorium between the Melrose district and Armstead, an area about 45 miles long (pl. 27*B*, *C*). The area is dominated by basins and low rolling hills, mostly along the Beaverhead River, which enters from the southwest at an altitude of about 5,500 feet and leaves at the northeast at an altitude of less than 4,700 feet. The Big Hole River drains the north end of the area and joins the Beaverhead at the northeast corner of the area to become the Jefferson River.

The low area is bounded on the northwest by the Pioneer Mountains, on the northeast by the Highland Mountains, and on the east by the piedmont plain west of the Ruby Range. The Blacktail Range enters the area from the southeast, and the Tendoy Mountains, from the southwest, although both ranges are reduced to a rather low level at their junction near the Beaverhead River. McCarthy Mountain, near the north-central part of the area, is a small isolated highland.

The Dillon district is serviced by the Oregon Short Line Railroad of the Union Pacific Railway system and by U.S. Highway 91, both of which connect with Butte, Mont. and Salt Lake City, Utah, and by State Highway 41 between Dillon and Whitehall. A number of county roads cross the area, and smaller trails make nearly all parts of the area accessible, except the more rugged parts of the mountains.

The Retort Phosphatic Shale Member has been explored for coal at Dalys Spur and for oil shale at Small Horn Canyon by limited underground workings, but no phosphate has been mined.

Geologic setting

The Dillon district (pl. 27*B*, *C*) includes the central third of that part of the southwest Montana synclinorium in the report area. (See p. 670.) Geologic descriptions noted herein are based primarily on the detailed mapping by Lowell (1949, 1953) and by Myers (1952).

Crystalline Precambrian rocks underlie the eastern and southeastern parts of the district. They form the southeastern part of the Blacktail Range and all but the northern part of the Ruby Range, to the east, and they are exposed in the core of an anticline northwest of Armstead, near the southwest corner of the district. Belt Series sedimentary rocks of Precambrian age underlie much of the northwestern part of the district and are exposed in and near the Pioneer Mountains northwest of Dillon. A large pluton of quartz monzonite forms the heart of the Pioneer Mountains, and a small pluton forms McCarthy Mountain in the northeastern part of the district. Thick Tertiary continental deposits, made up of diverse volcanic rocks, are interlayered with clastic sediments rich in gravel, and with alluvium in the broad lowlands; the deposits cover more than half the bedrock in this district.

The Dillon district lies at the apparent junction of two major zones of thrust faulting, as shown by the detailed maps by Myers (1952) and by Lowell (1953) and by reconnaissance of a larger area. The main north-trending zone between Lima and Drummond traverses the west side of the Dillon district. A thrust zone that swings eastward in a broad arc into the central Montana embayment east of the Boulder batholith appears to join the north-trending zone in the area of extensive Tertiary cover near Dillon. Most of the northeast-trending zone is covered in the Beaverhead-Jefferson River valley area, between Dillon and a point east of Silver Star.

The structure in this district is significant to the interpretation of stratigraphy. To the north (T. 5 S.), extensive folding and thrusting has affected both sides of the 11-mile-wide interval between South Greenstone (lot 1250) and Big Hole Canyon (lot 1358). The central part of that interval, though mostly covered, appears — on the basis of projection from the south — to involve similar structures. This interval has been structurally foreshortened, perhaps by as much as several miles, producing an east to west telescoping of thicknesses and of facies variations. Other folds and thrust faults occur between the Greenstone and Kelley Gulch (lot 1249) sections and have caused further foreshortening. Similarly, folds and thrust faults occur between the Sheep Creek and Cedar Creek (lots 1234, 1256) localities farther south and have caused a somewhat comparable foreshortening.

The thick Tertiary continental deposits in this district unconformably overlie Paleozoic and Mesozoic formations that had been beveled to generally low to moderate relief. The full thickness of these deposits is unknown, but it appears to be more than several thousand feet. The area has been differentially uplifted along fairly recent, and presumably high angle, faults and by broad warping.

Stratigraphy

Vitreous orthoquartzite of the Quadrant Formation underlies the Permian sequence throughout the Dillon district and is as much as 650 feet thick (Myers, 1952, pl. 1). It is overlain by the Grandeur Member of the Park City Formation and is composed dominantly of dolomite and siltstone, whose range in thickness of 30 to 105 feet in this district may well reflect unconformable relations to the Quadrant, as in the Melrose district.

The Meade Peak Phosphatic Shale Member of the Phosphoria Formation is very thin in this district, averaging only about 4 feet thick (pl. 26). Near the Big Hole Canyon localities, southeast of McCarthy Mountain (lots 1354, 1358), the Meade Peak Member is locally absent but in some places is as much as 6½ feet thick. In the Pioneer Mountains the Meade Peak Member was measured at one locality (lot 1249), where it is less than 2 feet thick. The member is apparently absent near Melrose, so it probably lenses out in the interval of about 20 miles between measured sections.

The phosphorite is dominantly oolitic, partly sandy, and tan to light gray; these characteristics are typical of a shoreward facies. At South Big Hole Canyon No. 2 (lot 1354) it is more than 2 feet thick and is believed to represent a lenticular bed of limited areal extent. The Meade Peak Member is believed to have no other minable phosphate reserves in the Dillon district.

The strata between the Meade Peak and Retort Phosphatic Shale Members are less than 75 feet thick in the northern part of the district. The rocks in this interval are composed dominantly of cherty dolomite but include a few feet of Rex Chert Member at the base; sand is a major constituent to the west. To the south the interval is about 90 feet thick at Dalys Spur (lot 1223), and the rocks in it are composed entirely of sandstone and chert. At Sheep Creek (lot 1234), however, the rocks of the interval are 140 feet thick and include 38 feet of Rex at the base, nearly as much sand as at Dalys Spur, about 35 feet of dolomite, and some mudstone.

In much of the Dillon district the Retort Phosphatic Shale Member is divisible into three units — an upper and a lower phosphatic unit and a middle almost barren unit (fig. 181) — and ranges in thickness from 51 to 64 feet. At Big Hole Canyon (lot 1358), however, the mudstone unit is absent and the member is only 35 feet thick. The mudstone unit normally occurs in the upper middle part of the member. At Cedar Creek (lot 1256), near the southwest corner of the district, the upper phosphatic unit is absent. The phosphatic units are composed chiefly of interbedded phosphatic mudstone and phosphorite, but they also contain some carbonate.

At two localities in the southern part of the district, the member contains a large amount of oil. (See discussion, p. 765.) Most of the oil is in the middle, mudstone unit, but, locally, large amounts are in some of the phosphatic beds. No information is available on the oil content of the member in other parts of the district.

The correlation is fairly good between the strata of the Retort Member in the Melrose district and those at Big Hole Canyon in the northeastern part of the Dillon district, a distance of about 20 miles. The thicknesses of the sections are comparable, 25–30 and 35 feet, respectively, and the distribution of phosphorite and other rock types is similar. One principal difference between the sections is the increase of carbonate rock southeastward; otherwise, the sections appear to be nearly on line with the strike of the facies.

Between Big Hole Canyon and the rest of the Dillon district, however, there is a big difference both in the thickness of the member and in the distribution of phosphate within it. Note that in figure 181 (lot 1358) most of the member at Big Hole Canyon is shown to be correlative with the lower phosphatic shale unit of

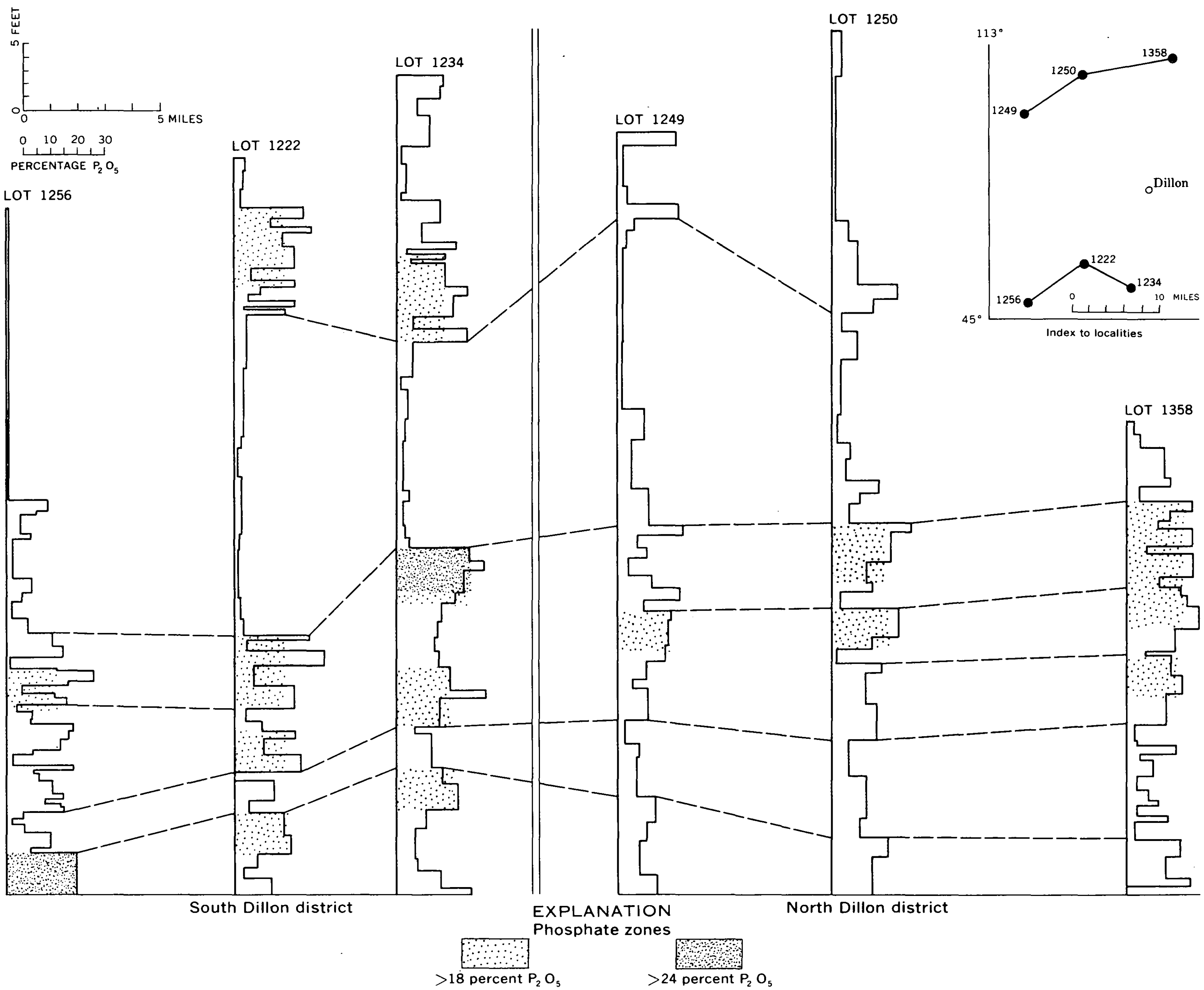


FIGURE 181.—Correlation of the Retort Phosphatic Shale Member of Phosphoria Formation in the southern and northern parts of the Dillon district. Note: This is an alternate interpretation to that of plate 24 of Cressman and Swanson (1964). Vertical exaggeration, × 2640.

the rest of the district. This is an alternate interpretation to that shown on plate 24 of Cressman and Swanson (1964).

On the basis of either correlation, a major loss of section, either from the middle of the member, as suggested on plate 24 of Cressman and Swanson (1964), or from the top of the member, as suggested by the present author (fig. 181), must be accounted for between Big Hole Canyon and the rest of the district. If the loss is from the top, some of it might be accounted for by the eastward thinning of mudstone layers. Such thinning is suggested for the upper part of the member at Cave Creek (lot 1257). (See p. 707.) Districtwise, however, the member seems to thicken eastward, so this does not seem to be a satisfactory explanation. The sandstone above the Retort Member at Big Hole Canyon is part of a large tongue that extends south-southeastward from Butte. (See Cressman and Swanson, 1964, fig. 147.) If this tongue started to form while Retort sediments were accumulating elsewhere, much of the thinning of the member at Big Hole Canyon would reflect a change in facies, and the sandstone beds above the Retort there would be equivalent to the upper Retort strata farther west. Finally, the upper part of the Retort Member in the rest of the district may be represented by a hiatus at Big Hole Canyon and in the Melrose district. Some support for this concept is offered by the thin bed of conglomerate, or pebbly phosphorite, at the top of the Retort Member in part of the Melrose district, and by the absence from that district of the low-grade shales that occur at the top of the member at Big Hole Canyon. Possibly all three factors were involved. The interpretation could be significant to mining in some of the northern part of the Dillon district.

The rocks above the Retort Member in the Dillon district range widely in thickness and in stratigraphic sequence. At Big Hole Canyon to the northeast, only 76 feet of the member is exposed. The contact with the Dinwoody Formation is beneath a narrow covered interval. Chert and sandstone are interbedded in almost equal amounts; beds are thick in the lower part (where a 26-foot-thick bed of sandstone just above the base is overlain by a 22-foot-thick bed of chert) and are thin in the upper part. At Sheep Creek farther south (lot 1234), the section is 110 feet thick and contains more sandstone. It also contains much mudstone interbedded with the chert, particularly near the base and near the top. Most of the beds are somewhat cherty. At Dalys Spur (lot 1223) and Cave Creek (lot 1256) to the west and the northwest, the section is about 140 feet thick, is made up mostly of chert, and contains beds of quartzitic sandstone in the upper part. In contrast, the allochthonous Kelley Gulch section (lot 1249) west of Cave Creek, which is of comparable thickness, is made up mostly of thin-bedded muddy chert and contains much less sand. The Dinwoody Formation of Triassic age appears to overlie the Permian strata conformably.

Phosphate

The average P_2O_5 content of the Retort Member decreases westward in the Dillon district (pls. 26, 27*B*, *C*). At Big Hole Canyon in the northeast (lot 1358) the P_2O_5 content averages 13½ percent, and at Sheep Creek in the southeast (lot 1234) it averages 11½ percent. At South Greenstone (lot 1250) and at Dalys Spur (lot 1222), west of the localities just mentioned, the P_2O_5 content averages 9 percent, and at the westernmost localities — Kelley Gulch (lot 1249) and Cedar Creek (lot 1256),— it averages only 7½ percent.

Most of the Retort Member at Big Hole Canyon, and the lower part of the member at the other localities in the Dillon district, is composed of alternating beds of phosphorite and phosphate mudstone, and a few interspersed beds of carbonate rock that weathers to siltstone. In the northern part of the district, the phosphatic beds average 28 feet in total thickness, and they range in average P_2O_5 content from 10.3 percent at Kelley Gulch (lot 1249) to 14.7 percent at Big Hole Canyon (pl. 26, lot 1358). At Cave Creek (lot 1257), 21 feet of the member averages 15.3 percent P_2O_5, but this section is possibly complicated by structure. (See discussion on p. 707.) Farther south the lower, phosphatic part of the member ranges from 19 to 26 feet in thickness and from 14.6 to 16.2 percent in P_2O_5 content (pl. 26). These beds may be the equivalent of the entire member in the Melrose district; they are comparable in thickness but contain less P_2O_5. The drop in P_2O_5 content is also reflected in the generally lesser thickness and quality of beds of minable grade in the Dillon district, as compared with the Melrose district, which helps to account for the relatively low phosphate reserve of the Dillon district (table 3).

The upper part of the Retort Member is composed mostly of slightly phosphatic mudstone, but at most places it also contains a sequence of low-grade phosphorites, individual beds of which may contain more than 24 percent P_2O_5. Except at Cave Creek (lot 1257), where special conditions are believed to prevail (p. 707), a minable thickness of rock containing more than 18 percent P_2O_5 is present in this sequence at only two localities — the Sheep Creek and Dalys Spur localities (lots 1234, 1222). In general, the upper phosphatic beds

TABLE 3.—*Phosphate resources of the Phosphoria Formation, Dillon district*

[Phosphate resources given in millions of short tons]

Resource block	Bed area [1]			Average member thickness (ft)	Average grade (percent P_2O_5)	Total tons P_2O_5 in block	Rock containing >24 percent P_2O_5					Rock containing >18 percent P_2O_5				
									Tonnage					Tonnage		
	Above entry level	First 100 ft below entry	Total block				Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member																
Northern Dillon district																
McCarthy Mountain area	5.6	4.4	586	35.0	13.5	250						10.5	20.0	3.5	3.0	500
The Hogback syncline	8.1	4.4	72	35.0	13.5	30						12.0	20.0	8.0	4.5	70
Beaverhead Rock–Hogback area	11.4	12.6	1,178	30.0	13.5	400						11.8	20.0	10.0	10.0	1,000
Browns Lake–Lost Creek area	98.8	5.1	538	50.0	10.0	200						5.0	20.0	35.0	2.0	200
Lost Creek–Willow Creek syncline	15.7	4.4	553	65.0	9.0	250						7.5	20.0	6.0	2.0	300
Birch Creek–Cave Gulch area	11.7	4.3	403	50.0	10.0	150	3.4	29.0	3.0	0.9	95	12.5	18.5	9.0	3.5	350
Frying Pan complex area	12.8	4.7	663	50.0	9.0	250	3.4	29.0	3.0	1.0	150	12.5	18.5	10.0	4.0	550
Totals and averages	164.1	39.9	3,993	43.7	11.3	1,530	3.4	29.0	6.0	1.9	245	10.3	19.6	81.5	29.0	2,970
Southern Dillon district																
Peterson Flat syncline	13.9	4.9	345	50.0	7.5	100	3.0	26.0	3.0	1.0	80	6.0	22.0	6.0	2.0	150
Cedar Creek syncline	24.7	7.3	128	50.0	7.5	40	3.0	26.0	6.0	2.0	30	6.0	22.0	10.0	3.5	60
Henneberry Ridge syncline	7.1	4.6	152	53.0	8.0	55						10.0	18.0	5.0	3.5	100
Dalys Spur area	.8	.3	45	55.0	8.5	20						17.5	18.5	1.0	.4	65
Small Horn Canyon area	46.4	10.0	425	60.0	11.5	250	3.2	26.0	10.0	2.5	100	16.5	20.5	70.0	16.0	700
Totals and averages	92.9	27.1	1,095	54.5	9.2	465	3.1	26.0	19.0	5.5	210	11.1	20.4	92.0	25.4	1,075
Grand totals and averages, Retort Member	257.0	67.0	5,088	46.0	10.0	1,995	3.3	27.6	25.0	7.4	455	10.5	19.8	173.5	54.4	4,045
Meade Peak Phosphatic Shale Member																
The Hogback syncline	8.1	4.4	72	4.3	10.0	15	3.0	25.0	1.0	0.5	5	3.5	22.0	1.0	0.6	6
Grand totals and averages (both members)	265.1	71.4	5,160	45.4	10.4	2,010	3.3	27.5	26.0	7.9	460	10.4	19.8	174.5	55.0	4,051

[1] Area in the plane of the bedding, in millions of square feet.

occur progressively higher in the section and are thinner and lower grade westward across the district. These beds are absent from the Cedar Creek locality.

NORTH END OF THE DILLON DISTRICT

The three townships just south of the Melrose district (T. 3 S., Rs. 8–10 W., on pl. 27*B*), span the synclinorium but have not been mapped in detail. Reconnaissance mapping by Sahinen (1939) on the east side of this area showed the Quadrant and older Paleozoic formations to be upturned along the southwest side of the Highland Mountains; younger strata were shown to be covered by alluvial deposits. The continuity and the approximate location of the Permian can be inferred beneath the cover, therefore, and can be extended many miles farther southeast to Beaverhead Rock in the south-central part of T. 5 S., R. 7 W., where Mississippian to Triassic strata are exposed. On the west side of the synclinorium upturned upper Paleozoic and lower Mesozoic formations bound the northeast side of the Pioneer Mountains pluton. In the central part of the synclinorium, upper Cretaceous strata, Tertiary volcanics, and alluvial deposits crop out. Near the southeast corner of the area, quartz monzonite of the McCarthy Mountain stock intruded the Cretaceous and older strata.

The approximate structure of this part of the Dillon district was inferred from the maps of adjacent areas by Theodosis (1955) to the north, by Sahinen (1939) to the east, and by Myers (1952) to the southwest, as well as from the State geologic map (Ross and others, 1955). The absence of outcrops of Permian rocks from all but the west side and the great depth to which these rocks are generally buried preclude any mining in most of this area. Along the west side of the area, Permian rocks crop out, but they are probably altered near the batholith and, therefore, probably are not amenable to mining. No information on phosphate rock of this area is available, but data for localities farther south suggest that very little high-grade phosphate rock is present.

Tonnage estimates for the northern part of T. 3 S., R. 10 W., are included with those for the Trapper Creek syncline to the north; those for the southern part of the township are included with those of the Browns Lake–Lost Creek part of the Pioneer Mountain area to the south (figs. 180, 182). None are calculated for the other two townships because of lack of information on the quality of phosphate, the geologic structures in which the Permian rocks occur, and the configuration and effects of the McCarthy Mountain stock at its contact with the Permian rocks. However, phosphate rock of greater than minimum thickness and grade is presumably present.

MCCARTHY MOUNTAIN TO BEAVERHEAD ROCK AREA

The McCarthy Mountain–Beaverhead Rock area is on the east side of the synclinorium about 15 miles southeast of Melrose and a like distance north of Dillon. The area includes geologic blocks *e*, *f*, and *g* in figure 182. The area was first investigated for phosphate by Gale (1911) in 1910. In 1913 he mapped the geology of the two principal townships of the area, Tps. 4 and 5 S., R. 8 W. Using Gale's field notes and geologic map, Pardee (Richards and Pardee, 1925) described the geology of the area. No further work was

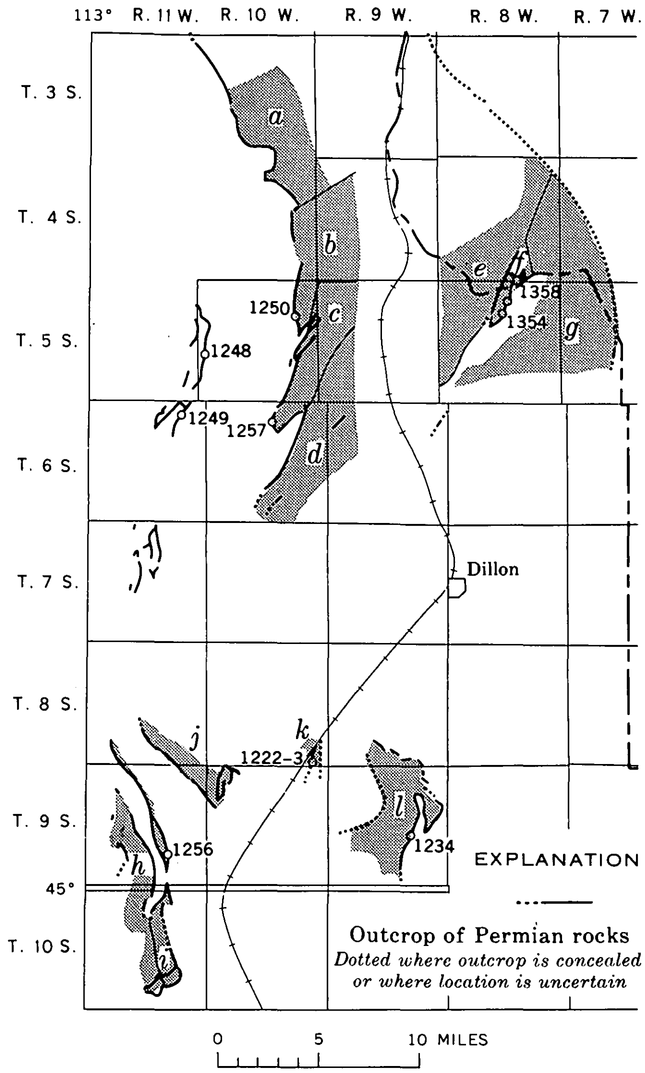


FIGURE 182.—Index to resource blocks in the Dillon district. Area for which resource calculations were made is shaded. *a*, Browns Lake-Lost Creek area; *b*, Lost Creek-Willow Creek syncline; *c*, Birch Creek-Cave Gulch area; *d*, Frying Pan complex area; *e*, McCarthy Mountain area; *f*, The Hogback syncline; *g*, Beaverhead Rock-Hogback area; *h*, Peterson Flat syncline; *i*, Cedar Creek syncline; *j*, Henneberry Ridge area; *k*, Dalys Spur area; *l*, Small Horn Canyon area. Circle and number indicate sample locality and lot number.

done in this area until 1951, when J. A. Peterson and R. F. Gosman sampled the phosphatic-shale members and measured the entire Permian section near the Big Hole River (lots 1354, 1358). They also examined the outcrops west of Beaverhead Rock near the center of T. 5 S., R. 7 W., for a possible sample site (oral commun., 1951), but they found the Retort Member to be too deeply covered with soil and talus to warrant exposure by hand. Sloss and Moritz (1951, fig. 12) showed that an abnormal thickness of more than 600 feet of Permian rocks occurs at this locality, although about half of it is covered. This thickness seems to be too great when compared with other parts of the region. On the basis of regionwide measurements the Permian rocks are shown in figure 172 to be about half that thickness.

Rocks of Carboniferous to Cretaceous age are exposed in the McCarthy Mountain–Beaverhead Rock area. In the northwestern part of this area they were invaded by the small McCarthy Mountain stock of quartz monzonite. The pre-Tertiary rocks were extensively eroded and they are concealed in much of the area by Tertiary and Quaternary continental deposits.

The pre-Tertiary formations were compressed into a series of north- to northeast-trending asymmetric folds, generally overturned toward the east, and then displaced by a number of moderate- to low-angle west-dipping thrust faults that are nearly parallel to the strike of the folds.

The Permian strata are best exposed on the west limb of a thrust-faulted anticline. The thrust fault is probably near the axial plane of the fold, thrusting the resistant Quadrant Sandstone over the nonresistant Kootenai Formation and forming a sharp ridge of Quadrant strata known as The Hogback. North of the Big Hole River the east limb of the anticline is also preserved, though the Permian strata on the steeply dipping east limb are exposed for only about half a mile. The thrust fault may die out northward along the axis of the fold, as suggested on Gale's map, or it may transect the Permian strata on the east limb beneath the alluvial flood plain of the river and cross into the Dinwoody Formation on the east limb, where it would be poorly exposed and difficult to identify. The later is suggested by a large stratigraphic displacement in the south wall of the canyon. Southward, the thrust fault bifurcates and has Madison Limestone in the central block; total displacement appears to increase in this direction.

The syncline west of The Hogback is sharply asymmetric, and the Dinwoody strata of the west limb are overturned and crumpled into a series of small chevron-shaped drag folds that are well exposed in the steep west wall of the synclinal valley. Cherty quartzite of the upper member of the Shedhorn makes up the east limb of the adjacent syncline on the west and is not overturned; the unit is thrust over the Dinwoody and forms a small hogback. Southward this small thrust crosses toward the axis of the syncline that lies between the two hogbacks, and it probably joins The Hogback thrust beneath the Tertiary deposits in the southwestern part of T. 5 S., R. 8 W. In the block above this upper thrust, Permian strata are exposed for only about 1 mile south of the river and about 1½ miles north of the river. The soft phosphatic shales of the Retort Member may have provided the glide plane for this fault. If so, no phosphorite would occur in the hanging-wall block for some distance down the dip of the fault.

Two other thrust faults were mapped in the northern part of T. 4 S., R. 8 W. These involve only Mesozoic strata at the outcrop, overlie the two previously mentioned faults, and are east of the McCarthy Mountain stock; however, they probably cross Permian strata at depth.

About 6 miles southeast of The Hogback the Madison Limestone forms Beaverhead Rock, a prominent bluff on the west side of the Beaverhead River. The Madison and overlying strata dip gently west and are exposed in a large window surrounded by younger continental deposits; rocks as young as Triassic are exposed in the window. The harder of the layers of this sequence form a series of low cuestas, and the upper member of the Shedhorn forms one of the more prominent ridges. The strata at Beaverhead Rock are apparently continuous beneath the Tertiary cover with the southwest-dipping rocks mapped by Sahinen (1939) east and southeast of Melrose. (See also Ross and others, 1955.) These strata represent the east side of the synclinorium. Thus, the entire area between this bluff and The Hogback, a zone about 5 miles wide, is probably underlain by Permian strata.

In the northeast corner of T. 6 S., R. 9 W., W. B. Myers (oral commun., 1953) mapped a small exposure of Permian and Triassic rocks; these are shown on the Montana geologic map (Ross and others, 1955). The rocks are isolated from the nearest exposures of rocks of the same age to the west and northeast by several miles of Tertiary cover. By projection, the thrust faults near The Hogback appear to be related to, and are perhaps extensions of, a series of faults mapped by Myers (1952) in the southeastern part of the Argenta quadrangle, 8–10 miles northwest of Dillon. The small outcrop just mentioned appears to lie beneath these thrusts, but it may occur in one of the lower plates. The rocks are too deeply weathered and too poorly exposed to yield reliable stratigraphic data.

Both the Meade Peak and the Retort Phosphatic Shale Members include a minable thickness of phosphate rock containing more than 18 percent P_2O_5 in the general vicinity of The Hogback. In fact, nearly 2 feet of acid-grade phosphorite was sampled in the Meade Peak Member about 1½ miles south of the Big Hole River, where the member is 6½ feet thick. However, the member pinches out within about 1 mile to the north, and just north of the river it is only 3½ feet thick and contains only one thin bed of phosphorite (lot 1358). The phosphorite in the Meade Peak Member is therefore assumed to be very lenticular in this area, and no reserves were computed for it. Only the lower part of the Retort Member is exposed south of the river (lot 1354), but it contains 4½ feet of 22-percent phosphorite. North of the river all units of the member were sampled (lot 1358); in the upper part it includes 9½ feet containing 20.7 percent P_2O_5, and a total of 16½ feet averages more than 18 percent. At this locality, however, the beds in the lower part of the member are of lower grade.

The limited stratigraphic and analytical information, as well as the extensive cover and the complex structure, make definition of reserves in the Retort Member of the McCarthy Mountain area rather tenuous. Significant tonnage of furnace-grade rock 3 feet or more thick probably cannot be anticipated, although a significant tonnage of rock containing more than 18 percent P_2O_5 is believed to occur throughout the area (table 3). The phosphorite near Beaverhead Rock may be a more shoreward facies and may be of a little better quality. The short length of outcrop and the generally low relief preclude the presence of very large tonnage above or near entry level; however, the total tonnage of low-grade rock appears to be large. The amount of this tonnage depends largely on the distance that the structures at Beaverhead Rock are projected beneath the blanketing Tertiary rocks. For the present purposes this projection was kept rather small. Near the McCarthy Mountain stock, Gale (in Richards and Pardee, 1925, pl. II) showed a considerable area of rock metamorphosed to quartzite and hornstone; he also showed several sills of andesite. No resources were computed for the area near the stock.

PIONEER MOUNTAINS AREA

The Pioneer Mountains area is in the northwestern part of the Dillon district and covers the western part of the synclinorium from the Trapper Creek syncline of the Melrose district on the north to the latitude of Dillon on the south (area north of Dillon and west of the railroad in fig. 182). It includes about 40 linear miles of Permian outcrop. At the south the outcrop is 16 miles west of Dillon. The central part of the synclinorium is covered by Tertiary deposits that conceal most of the bedrock, but the Permian strata, although broken by faults, are probably continuous at great depth with those in the McCarthy Mountain area to the east. Most of the outcrops of Permian strata are at low to moderate altitudes (between 5,700 and 7,000 ft; the altitude at Dillon is 5,100 ft), but near the large quartz monzonite pluton to the northwest, the outcrops locally rise to an altitude of more than 8,000 feet. The depth to Permian rocks beneath the basins is not known, but over large areas these rocks may lie below sea level, and they are believed to reach that depth to the north within 1½–2 miles east of the pluton.

The Retort Member was measured and sampled at three localities within the area (lots 1249, 1250, 1257); it was partially measured at a fourth locality (lot 1248), but the exposure is along a minor thrust zone. The entire section of Permian strata was measured at lot 1249, and most of the section above the base of the Retort Member was measured at lot 1257. The Meade Peak Member is probably very thin throughout this area and, thus, does not contain sufficient phosphate to warrant resource consideration.

In the northwestern part of the Pioneer Mountains area the upper Paleozoic and Mesozoic rocks dip steeply away from the east flank of a large pluton of quartz monzonite. Farther south these rocks are tightly folded and extensively thrust faulted, but they are apparently less tightly folded and faulted in the area between the pluton and the McCarthy Mountain stock. However, a number of minor folds were noted in the western part of that area by Myers (1952), and an anticlinal fold is indicated north of the fault at Lost Creek on the State geologic map (Ross and others, 1955).

The belt of steeply dipping strata east of the pluton was traced southward by Myers (1952) as far as Rattlesnake Creek, about 8 miles beyond the pluton. The upper Paleozoic and lower Mesozoic formations in the southeastern part of the Pioneer Mountains area are crumpled into tight asymmetric en echelon folds that plunge northward and are broken by a complex series of thrust and cross faults. The intensity of folding and faulting was apparently greater southward. For the southeastern part of his map area, Myers postulated that a buried fault is present — the Ermont thrust — which he related to a series of thrusts that crop out farther west and on which he believed the displacement to be "at least several miles" (Myers, 1952, p. 24). If the displacement is that large in this area, the fault must extend northward for some distance. The thrust is probably part of the northeast-trending series that crosses the northwest corner of the positive area. (See p. 670.) The trace of the thrust fault is buried by the Tertiary deposits near, and northeast of, Dillon. Myers (1952) cited evidence that suggests a southward component of movement on the Ermont thrust.

West of the tightly folded zone in T. 6 S., R. 10 W., is a broad south-plunging anticline that exposes the Precambrian Belt rocks of its core (called "the Humbolt Mountain anticline" by Myers). Myers believed that the structure had its inception in pre-Middle Cambrian time. On its west side is a synclinal zone that is crumpled into a series of narrow folds overturned to the east and broken by minor thrusts. This folded zone is bounded on the west by the Kelley thrust, which trends north-northeastward and dips at the surface from horizontal to as much as 45° W. Belt strata constitute the upper plate of the thrust and the west boundary of the synclinorium. Myers (1952, p. 22) believed that the displacement across the Kelley thrust and associated minor thrusts "can hardly be less than five miles" and that it "may be much greater." This western zone of thrusting is interrupted at the north by the quartz monzonite pluton. It lines up and may once have been continuous with the zone of thrusting at the west side of the Melrose district, but no trace of the structure remains in the intervening 12 miles now occupied by quartz monzonite.

Permian rocks also crop out in the northern part of the synclinal zone just east of the Kelley thrust; 5 miles farther south, in T. 7 S., R. 11 W., these strata are repeated several times by folding in a 3-mile-long area that is a southward extension of the same synclinal zone (Lowell, 1953). Because of the complexity of the structure in these areas near the Kelley thrust and because of the low phosphate content in the shale members, no structure contours of these rocks were drawn.

Myers (1952) stated that extensive contact metamorphism had occurred in a zone as much as 1 or 1½ miles wide along the east side of the quartz monzonite pluton. In this zone the carbonate rocks have been recrystallized to marble, the quartz-rich rocks to quartzite, and the argillaceous sediments to hornfels. He also reported that the tactite-producing additive metamorphism was limited to areas a few scores of feet to a few hundreds of feet from the contact. In the 15 miles along the east side of the pluton, the Permian outcrop is interrupted in a few places by the intrusive, and the strata in these places were presumably assimilated by it. Elsewhere, Permian strata crop out as much as half a mile or more from the intrusive. The strata generally dip steeply; therefore, they may be intruded at depth in some areas. Myers (oral commun., 1953) noted, however, that the intrusive became emplaced largely by assimilating carbonate rocks, such as the Madison Group, and it stopped against siliceous rocks, such as the quartzitic Quadrant Formation. The same relations probably prevail at depth. The Permian strata are probably metamorphosed to some degree near the pluton, but no studies have been made of such rocks. The South Greenstone section (lot 1250)—the only section in this study that is in the general area of the intrusive—is about half a mile from the contact and does not show recognizable metamorphic effects. The sedimentary formations have gentler dips eastward and are probably farther from the intrusive at depth after the first few thousand feet.

In the southern part of the complexly folded area that overlies the Ermont thrust (pl. 27*B*), the structural configuration of the Permian rocks has been shown by structure contours down to the presumed plane of that thrust, which assumedly dips rather gently northward. Thus, the troughs of the synclines are considered to have been cut off, and the Permian strata remain only in the unbreached anticlines and in the upper parts of the limbs of the synclines. No structure can be predicted beneath the thrust. The area is highly faulted, and probably much of its phosphate has been spoiled by shearing. The uncertainty about the configuration of the Ermont thrust prevents the projection of strata and structures eastward very far beyond the limits of Myers' map (1952) into the broad basin area covered by Tertiary deposits. Permian strata probably underlie most of the basin between the Pioneer Mountains on the west and the Highland Mountains–Beaverhead Rock area on the east. These strata are probably also present beneath much of the Ermont thrust, even though the structure of that lower plate is unknown. South of Beaverhead Rock, the eastern limit of the area underlain by Permian strata cannot be predicted.

Phosphate of the Retort Member in the Pioneer Mountains area is generally of very low grade; but at South Greenstone (lot 1250), near the southeast corner of the pluton, two zones of minable thickness (totalling 7½ ft) contain nearly 20 percent P_2O_5. These minable zones are near the top of the lower phosphatic zone. Much of the phosphate in the Greenstone area may have been spoiled by shearing.

At Cave Creek (lot 1257), about 6 miles farther south, 9 feet of strata (at apparently the same horizon as the two phosphate zones at South Greenstone) contains 18.2 percent P_2O_5. Here, the thickness of the Retort Member is only 36 feet, as compared to 64 and

56 feet at lots 1249 and 1250, the two nearest localities. Several thin vitrophyric sills logged near the top of the member may have intruded along shear zones that represent minor faults. However, both the lower and upper parts of the member are abnormally thin, and it may be that the sea bottom subsided less at this locality during the accumulation of Retort sediments.

Also notable at this locality is the presence of fairly high grade phosphorite at the top of the Retort Member — 3.4 feet containing 29.8 percent P_2O_5. No phosphorite of comparable grade and thickness occurs in the upper part of the member elsewhere in the Dillon district. The Cave Creek section is on the east flank of the Humbolt Mountain anticline and is due east of an area that Myers described as having been positive during early Paleozoic time. Strata as high as the lower part of the Jefferson Limestone (Devonian) lap against the Belt rocks in the positive area. The area may also have been positive during Retort time, causing the member to be abnormally thin and perhaps also causing the anomalous bed of phosphorite. This 3½-foot bed of phosphorite, therefore, may have been deposited during the same time interval as the entire upper phosphate zone at most of the other localities in the Dillon district was deposited. The phosphorite bed is thinner and of higher grade owing to lesser subsidence and consequent shallower water deposition that allowed the winnowing of the fine silty and argillaceous sediments. This 3½-foot bed of phosphorite and the top 21 feet of the nearby South Greenstone section contain nearly identical amounts of P_2O_5— that is, 101.21 and 101.56 feet-percent of P_2O_5, respectively. Such a history indicates that the rich phosphate is limited to a small area about the Humbolt anticline positive area and that beds of low-grade shales intertongue and pinch out from the north, south and east sides. Resources in the upper part of the Retort Member for both the Cave Gulch syncline and the Frying Pan complex (eastern part of T. 6 S., R. 10 W.) geologic blocks were calculated on the basis of this premise (table 3).

At Kelley Gulch (lot 1249) no sequence of beds more than 3 feet thick contains 18 percent P_2O_5, although a zone of 3.6 feet thick contains 17.8 percent P_2O_5. At a thickness of 5.4 feet, that zone contains 17.1 percent P_2O_5. The rocks there are complexly folded and faulted, so much of the phosphate present must have been spoiled by shearing. Consequently, no tonnage estimate was made for the synclinal zone east of the Kelley thrust.

The thickness and grade of phosphate rock along the east side of the Pioneer Mountains pluton had to be estimated on the basis of measured sections that are about 18 miles apart; therefore, these estimates are very general. Because most of the phosphate rock is probably not of very high grade, the lack of data is not critical. The phosphate is probably variably metamorphosed. The cover of Tertiary deposits in the basin areas east of the Pioneer Mountains causes some uncertainty as to the projection of Permian strata beneath them, but the area seems to be well enough known (even though not mapped in detail) that projection is warranted. In the basin area just north of Dillon and in the areas of Tertiary cover west and south of Dillon, resources were not calculated because the Tertiary rocks cover unknown, but undoubtedly complex, structure of the older rocks.

ARMSTEAD AREA

The Armstead area includes the southwestern part of the Dillon district (pl. 27*C*) and extends from about 9 miles north of Horse Prairie Creek to about 4 miles south of the creek near Armstead. Horse Prairie Creek joins the Beaverhead River from the west and drains an area of more than 700 square miles between the northern part of the Tendoy Mountains and the Beaverhead Range at the Continental Divide and appears to have been superposed across the north end of the Tendoy Mountains a few miles south of the junction with the Blacktail Range. The area containing Permian rocks is separated from the southwest prong of the Pioneer Mountains area, about 7 miles to the north, by an area underlain chiefly by older strata and Tertiary deposits. The Armstead area contains 20–25 linear miles of Permian outcrop and 5–10 additional miles that is covered by probably thin Quaternary talus and alluvium and Tertiary gravels and volcanics. The Armstead area has low to moderate relief, ranging in altitude from 5,500 to 7,500 feet; most of the area is below an altitude of 6,700 feet. The Permian strata occur at altitudes above 4,000 feet in most of the area, so their structural relief, which at one time was probably more than 11,000 feet, is now only 3,000–4,000 feet owing to erosion from the crests of the anticlines.

The geology of the area north of Horse Prairie Creek was mapped in detail by Lowell (1953); his map serves as the principal basis for the descriptions noted here. Geology of the northern part of the Tendoy Mountains was mapped in reconnaissance by Kupsch (Scholten and others, 1955). Modern topographic maps at a scale of 1:24,000 are available for the area north of lat 45° N.

The Retort Member has been measured and sampled at one locality in this area — Cedar Creek (lot 1256) about 3 miles north of Horse Prairie Creek. The rest of the Permian section was not measured here, but a generalized measurement indicates that the Retort Member is about 400 feet above the Quadrant Formation. The broad stratigraphic relationships are summarized above in the discussion of the Dillon district. At two localities to the east (lots 1223, 1234), the Meade Peak Member is too thin and low grade for computation of the phosphate resources. The fact that Lowell found very little phosphorite float at this horizon in the Cedar Creek area suggests that it is also thin and of low grade there.

The Armstead area includes part of the tightly folded and faulted west side of the southwest Montana synclinorium; the west boundary is buried by Tertiary debris. The folds are asymmetric, are overturned to the east, and generally trend north-northwest. Moderately to steeply dipping reverse faults parallel the folds, and low-angle thrust faults are present that appear, at least in part, to be a southerly continuation of the Ermont thrust mapped by Myers (1952). (See description, p. 705, 706. Along one thrust fault on the east side of the Armstead area near the Beaverhead River, Madison Limestone has been thrust over early Tertiary sediments. To the northwest, this thrust is covered by younger Tertiary volcanics; hence, the correlation with the Ermont thrust cannot be verified. If this correlation is correct, the Ermont thrust makes a large westward arc from the southeast corner of T. 6 S., R. 10 W. (where Myers suggested on his cross section that it is about 1,500 ft below the surface), to the northeast corner of T. 7 S., R. 11 W., thence south-southwestward through T. 7 S., and finally southeastward to the northwest corner of T. 9 S., R. 10 W. This arc is about 12 miles across, north to south, and 5 or 6 miles wide; it is in line with a northwesterly projection of the Blacktail Range. No Permian rocks crop out in the arcuate area, but to the north and the south they crop out in synclinal structures that are about parallel to the two ends of the arc. The basement structures near the west margin of the southwest Montana positive area are believed to have exerted much control in formation of the geologic structure of the area near the junction of the Blacktail and Tendoy Ranges. Subsequent uplift on steep faults that probably reflect older structures has further complicated the structure.

The major structure in the folded zone of the Armstead area in Tps. 9 and 10 S., R. 11 W., is a moderately broad anticline containing a core of crystalline Precambrian rocks that are exposed for a width of nearly 1½ miles. The anticline is between the Henneberry Ridge syncline on the east and the Cedar Creek syncline on the west. It is asymmetrical and has a steep to overturned east limb. The west side of the anticline is bounded by a moderately steep west-dipping reverse fault that appears to be just west of the axial part of the fold, where Devonian to Mississippian and younger rocks are thrust over the Precambrian.

The Henneberry Ridge syncline, at its south end, contains Carboniferous rocks that immediately overlie the low-angle thrust near the Beaverhead River. Northward, the Permian and Triassic strata are exposed in the trough of the fold; farther north, Tertiary volcanics cover both the thrust fault and the syncline and lap against the anticline, thereby covering all the Permian strata and the upper part of the Quadrant Formation.

The shallow Cedar Creek syncline to the west of the anticline contains Permian strata for all but a short interval (perhaps a quarter of a mile) of the 9½ miles north of Horse Prairie Creek where Permian rocks are preserved. This syncline is divisible into three segments; a central canoe-shaped trough about 3 miles long, separated from the northern and southern segments by cross arches. The west limb is generally overturned, and steep reverse faults cut out the northern part of the east limb.

Peterson Flat syncline is the next syncline west of the Cedar Creek syncline, and is separated from it by a narrow anticline. This syncline is deeper and broader than the Cedar Creek, and only a very small part of its west limb is exposed. It contains two small anticlinal folds, one of which exposes Permian strata. The western part of this syncline is mostly covered by Tertiary deposits, but to the north the Madison Limestone has been thrust over the early Tertiary deposits that cover the syncline and appears to define the west boundary. The minor folds in this syncline were probably accompanied by steep reverse and cross faults, which probably indicate considerable local shearing of phosphatic strata.

South of Horse Prairie Creek, Kupsch (Scholten and others, 1955) showed a fairly broad synclinal zone, which appears to be the continuation of the Cedar Creek syncline. This zone abruptly widens south of the creek, as indicated by outcrops of Triassic and Cretaceous strata in secs. 9 and 16, T. 10 S., R. 11 W., that dip south at a moderately low angle, whereas north of the creek this same limb dips steeply east. The syncline is abruptly terminated on the west by the Limekiln thrust fault, which also cuts off the Permian strata in the southeast limb a little more than 3 miles south of the creek. Except for superficial cover and small intrusives, all rocks farther south for the next 12 miles are older than Permian.

At the Cedar Creek sample locality (lot 1256), the basal 3 feet of phosphorite in the Retort Member contains 26.3 percent P_2O_5. The next 16 feet of rock averages 14.3 percent P_2O_5 and includes many thin beds that contain more than 20 percent P_2O_5; only the upper 3 feet of this sequence averages as much as 18 percent P_2O_5. The top 32 feet of the Retort Member is mostly very low grade shales but includes some carbonate rock.

At Dalys Spur (lot 1222), to the northeast, the basal bed of phosphorite found at Cedar Creek is thin or has not been recognized, but in the basal 19 feet of the member three zones—each more than 3 feet thick and totalling 11½ feet in thickness—contain 18½ percent P_2O_5. Another 6-foot-thick zone near the top of the member contains rock of the same grade. Presumably, some of these phosphatic zones at Dalys Spur are also present in the northeastern part of theArmstead area and there contain more than 18 percent P_2O_5. Accordingly, resources were estimated for a limited distance downdip beneath the Tertiary cover from the presumed buried outcrop of the phosphatic shales (table 3).

BLACKTAIL RANGE AREA

The Blacktail Range phosphate area is south-southwest of Dillon in Tps. 8 and 9 S., Rs. 9 and 10 W., and is on the northwest end of that range. The central part of the area is composed of older Paleozoic formations, and the southeastern part, of Precambrian crystalline rocks. Also included in this area is a small subarea in the Beaverhead Valley near Dalys Spur that is surrounded by Tertiary deposits. It, too, was probably part of the original Blacktail Range but was reduced by erosion, was covered by Tertiary deposits, and was finally exposed by the present drainage which has been superposed across the northwestern part of the range. The Blacktail Range area contains about 9 linear miles of outcrop of Permian strata and another 8 miles of strata that are believed to lie beneath shallow to moderately thick Tertiary or Quaternary cover. This area is characterized by moderate relief; altitudes range from about 5,300 feet in the canyon of the Beaverhead River and 5,300–5,600 feet along the northeast edge of the range to more than 7,500 feet on some of the higher points. Most of the phosphatic rock is below an altitude of 7,000 feet. In the main part of the area, near Small Horn Canyon, the phosphatic rocks probably do not occur below 4,000 feet; but west of Dalys Spur, where the extensive cover prevents an accurate projection, these rocks probably extend much deeper. About 10 miles southeast of Sheep Creek, the highest parts of the Blacktail Range are now underlain only by crystalline Precambrian rocks. There, the phosphatic rocks may have been 10,000 feet higher than those near Dalys Spur, at the low, northwest end of the range.

The geology of the Blacktail Range phosphate area was described briefly by Lowell (1949, 1953), who mapped the area in detail. The following discussion of the geology is based largely on Lowell's map. Complete sections of Permian rocks were measured and sampled at Dalys Spur (lots 1222, 1223) and at Retort Mountain, in the Small Horn Canyon area (Sheep Creek, lot 1234).

In the Blacktail Range phosphate area, the bedrock includes Carboniferous to Lower Cretaceous strata that are unconformably overlain by conglomeratic and volcanic deposits of Tertiary age. Older Paleozoic formations crop out to the east. In general the folds are fairly open; however, the west limbs of the synclines are steep to locally overturned, and in places the rocks are extensively faulted. Both south and northwest of the synclines, the Tertiary cover is extensive and apparently very thick.

In the northeastern part of the Blacktail Range area, the southwest side of the alluvium-floored Blacktail Valley (part of the large basin surrounding Dillon) is marked by a prominent fault scarp. This scarp is most obvious east of the mouth of Sheep Creek, where the Paleozoic and Precambrian rocks of the Blacktail Range rise abruptly from the valley. Northwestward, this scarp loses its prominence, and the adjoining slopes are less abrupt. The boundary between the range and the valley, however, remains fairly straight northwestward, which suggests that the fault continues to the northwest but that late movements did not affect that area. W. B. Myers (oral commun., 1954) found evidence that the fault extends many miles beyond the Beaverhead River. Where late movement did not occur, alluvial deposits cover the fault and lap onto the adjoining hills, making the range front locally irregular.

The main part of the Blacktail Range phosphate area, near Small Horn Canyon, is a north-trending syncline. This syncline is separated from a smaller syncline to the east by a narrow anticline that is locally overturned to the east. The anticline and the smaller syncline plunge northward and then bend in an arc to the northwest, where the anticline appears to die out and the two synclines merge into a single northwest-trending syncline.

West of the larger syncline is a large domal structure that appears to have a northwestward elongation or axial trend. At the southeast corner of this dome, the beds dip steeply or are overturned, and the structure appears to terminate against the syncline. Much of the synclinal area and nearby all but the axial part of the domal structure are covered by Tertiary rocks. The syncline, at its northwest end, abuts against the uplifted and locally overturned northeast flank of the dome.

Along the northeast flank of the syncline, adjacent to the alluvial deposits of the Blacktail Valley, formations ranging from Madison (Mississippian) to Kootenai (Lower Cretaceous) strike generally northwest and dip steeply southwest but are locally overturned and dip northeast. They are offset on a number of faults that strike north to northeast and alternate from right to left lateral in displacement. This zone is believed to represent the southwest flank of a large asymmetric anticline, as can be inferred from the large block of Precambrian rocks in the Ruby Range, to the northeast.

The Dalys Spur area is about 3 miles west of the northwest corner of the Small Horn Canyon syncline and is on the west side of the dome. There, the older rocks are exposed in a small inlier, for the Tertiary cover has been eroded away by the Beaverhead River and by Grasshopper Creek. The Permian strata are repeated by a steep fault that trends north-northwest and is followed in part by the canyon of the river. The downdropped block on the east is almost completely covered, but the Permian may be inferred to underlie the Dinwoody Formation, which is exposed near the fault, and to overlie the Madison Limestone, which crops out two-thirds of a mile to the east. In the western block, strata from the Quadrant Formation to the lower part of the Colorado Group are exposed. These strata dip west toward the low-angle thrust fault that forms the east boundary of the Armstead area; the intervening 3 miles are completely covered by Tertiary rocks. The Tertiary rocks and presumably the older underlying rocks are locally overturned in front of the thrust. The magnitude of the displacement on the thrust fault cannot be judged, but it may be several miles, which would signify a noteworthy foreshortening of the original interval between the outcrops at Cedar Creek and Dalys Spur. Lowell (1953) also showed a thrust fault (too little exposed to show on pl. 27*C*) 1¾ miles east of the steep fault at Dalys Spur, near the crest of the domal structure. It represents some additional foreshortening between the Dalys Spur and the Small Horn Canyon outcrops.

The Retort Member (pl. 26) contains minable-grade phosphate in the Blacktail Range (table 3), but the Meade Peak Member is thin and has a very low content of phosphate. At Dalys Spur the Meade Peak includes two very thin beds containing 36 percent P_2O_5. At both these localities (Dalys Spur, lot 1222; Sheep Creek, lot 1234) the lower and the upper phosphatic zones of the Retort Member include a minable thickness of low-grade phosphatic shale. In the lower zone, three separate layers of minable thickness occur at each locality. These layers total about 11 feet in thickness and contain more than 18 percent P_2O_5. At Sheep Creek the uppermost of the three layers includes a 3.2-foot-thick bed that averages 26.3 percent P_2O_5. The phosphate rock in the upper phosphatic zone is 6 feet thick and contains a little more than 18 percent P_2O_5. At Retort Mountain (Sheep Creek) both phosphatic zones are thicker than at Dalys Spur, and the interval between them is thinner.

LIMA DISTRICT

The Lima district (pl. 27D) includes the south end of the synclinorium and is near the southwest corner of the State. It is separated from the Dillon district by an interval of about 12 miles from which Permian and Mesozoic rocks have been removed by erosion. (See maps by Scholten and others, 1955; Ross and others, 1955.) The Red Rock River east of Lima is arbitrarily taken as the boundary between the Lima and the Ruby Valley districts.

General features

The Permian rocks in the Lima district (pl. 27D) are in the Tendoy Mountains. These mountains trend generally N. 30° W., but near the State line at the south side of the district they trend almost due west. The mountains are bounded on the northeast by an alluviated valley through which the Red Rock River flows for 28 miles in a nearly straight line between Lima and Armstead. In the southern part of this valley, the prominent Red Rock fault scarp (Pardee, 1950, p. 376) is at the base of the Tendoy Range. The range rises fairly sharply from the valley and has faceted spurs near the fault, but prominent rock exposures are sparse. Large-scale topographic maps (1:62,500 or larger) of the area are not available, but the small-scale Dubois sheet ofthe Army Map Service series (1:250,000; contour interval, 200 ft) includes this district and adjoining areas. Lima is at an altitude of about 6,250 feet, and Garfield Mountain, 8 miles south of Lima, is 10,935 feet in altitude and is the highest in the range.

The Lima district is serviced by the Oregon Short Line railroad of the Union Pacific Railway system and by U.S. Highway 91, both of which connect Butte and Salt Lake City. Dirt roads up sharp canyons across the main trend of the range give access to the mountain area.

No phosphate has been mined in this district.

Geologic setting

The description of the geology in the Lima district is based on the detailed map of Lowell (1949), on the smaller scale map and accompanying text of Scholten, Keenmon, and Kupsch (1955), and on observations made during the phosphate sampling program. The general area is underlain chiefly by thick Carboniferous formations and by broad expanses of thick Tertiary deposits. The Tertiary units described by Scholten, Keenmon, and Kupsch (1955) for a large area that overlaps the Dillon district on the north have a combined thickness of nearly 20,000 feet. These units conceal most of the older rocks in the basins, as well as in many of the foothills, and locally they form the prominent peaks.

The rocks in and near the Lima district, as contrasted with those of the Dillon and Melrose districts, are not tightly folded, although they have been extensively thrust faulted. The structural pattern of this area has probably been governed by the Precambrian basement rocks that underlie the area. Crystalline Precambrian rocks directly underlying the Paleozoic formations occur farther west in the southwesternmost part of Montana than anywhere else in the State, except possibly in the plains region near the Canadian border. Even this southwestward salient has probably been somewhat shortened by thrusting.

By referring to the Montana geologic map (Ross and others, 1955) one can readily see that the general area of the Tendoy Range — from Armstead south to the Idaho border — lies at the southwest end of a broad uparched zone that extends northeastward for nearly 100 miles to the vicinity of Three Forks Basin. In much of this uplifted area, the base of the Paleozoic column has been raised to at least 12,000–15,000 feet above sea level (present altitudes). Southwestward, the amount of uplift appears to be less, and the uplifted area, somewhat narrow.

On the east flank of the Beaverhead Range to the west, at the Montana-Idaho State line, Scholten, Keenmon, and Kupsch, (1955) showed that the Precambrian rocks are Belt Series sediments. By cross section (1955, pl. 6) they suggested that these rocks represent a fairly thin veneer (about 2,000 ft thick) covering the crystalline rocks and that the minimum thickness of the veneer is 1,000 feet. Their map indicates that a steep fault is present between the two Precambrian rock units at all but two localities. Furthermore, their map indicates that Tertiary and Quaternary cover separates the outcrops at all but one locality, which is on the west flank of the Tendoy Range about 10 miles south and 4–5 miles west of Armstead. There, a small plate of Belt is shown to be preserved on top of, and in partial fault contact with, the older crystalline rocks. Both Precambrian rock units in this Tendoy–Beaverhead Range area are in thrust plates, so the thickness of the Belt is not definitely known. All Belt occurrences, except for that just noted, are west of the crystalline rocks. The proximity of the two units also suggests nearness to the west edge of the southwest Montana positive area. In addition, the Belt strata were described by Scholten, Keenmon, and Kupsch, (1955, p. 353) as "predominantly of maroon, green, and light-gray graywackes with minor conglomerate and an occasional lens of brown chert," which suggests deposition near a shoreline.

The rocks in the Tendoy Range area, of which the Lima district is a part, occur in the southern part of the southwest Montana synclinorium. The contrast in structure between this part of the synclinorium, where thrust faults are prevalent, and those parts farther north, where tight folds and thrust faults are present, is believed to be due almost entirely to the fact that the rigid positive area underlain only by Precambrian rocks of crystalline type projects farther westward. Thus, more shearing as thrusts and less crumpling as folds took place during the Laramide tectonism.

The Lima district, as the term is here used, includes only the southeasternmost part of the southwest Montana synclinorium, the part containing Permian strata. (Just north and west of this district, uplift by thrusting and by subsequent normal faulting has been greater, and only the older rocks are preserved.) Cressman (1954) noted Phosphoria strata and associated strata near Hawley Creek on the west flank of the Beaverhead Range, about 28 miles west and 3 miles north of Lima. Because very little map information is available on that locality and because the strata have not been measured and sampled in the detail necessary for resource estimation, the area was not included in the calculation of phosphate and other resources for this report. However, the stratigraphy of the Permian rocks of that locality is given by Cressman and Swanson (1964).

The Lima district lies at the junction of the north-trending southwest Montana synclinorium and the prominent northeast-trending uparch of the southwest Montana positive area; the district therefore includes important structural features of both major units. The Permian and associated strata strike generally N. 30° W. throughout most of the district and dip moderately southwest, off the southwest end of the major uparch axis. At the east end of the district, the strata trend eastward and then northeastward into the Snowcrest Range alinement, which represents the upturned strata on the southeast side of the major uparch. Most of the district is underlain by the southwest-dipping Tendoy thrust (Scholten and others, 1955), which offsets the strata in the Snowcrest alinement by several miles. Farther southwest the Permian strata are cut off by the Medicine Lodge thrust, discussed by Scholten, Keenmon, and Kupsch (1955), which brings Madison (Mississippian) strata across upper Paleozoic and younger strata including the Beaverhead Formation of late Cretaceous, Paleocene, and Eocene age. Other thrusts farther west bring up still older rocks and prevent a recurrence of Permian strata on the back (southwest) side of the Medicine Lodge thrust plate.

The strata on the northeast side of the Tendoy Mountains within the Lima district are folded into two broad anticlinal arches — the Garfield arch on the south side and the Big Sheep arch on the west side. These arches are separated by the gentle Little Sheep syncline. The Garfield arch includes two anticlinal axes that probably merge northward: the Garfield Mountain anticline on the east, and the Little Sheep anticline on the southwest. The Garfield and Big Sheep arches probably merge farther northeastward. At the northwest corner of the district is part of the southeast side of another large anticlinal structure. This fold is separated from the Big Sheep arch by the narrow Little Water syncline, and has a partly overturned northwest limb. The Permian rocks in the Cedar Creek syncline of the Armstead area terminate on the northwest side of this part of the broad uparched area.

Scholten, Keenmon, and Kupsch (1955, fig. 6) showed that the Big Sheep and the Garfield arches are a single anticlinal structure; they believed that this structure and the large anticline north of the Little Water syncline merge near the east end of the Blacktail Range to form the Blacktail-Snowcrest anticline. However, this author believes that the anticlinal structure northwest of Little Water syncline may project N. 25°–30° E. toward the west end of the Blacktail Range and Dillon, instead of N. 60° E. as proposed by Scholten, Keenmon, and Kupsch (1955). The projection must necessarily be made across a wide interval of Tertiary cover for either interpretation, but the latter explanation seems to be more nearly in accord with the overall structural pattern and the physiographic features characteristic of much of southwest Montana.

After the initial folding, the rocks in the Lima district were broken by a series of high- and low-angle thrust faults that strike generally N. 30° W., and, later, by normal faults of similar strike. The thrust faults dip west and probably represent a considerable foreshortening of the crust. Scholten, Keenmon and Kupsch (1955, p. 383) believed that the "displacement must have been on the order of at least 10 miles" along the low-angle Medicine Lodge thrust, as indicated by the juxtaposition of geosynclinal facies onto shelf facies and by the thrusting of geosynclinal facies rocks over Beaverhead conglomerate composed of dominantly Precambrian-source pebbles. A series of younger steep faults, both reverse and normal, displace the low-angle thrusts, particularly in the broad arch northwest of Little Water Canyon. Since this displacement, the area has been deeply eroded, partly covered by Tertiary sediments and volcanics, and broken by normal faults, some of which apparently represent considerable displacement.

The low-angle Medicine Lodge thrust on the west side of the Lima district may cover an extensive area underlain by Permian rocks. The steeper Tendoy thrust has resulted in both the uplift and the eastward shifting of the crustal block that contains the phosphate deposits of the Lima district. It transects the Permian rocks in the northeast corner of T. 15 S., R. 8 W., on the southeast side of the Garfield anticline and thrusts them over the Cretaceous and early Tertiary sediments. The Upper Pennsylvanian to Cretaceous formations in this area have been dragged into a sharp anticline and have been sheared and broken by many small faults. The thrust also transects the Little Water syncline in T. 13 S., R. 10 W., at the northwest corner of the district.

Most of the area east of Lima and south of Red Rock River is covered by the Upper Cretaceous, Paleocene, and Eocene Beaverhead Formation (Lowell and Klepper, 1953). The Beaverhead overlies Cretaceous rocks in most of this area, but within about 2–3 miles east of Lima it probably overlies lower Mesozoic and upper Paleozoic strata on the southeast limb of the Garfield-Snowcrest anticline. At Wadhams Spring, just north of the Red Rock River, the upper Paleozoic and lower Mesozoic rocks strike more toward the north than they do farther northeast, which suggests that the northeast flank of a small southeast-trending anticline cuts across the major structural trend. This concept is further supported by some evidence found near Lima, which indicates that the axis of the anticlinal cross fold is near the Red Rock River. (See the section "Ruby Valley District" for a discussion of related structures.) Southeast of Lima, in front of the Tendoy thrust, Scholten, Keenmon, and Kupsch (1955, pl. 11) showed that the Cretaceous and the Beaverhead strata have been crumpled into a series of minor folds. These folds probably die out at depth.

According to Bateman,[3] a well drilled in the autochthonous block below the Tendoy thrust in sec. 33, T. 14 S., R. 7 W., penetrated to a depth of nearly 4,500 feet below sea level before reaching the top of the Jurassic. The thickness of Jurassic and Triassic strata in this area, according to Scholten, Keenmon, and Kupsch (1955, table 1), is more than 800 feet and less than 2,700 feet. The greater thickness is probably more applicable to this part of their mapped area. The base of the Permian, therefore, probably lies more than 6,000 feet below sea level in this area. The structure contours on plate 27D were drawn on the basis of this premise.

Stratigraphy

The Carboniferous rocks in the Lima district have a total thickness of more than 5,000 feet. The Quadrant Sandstone, which immediately underlies the Permian strata, makes up more than 2,500 feet of this thickness. This thickness of the Quadrant is two to several times as great as it is in the nearest phosphate districts, which are to the east and to the north. The overlying Permian rocks attain a maximum thickness of 850 feet, the greatest thickness known in Montana. These rocks are overlain by about 2,500 feet of Triassic and Jurassic strata and by nearly 5,000 feet of Cretaceous strata. In the east end of the district the Cretaceous rocks occur north of the Tendoy thrust and between the Tendoy and Medicine Lodge thrusts east of Garfield Mountain; in the west end a small remnant is preserved in the Little Water syncline.

The Grandeur Member of the Park City Formation appears to overlie the Quadrant Sandstone conformably and attains a thickness of nearly 350 feet near Big Sheep Creek. The lower 250 feet is mostly cherty and sandy dolomite, and the upper 100 feet is chiefly dolomitic mudstone, part of which is orange red. According to one interpretation, the Meade Peak Member of the Phosphoria Formation may be as much as 42 feet thick;[4] it is most phosphatic in the lower 10 feet. The overlying Rex Chert Member is as much as 76 feet thick, and its lower part intertongues with the Meade Peak Member. The Franson Member of the Park City Formation overlies the Rex and is chiefly cherty and sandy carbonate rock about 200 feet thick at the east side of the district, but westward it is thinner and sandier.

The Retort Member at Big Sheep Creek is 85 feet thick, the maximum known thickness of the member in the western phosphate field, and is composed of interbedded phosphorite and mudstone; some layers are fairly rich in carbonate. A bed of phosphatic sandstone at the base indicates a gradational lower contact with the Franson. The Retort is overlain by 150 feet of the cherty shale and the Tosi Chert Members.

The Dinwoody contact with the Permian appears to be conformable and has even been suggested to be gradational (Moritz, 1951, p. 1785, personal commun. from L. L. Sloss). In general, however, the siltstone below the contact tends to be darker and more siliceous than that above which is more calcareous.

Phosphate

The Meade Peak and Retort Phosphatic Shale Members are thicker and contain more total phosphate in the Lima district than in any other district (fig. 174) in Montana. The resource of minable phosphate in the Lima district (table 4), however, is fairly low owing chiefly to the dilution of the phosphate by intermixed and interbedded low-grade mudstone (pl. 26). The highest grade phosphate occurs at the base of the Meade Peak Member, where 3 feet or more of strata contains more than 24 percent P_2O_5 throughout much of the district, and where 7 feet of strata contains more than 18 percent P_2O_5. This zone is thicker and of higher grade in the western part of the district than in the eastern part. Above this basal zone, scattered beds of the Meade Park Member are phosphatic, but none is rich enough or thick enough to be minable.

In the measured sections of the Retort Member, the upper part of the member is faulted out at two localities (lots 1295, 1341; fig. 170), the whole member is sheared at a third locality (lot 1297), and the lower part could not be exposed by trenching at another (lot 1247). From the one complete section (lot 1224) and the limited data at the other localities noted above, it is fairly clear that no beds of minable thickness contain as much as 24 percent P_2O_5; however, one or more beds of minable thickness contain more than 18 percent P_2O_5 throughout most of the Lima district. The phosphatic zone at or near the base of the Retort generally contains so much interbedded mudstone that the average grade is less than 18 percent, but at Crooked Creek (lot 1297) 4 feet of strata contains nearly 20 percent P_2O_5. At Little Water Canyon (lot 1341), two zones, each a little more than 3 feet thick (one 15 ft and the other 20 ft above the base), contain

[3] A. F. Bateman, U.S. Geological Survey, Great Falls, Mont. (written commun., 1958). Well 1 of the Emerich-Lima unit of the Cities Service Oil Co. was drilled in the W1/2NW1/4NE1/4 sec. 33, T. 14 S., R. 7 W. It was started in "Tertiary Lake beds" at an altitude of 6,749 feet KB (Kelly bushing) and was drilled to a depth of 11,213 feet, where it was stopped in the Jurassic. Depths of top of Kootenai (Lower Cretaceous) and Jurassic were 9,885 and 11,042 feet, respectively.

[4] This thickness is 13 feet more than that reported by Cressman and Swanson (1964, p. 420–421) and reflects an interpretation of intertonguing between the Meade Peak and the Rex Chert Members whereby Cressman and Swanson's beds 77–80 and 83 were identified as Rex and beds 81, 82, and 84–90 were identified as Meade Peak.

TABLE 4.—*Phosphate resources of the Phosphoria Formation, Lima district*

[Phosphate resources given in millions of short tons]

Resource block	Bed area [1]			Average member thickness (ft)	Average grade (percent P_2O_5)	Total tons P_2O_5 in block	Rock containing >24 percent P_2O_5					Rock containing >18 percent P_2O_5				
									Tonnage					Tonnage		
	Above entry level	First 100 ft below entry	Total block				Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member																
Little Water Canyon area	39.7	7.0	343	77.6	9.0	200						7.4	21.0	25.0	4.0	200
Little Sheep Creek area	16.3	11.9	275	80.2	9.0	200						6.3	21.0	8.5	6.0	150
East end of Lima district	37.0	9.6	962	75.1	9.0	550						4.8	21.0	15.0	4.0	350
Totals and averages	93.0	28.5	1,580	76.5	9.0	950						5.6	21.0	48.5	14.0	700
Meade Peak Phosphatic Shale Member																
Little Water Canyon area	39.0	6.3	366	33.9	8.0	85	3.3	25.0	10.0	1.5	100	6.8	20.0	20.0	3.5	200
Little Sheep Creek area	30.1	15.6	324	26.9	10.6	75	3.2	29.5	6.0	3.5	90	8.0	23.0	15.0	8.5	200
East end of Lima district	28.8	7.4	965	18.6	12.6	200	3.0	28.2	3.0	1.0	60	5.5	21.3	15.0	4.5	450
Totals and averages	97.9	29.3	1,655	23.6	10.7	360	3.1	27.4	19.0	6.0	250	6.3	21.4	50.0	16.5	850
Grand totals and averages, both members	190.9	57.8	3,235	49.5	9.4	1,310	3.1	27.4	19.0	6.0	250	6.0	21.2	98.5	30.5	1,550

[1] Area in the plane of the bedding, in millions of square feet.

more than 18 percent P_2O_5. At Big Sheep Creek (lot 1224), two zones totaling 8 feet thick and averaging about 20 percent P_2O_5 oc̜cur about 50 feet above the base.

The areas for which phosphate resources have been calculated (table 4) are shown in figure 183.

LITTLE WATER CANYON AREA

The Little Water Canyon area is west-southwest of Dell at the northwest end of the Lima district and extends as far south as Big Sheep Creek (fig. 183). The geology of the area was mapped in detail by Lowell (1949). Kupsch (in Scholten and others, 1955) included this area in his map of a much larger area in the Tendoy and Beaverhead Mountains. Pardee (1950) described some of the physiograpyhic features of the region and first called attention to the Red Rock fault along the northeast side of the Tendoy Mountains. The Permian strata in this area were measured and sampled near Big Sheep Creek (lots 1224-1227), and on the south side of Timber Butte (lot 1341).

Little Water Creek flows northeastward in a narrow synclinal valley between Timber Butte on the northwest and Dixon Mountain on the southeast, both of which are underlain chiefly by quartzite of the Quadrant Formation. The syncline contains rocks as young at Early Cretaceous; it is very narrow in the northeastern part of this area, near the mountain front, but widens very abruptly southwestward. The strata on the southeast limb, on the west side of Dixon Mountain, dip as much as 45° W. Those on the east side of Timber Butte are sharply overturned to the northwest for as much as 1½ miles from the mountain front, but farther west, as the strike curves westward, the strata dip south to southwest at fairly steep to moderate angles. Just south of the mouth of Little Water Canyon, the Tendoy thrust, which underlies Dixon Mountain, is apparently at the base of the Retort Member. Retort strata there dip 35° W. and suggest the local attitude of the fault.

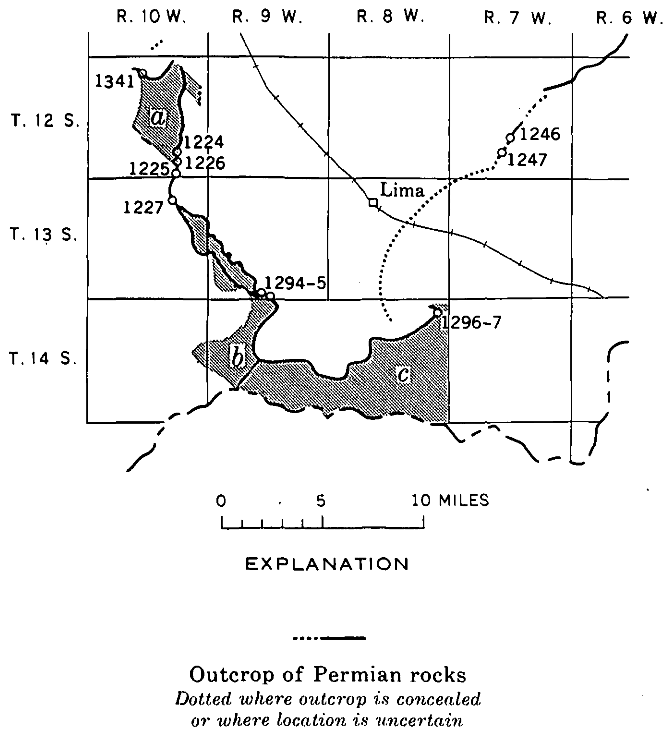


FIGURE 183.—Index to resource blocks in the Lima district. Area for which resource calculations were made is shaded. *a*, Little Water Canyon area; *b*, Little Sheep Creek area; *c*, East limb Garfield anticline. Circle and number indicate sample locality and lot number.

The syncline is interrupted on the west by Madison Limestone thrust over upturned lower Mesozoic strata. The thrust is probably a part of the Medicine Lodge thrust described by Scholten, Keenmon, and Kupsch (1955, p. 382), which includes both high and low-angle reverse faults. The thrust zone as mapped by Lowell is only locally exposed at the east side of the Muddy Creek basin, which is filled by Tertiary deposits. Kupsch (in Scholten and others, 1955) showed the thrust to be covered by these deposits, and he also showed a north-trending normal fault, up on the east, to be present along the east side of this basin. He showed that neither fault displaced the other where the two faults intersect on the southwest side of Timber Butte. Permian strata, including phosphatic shales, probably extend for a short distance beneath the thrust. However, some of the steep reverse faults of the thrust zone bring up slices of Pennsylvanian to Triassic formations (pl. 27D), and at least in these areas, the Permian strata assumedly do not extend for any great distance beneath the main thrust. Permian strata that extend as far west at the Muddy Creek fault may be dropped down on the west more than 100 feet. West of the fault they are buried by the Beaverhead Formation.

The rocks in the synclinal area are partly covered by a thin veneer of Tertiary sedimentary and volcanic rocks, but this cover is not extensive enough to greatly affect the evaluation of the phosphate deposits. The southern part of the synclinal area is drained by Hidden Pasture Creek on the southwest flank of Dixon Mountain and by Muddy Creek farther west; both creeks are tributaries of Big Sheep Creek, which cuts through the range in a deep canyon. Near the mouth of Muddy Creek, the Permian strata and all younger formations are cut on the south by, apparently, combined thrust and normal faults. These faults mark the southern limit of the Little Water Canyon area.

The Tendoy thrust underlies Dixon Mountain and apparently dips west at a moderate angle. On this thrust the Quadrant Sandstone (Pennsylvanian), which makes up most of the mountain, has overriden upper Paleozoic strata that are preserved in a long wedge between the thrust and the normal Red Rock fault at the base of the range. Near the north end of this wedge, Triassic strata dip northwest (Lowell, 1949). Because the stratigraphic sequence appears to be uninterrupted, Permian strata can be inferred to underlie the Triassic. Quadrant talus from the cliffs above the thrust completely covers the Permian strata, so the exact location of these strata is not known, though it can be approximated fairly accurately.

On the northeast side of Timber Butte (Lowell, 1949), outcrops of Quadrant and Thaynes (Triassic) strata are believed to define the approximate location of Permian strata, just as they do on the northeast side of Dixon Mountain. But the Permian strata are covered at this locality by conglomerate of the Beaverhead Formation (Upper Cretaceous, Paleocene, and Eocene). These Permian strata presumably are overturned and dip to the northwest. The two segments of covered Permian strata probably represent the two limbs of the Little Water syncline beneath the Tendoy thrust. Both the thrust and the syncline were later cut off by the Red Rock fault, whose scarp south of Little Water Canyon is about 75 feet high.

As interpreted on plate 27D, the Permian in most of the Little Water syncline is above 4,000 feet in altitude. Much of the Permian is above 6,500 feet in altitude, the lowest outcrop level; thus, a large tonnage of rock is above entry level. However, the phosphate resources in this district (table 4) are not large because the thickness of phosphate rock is rather small, and the quality is fairly low. Near the faults and in the overturned part of the northwest limb, much of the phosphate has probably been spoiled by shearing; elsewhere, the structure is not believed to have markedly affected the rocks in the area. No estimate was made for the phosphate that probably underlies the Medicine Lodge thrust.

LITTLE SHEEP CREEK AREA

The Little Sheep Creek area extends southeastward from just north of Big Sheep Canyon to the axis of the Little Sheep anticline on the southwest flank of the Garfield arch, a distance of about 10 miles. The area thus includes the Big Sheep arch and the Little Sheep syncline, as previously identified (p. 712). The geology of this and the adjoining area on the east was mapped by Scholten (Scholten and others, 1955). The Permian strata were measured and sampled near Little Sheep Creek (lots 1294, 1295).

The Permian strata west of Little Sheep Creek dip about 25° SW., whereas those near, and west of, Garfield Mountain dip 40°-50° S. Near Big Sheep Creek much of the Permian strata and all younger strata appear to be cut out by the Medicine Lodge thrust. Farther south, Triassic formations are preserved beneath the thrust, as long Little Sheep Creek where Triassic rocks underlie a plate of Madison Limestone for a distance of several miles. In the upper valley of the West Fork of Little Sheep Creek, the Triassic strata beneath the thrust have been crumpled into a series of small northwest-trending folds.

Presumably the Permian strata extend far beneath the Medicine Lodge thrust in much of the area, as shown by the wide exposure of Triassic strata in the valley of Little Sheep Creek. No estimate was made of phosphate beneath that thrust, however.

Most of the Permian strata that occur above entry level are exposed on near-dip slopes. Some of the phosphate—particularly in the Meade Peak Member—may therefore be amenable to strip mining. Since no topographic base map or detailed geologic map of these areas are available they were not defined.

EAST END OF LIMA DISTRICT

East of the axis of the Little Sheep anticline, the Pennsylvanian to Lower Cretaceous formations are exposed for about 11 miles in the overthrust block above the Tendoy thrust. Below the thrust, in the area east-southeast of Lima, only post-Kootenai (Lower Cretaceous) strata are exposed, for the older rocks are covered by the Beaverhead Formation (Late Cretaceous, Paleocene, and Eocene) and by Quaternary deposits. The geology of most of this area was mapped by Scholten, and that north of U.S. Highway 91, by Keenmon (Scholten and others, 1955). The Permian strata were measured and sampled at the head of Crooked Creek near the thrust (lots 1296, 1297) and immediately north of the Red Rock River at Wadhams Spring (lots 1246, 1247) in the southwest corner of the adjoining Ruby Valley syncline district.

Between the axes of the Little Sheep anticline, which plunges southwest at a low angle, and the Garfield Mountain anticline, which plunges about 45° S. and may die out in depth, the Permian strata strike about due east and dip 25°–45° S. Within a distance of 2 or 3 miles from the outcrop, these strata pass beneath the edge of the Medicine Lodge thrust.

The Permian and associated formations east of Garfield Mountain are broken into a series of segments that strike alternately east and north. Faults bound most of the segments. Most of the faults have a fairly small displacement and trend generally northwest, but they range in strike from west to north. The formations alternately dip an average of about 45° S. or 45° E. in successive fault blocks. The net effect is chevronlike plunging folds that have planar limbs and have breaking, but very limited bending, near their axes. The faults were not traced very far into the Quadrant Formation, where key horizons that could be used to identify structural details are generally sparse. The competent Quadrant Formation has apparently been broken into a series of fairly rigid blocks, however, and these blocks, acting as individual units, have been rotated into the positions that are marked by the less competent overlying strata. Farther away from the axis of the Garfield anticline, these peculiar folds probably die out at depth. The folds cannot be traced very far on the surface because much of the Cretaceous strata in this area is covered by the Beaverhead Formation.

Farther east the strike curves northeastward, and the dip steepens. Near the Tendoy thrust, the formations curve sharply northwest and are overturned, forming a drag fold just above the fault. The amount of displacement on the fault is not known, but plate 27D suggests that the Permian strata were displaced about 2 miles. Still farther east, the Kootenai is thrust over the Aspen Shale (both of Early Cretaceous age), and to the southeast in secs. 8, 16, and 17, T. 15 S., R. 7 W., Aspen strata are thrust over the Beaverhead Formation (of Late Cretaceous, Paleocene, and Eocene age).

North of the fault, Cretaceous rocks assigned to the Aspen have been crumpled into a series of small folds, striking west-northwest, that have perhaps been dragged beneath the fault. One of these folds, the Lima anticline, was traced about 7-8 miles. Along it the Cretaceous rocks attain their westernmost exposure, 2-3 miles southeast of Lima. Except for these Cretaceous rocks and a small questionable exposure of Madison Limestone 1½ miles east of Lima, only continental deposits occur in the 4- to 5-mile interval between the Lima anticline and the upturned Paleozoic rocks north of the Red Rock River.

At the Crooked Creek locality (lots 1296-1297) the phosphate occurs in thinner beds of generally lower grade than it does in other parts of the Lima district partly because of structural complexities. A 4-foot-thick zone of low-grade phosphate rock is present at the base of each phosphatic shale member. The bottom part of each zone is of fairly good quality (28-30 percent P_2O_5) but is too thin to mine. Inclusion of the overlying beds to attain a minable thickness reduces the net grade. Some of the rock may be amenable to surface mining methods, but the generally steep dip causes it to be less suitable for such consideration. Owing to the uncertainties of thickness of Tertiary cover and of location of Permian rocks beneath that cover, no phosphate was estimated for the underlying block north of the Tendoy thrust. Also, no phosphate was estimated for the area above the thrust in the Lima district east of R. 8 W. (fig. 183).

RUBY VALLEY DISTRICT

General features

The Ruby Valley syncline (pl. 28A) is the largest single area underlain by Permian strata in southwest Montana. That part of the syncline which contains Permian rocks and is discussed here is north of the east-trending Centennial Valley. The strata undoubtedly extend southward beneath this valley, however, and beneath the western part of the Centennial Mountains into Idaho, but they are deeply buried beneath volcanic rocks and Quaternary deposits. The synclinal area is about 30 miles wide at the north side of the Centennial Valley, but it narrows northward within about 35 miles to a width of less than 5 miles near the north end. The area is bounded on the west by the northeast-trending Snowcrest Range, which contains the generally overturned and faulted west limb of the syncline, and on the east by the Gravelly Range, which makes up the gently dipping east limb of the syncline.

Most of the area is drained by the north-flowing Ruby River, which leaves the area at the northwest through a canyon at an altitude of about 6,000 feet. The crest of the plateaulike Gravelly Range is at an altitude of slightly more than 9,000 feet; and the principal peaks along the narrow Snowcrest Range rise to an altitude of more than 10,000 feet, whereas those in the Green Horn Range, the extension of the Snowcrest Range north of the Ruby Canyon, are somewhat lower. The floor of the unusually flat Centennial Valley, drained by the Red Rock River, is at an altitude of a little over 6,600 feet.

The Centennial and Ruby Valleys are serviced by dirt or gravel county roads, and access to much of the rest of the area is easy in good weather by means of many Forest Service roads and trails. Access to the higher parts of the Snowcrest Range, however, is not good. The nearest railheads are at Alder to the north, Monida to the south, and Lima to the southwest (fig. 169). Truck haul to Lima from the nearest deposits (in the Wadhams Spring area) would be less than 10 miles, but the haul from the other parts of the district to nearest railhead would be much longer, generally more than 25 miles.

The geology of nearly all of the Ruby Valley synclinal area has been mapped, most of it at a scale of more than 1 inch to the mile. (See index on pl. 28A.) The only published maps, however, are a reconnaissance map by Klepper (1950), which includes most of the area west of the Ruby River and is at a scale of about 4 miles to the inch, and the map by Scholten, Keenmon, and Kupsch (1955), at a scale of about 2 miles to the inch, which includes the southwest corner of the synclinal area. The 15-minute Antone Peak quadrangle, which includes the central part of the west limb of the syncline, was mapped by Gealy (1953). The distribution of Permian rocks in part of the Varney quadrangle at the north was supplied by J. B. Hadley of the U.S. Geological Survey (written commun., 1957). Parts of the Varney and Monument Ridge quadrangles were mapped by Mann (1950), and the Monument Ridge and the Lower and Upper Red Rock Lake quadrangles were mapped in more detail by G. C. Kennedy (written commun., 1952) as part of the program of phosphate investigation by the U.S. Geological Survey. None of these larger scale maps had been published at the time this report was prepared.

In the Ruby Valley synclinal area, the Permian strata were measured and the phosphatic shale members sampled at 10 localities during this study (fig. 169, pl. 28A). Six of these localities are along the west limb of the syncline, three are on the east limb, and one (Warm Springs Creek, lot 1300) is on a minor anticlinal fold near the axis toward the north end of the syncline. Also, a reconnaissance section was measured 10 miles north of Warm Springs at Wigwam Creek (lot 1481) of the northernmost exposures of the Permian strata in the area.

Geologic setting

The Ruby Valley syncline is in the southwest Montana positive area, previously defined (p. 666). Though generally considered a downwarped area, in reality the syncline merely reflects less uplift than the adjoining areas, for all parts of this region have undergone considerable uplift after the long period of sediment accumulation, and probably no significant amount of downwarping has occurred since early Tertiary time. The Ruby Valley syncline and most other fold structures in the positive area represent not so much the effects of lateral compression across the structures as they do the primarily differential vertical movements of major rigid blocks of the underlying crust. The fold and fault structures in the overlying sedimentary layers were formed as the relatively thin veneer of these strata draped across the zones of disruption.

That some compressive movements occurred, however, is shown by the locally overturned strata and by the (generally) minor thrusts that are characteristic of the west limb of the syncline, as well as by the slightly crumpled and sheared strata throughout the overall structure. Hadley (1959) believed, however, that the thrusts at the north end of the west limb may represent displacement of several miles. The west limb of the syncline is arcuate toward the southeast; the southern part strikes as much as N. 55° E., whereas the northern part strikes about N. 15° E. South of Sawtooth Mountain (T. 12 S., R. 5 W.) the strata are right side up and dip southeast; north of that point most of the strata are overturned and dip west-northwest, and thus reflect generally greater compression during the formation of the structure.

The general northeasterly trend of the upturned strata in the west limb of the Ruby Valley syncline is interrupted by a number of minor fold pairs. The largest fold pair occurs between Sliderock and Hogback Mountains (Tps. 10 and 11 S., R. 4 W.). In plan this fold pair suggests a section across a very large drag fold; a small syncline near Spur Mountain and the Sliderock Mountain anticline combine to offset the strata more than 2 miles to the right along the principal strike. The folds of this fold pair are sharply asymmetric, like the larger structures, and plunge southward. The mutual limb dips about 25° SW., and their long limbs, which are steeply overturned, dip west. The folds apparently die out within a few miles to the south. Gealy (1953, p. 79) stated that the axial part of the syncline is shared by a steep reverse fault, west side up, on which stratigraphic displacement was small. He described similar discontinuous faults along the sharp nose of the anticline, particularly toward the north, where the anticline merges with the west limb of the Ruby Valley syncline. He also stated that small drag folds are present in both limbs, but that they are more abundant in the east limb of this fold. The type and the distribution of these structural features seem to reflect two major en echelon shears in the basement complex. These shears are roughly parallel and overlapping for several miles, the eastern extending farther north and the western farther south. Greatest uplift on each was probably near the middle, along strike; therefore, regional uplift was accomplished by a gradual shift from one major shear to the next one to the right.

A generally similar but much smaller fold pair a few miles farther north—abouth 1 mile south of Ruby River Canyon—was mapped by Mann (1950). The strata along the main trend of the syncline are offset less than a mile at this double fold, again to the right. A still smaller, but similar, offset fold just north of Sliderock Mountain was described by Gealy (1953, p. 82) to be associated with minor steep thrust faults.

The Sawtooth Mountain anticline in T. 12 S., R. 5 W., named by Gealy (1953, p. 77), appears to be a fold pair similar to, but not as strikingly developed as, the one between Hogback and Sliderock Mountains. Gealy's map shows the upper Paleozoic strata on both the top and the south side of the mountain to dip about 30° S., the dips of underlying strata to the north to be gentler, and those of overlying strata farther south to be slightly steeper. On the east side of the mountain, the strikes curve north-northeastward, and the dips change within a short distance to vertical and overturned, and from this point northward the dips remain overturned. Southwest of Sawtooth Mountain the Permain strata cross the southwestern part of sec. 16, the southern part of sec. 17, and into the southeastern part of sec. 18. In the unmapped interval to the west (which is nearly a mile wide), the trend of the strata apparently turns southwestward through the NW¼ sec. 19. In the adjacent township the formations strike southwest and dip southeast (Scholten and others, 1955, pl. 1). These two asymmetric folds, which are similar to those just described, plunge southward and share a normal limb; one fold has an overturned limb, and the fold pair offsets the strata to the right about 1½ miles.

A short distance farther southwest, in the southern part of T. 12 S., R. 6 W., the outcrop pattern of the Permian suggests a similar fold pair, but because topographic data and detailed field observations on attitudes of bedding are not available, it cannot be clearly recognized. The strata north of West Fork Blacktail Deer Creek strike northeast and dip southeast. South of the creek, however, these strata turn slightly north of west for about a mile before again turning southwest. The minor folds thus formed plunge south to southeast. The uplift was apparently not as great as it was farther north, and the structures in the exposed strata cannot be linked as clearly to shears in the basement rocks. Nonetheless, the structure pattern here appears to be similar to that farther north.

It is probably significant that at each of the three largest fold pairs the main southward trend or strike of the formations changes to the right 10°-15°, thus accounting for the arcuate trend of the strata in the Snowcrest Range, convex to the southeast. Apparently, the principal uplift of the Snowcrest Range block took place along a series of fanning en echelon shears in the basement complex. This explanation accounts not only for the arcuate pattern of the major structure but also for the peculiar subsidiary structures along the principal strike.

Southwest of the West Fork Blacktail Deer Creek fold, the strike bends southward in a broad curve and is about N. 35° E. at Wadhams Spring near the Red Rock River. The apparent offset to the west, previously described (p. 712), that occurs south of Wadhams Spring suggests an anticlinal structure at or near the Red Rock River that may well be similar to the subsidiary fold structures further north.

Near the north end of the Ruby Valley syncline, in the Green Horn Range about a mile north of the Ruby River, overturned lower Paleozoic strata are thrust eastward across the upper Paleozoic and lower Mesozoic formations. This thrust ends the exposure of the main belt of Permian strata on the west side of the syncline.

About 7 miles farther north—beyond the thrust—steeply dipping formations were noted east of Baldy Mountain on the ridge south of Arasta Creek. This area is part of the west limb, but the exposure is so small that discussion of it is combined with the description of the east limb of the Ruby Valley syncline.

Cretaceous strata are exposed in most of the Ruby Valley synclinal area, but in the southwestern part these strata are covered by a series of Tertiary continental deposits—chiefly sandstone and conglomerate—that were estimated by Gealy (1953, p. 61) to be 4,000 feet thick. Near the west limb of the syncline Gealy noted that these rocks overlie the Cretaceous with marked angular unconformity; but to the east, in the broad axial part of the syncline, he found apparent conformity and perhaps even a gradational contact. These rocks are probably part of the Beaverhead Formation (Lowell and Klepper, 1953).

Stratigraphy

In the area of the Ruby Valley syncline, the Carboniferous formations underlying the Permian have a fairly wide range in total thickness, from nearly 5,000 feet at the southwest corner near Wadhams Spring (Sloss and Moritz, 1951, p. 2155–2163), and more than 4,500 feet in the Snowcrest Range (Gealy, 1953, p. 26–38), to a little more than 2,200 feet in the Gravelly Range (Honkala, 1949a; Mann, 1950, p. 22–34). The thick sections represent an area of unusual downwarp, and the thin ones the stable shelf. The difference in thickness reflects both a general shelfward thinning of formations that are present over the entire area and an eastward pinchout of the fairly thick Mississippian shale, evaporite, and limestone sequence that is referred to as the Brazer Limestone or the Big Snowy Group. The most abrupt change in thickness occurs in the northern part of the area between the two limbs of the syncline. This thickness change marks the east edge of a large downwarp that persisted through much of Carboniferous and also Permian time. Because no geologic information is available for large areas immediately southeast and northwest of the Snowcrest Range, it is not possible to accurately delineate this downwarp. However, the downwarp appears to extend about 40 miles northeast from Lima and to be perhaps 20-25 miles wide.

The Permian rocks of the Snowcrest Range average more than 500 feet thick and are 800 feet thick at Hogback Mountain, the second largest thickness known for the system in Montana. In the northern part of the range, structural complexities cause uncertainty about the thickness of the Permian rocks. This area of uncertainty occurs in a critical location, for the rocks change considerably in thickness and lithology within the narrow interval between the northern part of the Gravelly and Snowcrest Ranges.

Overlying the Permian rocks in the Ruby Valley syncline is about 2,500–3,000 feet of Triassic to Lower Cretaceous strata and a thick sequence of Upper Cretaceous strata. All the formations represented are widespread and are interlayered marine and nonmarine deposits. Although he did not measure the Upper Cretaceous section, Gealy (1953, p. 56) estimated its thickness to be about 8,500 feet. On the basis of regional information, as well as that from the east side and the central part of the syncline, this estimate seems high. The Mesozoic strata are overlain—commonly with apparent conformity but locally with marked unconformity—by a thick series of coarse clastic continental deposits that Gealy (1953, p. 61) estimated to be 4,000 feet thick. However, from his map data this estimate, too, appears to be high. The combined thickness of Upper Cretaceous and younger continental deposits may be closer to 10,000 feet. These thicknesses are significant in determining the configuration of the phosphatic strata in the syncline.

Along the west limb of the syncline at Hogback Mountain, the Grandeur Member of the Park City Formation constitutes nearly half the Permian section. Elsewhere in the syncline this member represents a smaller part of the total thickness. Both phosphatic shale members of the Phosphoria Formation are fairly thick along the west limb: the Meade Peak averages about 15 feet thick and thins to the northeast, and the Retort averages more than 60 feet thick but reaches a maximum thickness of 83 feet at Hogback Mountain. The Rex Chert Member is nearly 100 feet thick at Sawtooth Mountain but thins to the southwest; to the northeast it almost lenses out. At Hogback Mountain the Permian interval above the Retort is made up mostly of sandstone, but contains some Tosi Chert strata. To the east and the west of Hogback Mountain, the interval contains more chert, but the total thickness is approximately the same. The thick sand apparently represents a narrow tongue that extends southward from Butte, Mont. (See Cressman and Swanson, 1964, p. 351.)

Throughout the area of the Ruby Valley syncline, the contact between the Quadrant Formation and the Grandeur Member of the Park City Formation apparently is conformable; however, the marked change in thickness of the Grandeur across the axis of the syncline may reflect both downwarping to the west and significant hiatuses on the stable shelf to the east, where the member is thin. The Dinwoody Formation of Triassic age appears to overlie the Permian rocks conformably in most of this area, but the brown carbonatic mudstone at the base thins toward the northeast. However, in both the Madison Range to the east and northeast and the Centennial Mountains to the southeast, fairly conclusive evidence of an unconformity at this contact has been recognized, and it is possible that such evidence may also exist in the Gravelly Range. Of particular note is the unusually thin (19 ft) upper member of the Shedhorn Sandstone at Wigwam Creek in the northern part of the Gravelly Range. That the Tosi Chert and the Retort Members are also abnormally thin (14 ft) at the Wigwam Creek locality suggests that less subsidence occurred in this part of the area during post-Franson time. But the thinness of the sandstone may be due in part to post-Permian erosion. Dinwoody strata may disconformably overlap the Permian in the Gravelly Range as a whole, which would suggest that some of the Shedhorn Sandstone was previously removed.

Phosphate

Both the Meade Peak and the Retort Phosphatic Shale Members contain phosphate rock of minable thickness throughout much of the Ruby Valley synclinal area, but the phosphate generally tends to be of low grade and the individual beds to be normally thin. Nearly all phosphate in the Meade Peak Member (pl. 29) occurs at its base, where the beds tend to be sandy. At several localities phosphorite constitutes the entire member, and northward it thins to a less than minable thickness.

In the Retort Member (pl. 29) more than one zone of phosphatic shale exceeding 3 feet in thickness and containing more than 18 percent P_2O_5 is present in most of the Snowcrest Range. In most of the Gravelly Range, however, only one such zone is present, and at

Alpine Creek (lot 1307) in the Gravelly Range, none is present. At Wadhams Spring and on Sliderock Mountain on the west limb of the syncline, the lower part of the Retort Member was not exposed, but by comparison with the sections in adjoining areas, it is reasonable to expect at least one more low-grade zone at each of these localities. Only at Warm Springs Creek in the north-central part of the syncline is a minable thickness of furnace-grade rock (more than 24 percent P_2O_5) present.

Further details on the grade and distribution of the phosphate are given in the descriptions of individual areas that follow. These areas (fig. 184) are separated by the axis of the main syncline; by the anticlinal axes that interrupt the continuity along the west limb, as described previously; and by folds and faults in the east limb. The phosphate resources of this district (table 5) were computed separately for these individual areas according to the thicknesses shown in figure 185.

WADHAMS SPRING-SAWTOOTH MOUNTAIN AREA

The Wadhams Spring-Sawtooth Mountain area includes the southwest corner of the Ruby Valley syncline. On the northwest flank of the syncline, Permian and associated strata crop out for a strike length of about 15 miles between Wadhams Spring (lot 1246)

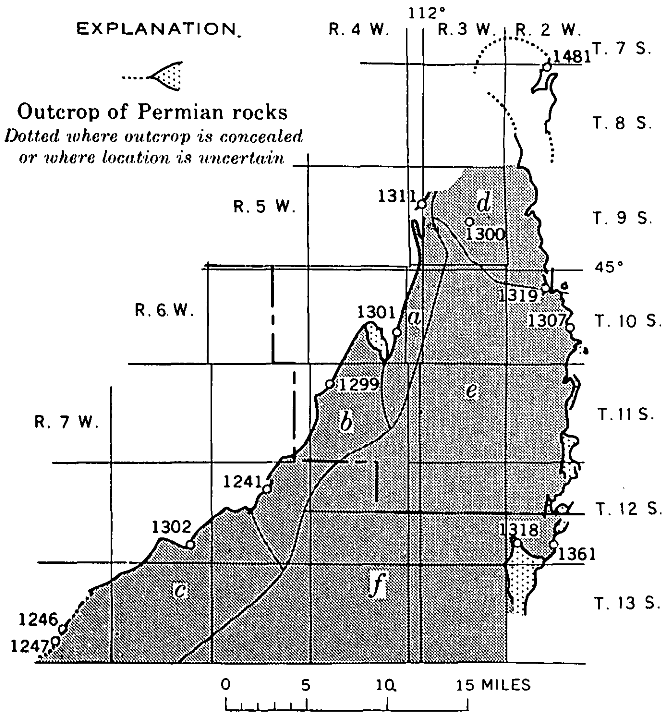


FIGURE 184.—Index to resource blocks in the Ruby Valley district. Area for which resource calculations were made is shaded. *a*, Wadhams-Sawtooth area; *b*, Sawtooth-Hogback area; *c*, Sliderock-Green Horn area; *d*, Warm Springs Creek area; *e*, Black Butte area; *f*, West Fork Madison River area. Circle and number indicate sample locality and lot number.

and the Sawtooth Mountain anticline (fig. 184). The area is in Tps. 12 and 13 S., Rs. 5, 6, and 7 W. Most of the area was mapped by Keenmon (Scholten and others, 1955), but the northeast corner was mapped by Gealy (1953). A gap nearly 1 mile wide at the west side of R. 5 W. has not been mapped in detail, but it is included in the reconnaissance map of Klepper (1950).

The area includes the low, southwest end of the Snowcrest Range, and local relief is generally less than 1,500 feet. The headwaters of Basin Creek and West Fork Blacktail Deer Creek drain northwest across the structural trend and divide the belt of upturned strata into three topographic units. The strata dip southeast an average of about 45° and are unconformably overlapped from that direction by the Upper Cretaceous and lower Tertiary Beaverhead Formation. On the northwest side the strata are overlapped by younger, continental deposits that were considered by Keenmon (Scholten and others, 1955, pl. 1) to be part of the Miocene Blacktail Deer Creek Formation of Douglass (1902).

In the Wadhams Spring-Basin Creek area, the Carboniferous formations are nearly 5,000 feet thick (Sloss and Moritz, 1951, p. 2155, 2163), including more than 1,700 feet of dominantly quartzitic sandstone of the Quadrant Formation at the top. The overlying Permian strata are more than 600 feet thick. All members of the Park City and Phosphoria Formations are present, but only a small part of the Shedhorn Sandstone is present. The two phosphatic shale members of the Phosphoria Formation have a total thickness of nearly 100 feet, and the two chert members a total of nearly 200 feet. More than half the total Permian section is assigned to the Grandeur and Franson Members of the Park City Formation. At West Fork Blacktail Deer Creek (lot 1302), all members of the Phosphoria Formation except the Rex are thinner, and the four members have a total thickness of about 200 feet or more. The Shedhorn Sandstone is more than 80 feet thick at this locality and possibly is much thicker. Parts of the section have not been measured at this locality, so the thicknesses of the Park City members, of the Rex, and of the lower member of the Shedhorn are unknown.

At Wadhams Spring (lots 1246, 1247) the Meade Peak Member is 15 feet thick; at West Fork Blacktail Deer Creek (lot 1302) it is 11 feet thick; and at Sawtooth Mountain (lot 1241) it is 18 feet thick and has about 2 feet of chert at the base. The only phosphate of note at each locality is at or near the base of the member and is mostly of less than furnace-grade quality (24 percent P_2O_5); that at Wadhams Spring,

TABLE 5.—*Phosphate resources of the Phosphoria Formation, Ruby Valley district*

[Phosphate resources given in millions of short tons]

Resource block	Bed area[1]			Average member thickness (ft)	Average grade (percent P_2O_5)	Total tons P_2O_5 in block	Rock containing >24 percent P_2O_5					Rock containing >18 percent P_2O_5				
									Tonnage					Tonnage		
	Above entry level	First 100 ft below entry	Total block				Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member																
West limb																
Wadhams-Sawtooth area	33.1	10.9	2,201	63.4	8.0	950						6.6	20.0	20.0	6.0	1,000
Sawtooth-Hogback area	81.4	12.6	1,613	66.2	8.7	800						6.5	20.0	45.0	7.0	800
Sliderock-Green Horn area	33.3	7.6	689	47.9	10.0	300						6.3	20.0	10.0	2.5	300
Totals and averages	147.8	31.1	4,503	62.0	8.5	2,050						6.5	20.0	75.0	15.5	2,100
East limb																
Warm Springs Creek area	130.2	18.5	956	18.6	12.9	200	3.2	29.0	3.0	0.5	90	4.8	22.5	45.0	7.0	350
Black Butte area	30.9	12.9	3,769	36.0	9.2	1,000	3.2	29.0			60	5.2	20.0	7.5	3.5	1,500
West Fork Madison River area	45.9	21.1	4,189	43.8	6.4	1,000						4.9	19.0	15.0	6.5	1,500
Totals and averages	207.0	52.5	8,914	37.8	7.9	2,200	3.2	29.0	3.0	0.5	150	5.0	19.8	67.5	17.0	3,350
Grand totals and averages, Retort Member	354.8	83.6	13,417	45.9	8.2	4,250	3.2	29.0	3.0	0.5	150	5.5	19.9	142.5	32.5	5,450
Meade Peak Phosphatic Shale Member																
West limb																
Wadhams-Sawtooth area	33.1	10.9	2,201	14.2	8.5	200						5.0	20.0	10.0	4.0	900
Sawtooth-Hogback area	81.4	12.6	1,613	11.9	16.2	250	3.9	27.0	25.0	3.5	500	5.8	20.0	35.0	5.0	700
Sliderock Green Horn area	12.5	3.6	536	5.4	20.0	50	4.0	26.5	1.5	.3	100	4.5	20.0	3.0	.7	200
Totals and averages	127.0	27.1	4,350	12.3	11.9	500	3.9	26.9	26.5	3.8	600	5.2	20.0	48.0	9.7	1,800
East limb																
Warm Springs Creek area	55.7	11.5	528	3.0	20.0	40						3.0	20.0	10.0	2.5	150
Black Butte area	96.0	23.0	3,948	6.3	20.5	400	4.2	26.5	30.0	5.5	1,000	5.4	20.0	35.0	7.5	1,500
West Fork Madison River area	45.9	21.1	4,189	10.0	17.8	600	5.2	26.5	20.0	9.5	1,500	6.8	19.0	20.0	10.0	2,500
Totals and averages	197.6	55.6	8,665	7.9	18.8	1,040	4.7	26.5	50.0	15.0	2,500	5.9	19.4	65.0	20.0	4,150
Grand totals and averages, Meade Peak Member	324.6	82.7	13,015	9.4	15.8	1,540	4.6	26.6	76.5	18.8	3,100	5.7	19.6	113.0	29.7	5,950
Grand totals and averages, both members	679.4	166.3	26,432	27.9	9.4	5,790	4.1	26.7	79.5	19.3	3,250	5.6	19.7	255.5	62.2	11,400

[1] Area in the plane of the bedding, in millions of square feet.

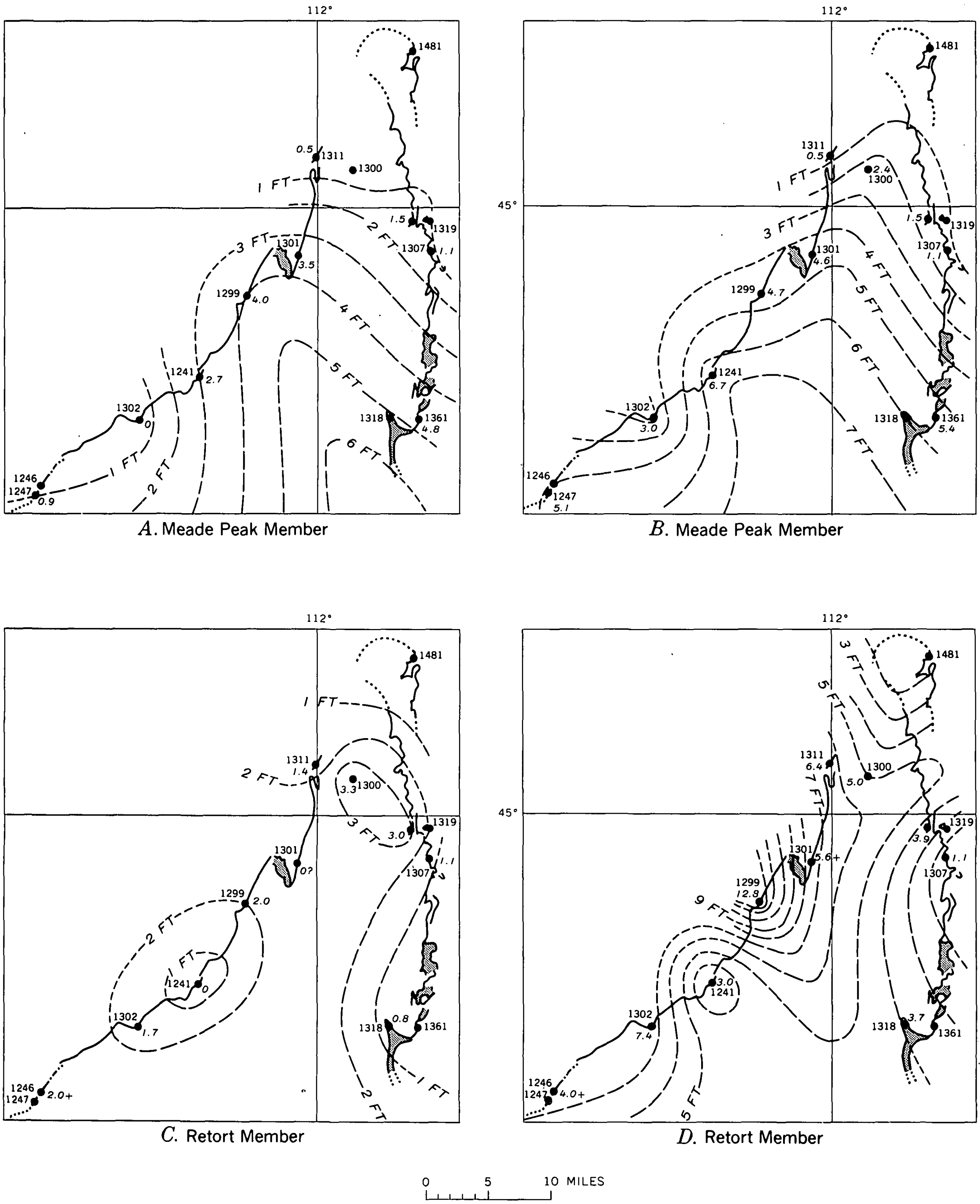


FIGURE 185—Total thickness of phosphate zones in the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation in the Ruby Valley district that contain more than 24 percent (*A, C*) and more than 18 percent (*B, D*) P_2O_5. Figure represents the thickest bed above cutoff grade if no zone 3 feet thick is present.

however, is only slightly less than furnace grade. At Sawtooth Mountain a 2.7-foot-thick bed is rich enough to be considered as furnace grade at a 3-foot thickness, even if the added 0.3 foot is barren.

The Retort Member averages a little more than 60 feet thick in this area; however, at Wadhams Spring the 67 feet used in averaging includes a 29-foot covered zone at the base of the Retort that probably conceals mostly Retort strata but may conceal some underlying strata. Low-grade phosphate occurs at the top of the member at Wadhams Spring and at West Fork Blacktail Deer Creek; at the latter locality another zone occurs 20 feet above the base. The rest of the Retort at these two localities and all of it at Sawtooth Mountain are composed of interbedded mudstone and low-grade phosphorite in units too thin to mine.

At Sawtooth Mountain the in general trend of the formations is offset about 1½ miles. The anticline and associated syncline at and just south of West Fork Blacktail Deer Creek offset the general trend more than 1 mile. At that locality Keenmon (Scholten and others, 1955, pl. 1) mapped a number of associated faults of small displacement that generally strike at a high angle to the strike of the strata. Farther southwest the general trend is convex to the southeast, then to the northwest, thus suggesting anticlinal and synclinal warping, although the change in strike does not deviate more than 15° from the average of N. 45° E. The dip of the formations is about 45° SE. for much of this distance; however, near the axis of the anticlinal warping, the dip increases to 60°, and at the south end, which appears to be near the axis of another anticlinal bend, it increases to 70° or more. Steepening of dip near anticlinal axes suggests that the structures do not persist very far downdip and thus further suggests that these offsets are related to the major uplift. In sec. 11, T. 13 S., R. 7 W., a left-lateral cross fault offsets the Quadrant Formation about 1,500 feet. Overlying strata are covered, but by projection of contacts, the displacement appears to diminish southeastward.

In the absence of a topographic base, the amount of phosphate that could be strip mined cannot be evaluated; but, in general, the strata have too high a dip for much mining by this method. Also the estimates of resources above entry level (table 5) are probably not very accurate, but they are believed to be of the right order of magnitude.

SAWTOOTH MOUNTAIN-HOGBACK MOUNTAIN AREA

The Sawtooth Mountain–Hogback Mountain area constitutes the central part of the west limb of the Ruby Valley syncline (fig. 184) and includes the interval between the anticlinal axes of Sawtooth Mountain and Sliderock Mountain. The area is about 13 miles long and is in Tps. 10, 11, and 12 S., Rs. 4 and 5 W.: it includes much of the ruggedest part of the Snowcrest Range, where several peaks rise to more than 10,000 feet in altitude, and Hogback Mountain—the highest peak in the range—which reaches an altitude of 10,605 feet. The range is breached by the upper valleys of three small streams: East Fork Blacktail Deer Creek on the north side of Sawtooth Mountain, Robb Creek at the Notch between Olson Peak and Hogback Mountain, and Ledford Creek north of Hogback Mountain. These creeks drain northwestward and cross the Permian strata at altitudes of about 7,500 feet, 8,300 feet, and 7,300 feet, respectively.

The main crest of the Snowcrest Range is composed of Carboniferous strata, particularly the Quadrant Formation. These strata are overturned and dip fairly steeply northwest, although overturned dips as low as 35° were recorded by Gealy (1953, pl. 1). Lower Mesozoic formations are exposed down slope from the Permian on the southeast (scarp-slope) side. These are unconformably overlain in places by the Upper Cretaceous and lower Tertiary Beaverhead Formation. The lower part of the main ridge on the northwest (dip-slope) side includes lower Paleozoic formations and some Precambrian crystalline rocks that are faulted against the Carboniferous strata. All these are unconformably overlapped by Tertiary (Miocene?) clastic and volcanic rocks, including the Blacktail Deer Creek Formation of Douglass (1902) as used by Keenmon (Scholten and others, 1955), that cover a wide area.

Gealy (1953, p. 37) measured 658 feet of Quadrant Formation on Spur Mountain at the north end of this area, but he expressed some uncertainty as to its true thickness owing to structural complications. The Permian strata total 800 feet thick at Hogback Mountain, the only locality in this range where a complete section was measured. Nearly 500 feet was measured on Sawtooth Mountain, but this measurement did not include either the base or the top of the sequence. The Permian strata apparently average more than 700 feet thick throughout this area, however.

The Grandeur Member of the Park City Formation is 384 feet thick at Hogback Mountain—the greatest thickness of this member known in Montana. There, the Meade Peak Member of the Phosphoria Formation is only 10 feet thick, but at Sawtooth Mountain it is 18 feet thick. The Rex Chert (Phosphoria) and Franson (Park City) Members are well developed in the area, and the section between the two phosphatic shale members includes several tongues of the lower member of the Shedhorn Sandstone. The Retort Member of the Phosphoria Formation is 83 feet thick at Hogback Mountain but is only 59 feet thick at Sawtooth Mountain. The post-Retort section is dominated by the upper member of the Shedhorn Sandstone in this part of the Snowcrest Range, but the Tosi Chert Member is very prominent to the southwest and the northeast. Probably all pre-Tosi units thin markedly toward the axis of the Ruby Valley syncline, for they are much thinner in the Gravelly Range. (See Cressman and Swanson, 1964 (pl. 21.)

At both Sawtooth and Hogback Mountains, a minable thickness of furnace-grade phosphate rock is present at or near the base of the Meade Park Member. At the Sawtooth locality the bed is only 2.7 feet thick, but it is rich enough to assure a minimum grade of 24 percent P_2O_5 for a minable thickness of 3 feet. At the Hogback locality the bed is 4 feet thick, and the basal 1 foot contains 34.6 percent P_2O_5. The thickness of rock of the cutoff grade of 18 percent P_2O_5 is not much greater than that for furnace grade, for most of the overlying mudstone is of very low grade.

The Retort Member apparently contains only one 3-foot zone of low-grade (18 percent P_2O_5) phosphate rock at Sawtooth Mountain. At Hogback Mountain no sequence 3 feet thick contains furnace-grade rock, although four low-grade zones 3 feet or more thick are present—one at the top of the member and three in the lower 30 feet.

The large offset in the general trend of the strata between Sliderock and Hogback Mountains was previously described, and a cause for the peculiar structure was suggested (p. 719). The axis of the Sliderock Mountain anticline is very sharp, and the beds have probably been sheared. The same is apparently true for the axis of the Spur Mountain syncline to the west. The mutual limb of these folds extends a little more than 2 miles along strike, is fairly planar, and dips about 25° SW. Both the folds and the shearing apparently die out to the south within a few miles. Except for two small left-lateral cross faults mapped by Gealy (1953) on Olson Peak and Sawtooth Mountain, the strata between the Spur Mountain syncline and Sawtooth Mountain anticline are apparently uninterrupted. Near the two ends of this zone the strata dip very steeply, but in the central two-thirds they are rather strongly overturned and are overlain by older rocks that have been raised on fairly steep thrust faults. Overturned Permian strata are believed to occur only above an altitude of 5,000 feet.

Except for the normal limb of the Sliderock Mountain anticline, there may be no significant tonnage of phosphate rock that could be mined by surface methods. On that limb there are probably several places where detailed mapping of phosphatic shale members would show a significant reserve minable by surface methods, as many of the surfaces are within 10° of being dip slopes. But the area is high, above 8,000 feet in altitude, and is not readily accessible by road. The large local relief favors a large resource above entry level (table 5), but part of that resource is probably spoiled by shearing along bedding planes.

SLIDEROCK MOUNTAIN-GREEN HORN AREA

The Sliderock Mountain–Green Horn area includes the west limb of the Ruby Valley syncline from the apparent intersection of the axes of the Sliderock Mountain anticline and the Ruby Valley syncline north about 14 miles to about 1 mile north of the Ruby River Canyon in T. 9 S., R. 3 W., where both the west limb and the axis of the syncline pass beneath the Green Horn thrust. Sliderock Mountain, near the south end of this area, reaches an altitude of 10,420 feet, and the crest of the ridge for a considerable distance to the north includes peaks above 9,000 feet. The Ruby River drains northwest across the general trend of the Permian formations in a short canyon at an altitude of a little less than 6,000 feet, the lowest exposure of Permian rocks in the syncline.

As is true farther south, the crest of the Snowcrest Range is dominated by Carboniferous rocks, and the Permian strata crop out on the east side near the top of the scarp slope. The Permian strata are overturned and dip to the west at angles as low at 30° in the northern part of the Antone Peak quadrangle (T. 10 S., R. 3 W.) (Gealy, 1953, pl. 1). Such low dips are believed to occur only in the higher parts of the range. Near Snowcrest Mountain in the southwest part of T. 9 S., R. 3 W., the Permian strata dip 40° W. (Mann, 1950), and at Canyon Camp (lot 1311) in Ruby River Canyon they dip 50° W. Mann showed dips as low at 35° beneath the Green Horn thrust north of the canyon.

The stratigraphy in this part of the Ruby Valley syncline is believed to be similar to that farther south, but the units are inferred to be much thinner on the basis of their proximity to the Gravelly Range, where the units are known to be thinner. Gealy (1953) showed the Brazer-Big Snowy unit extending to the north edge of T. 10 S. Mann (1950), however, did not identify such a unit in T. 9 S., although he recognized the possibility that such strata might be present. At neither the Sliderock Mountain nor Canyon Camp localities (lots 1301, 1311) was the full thickness of Permian strata measured owing to structural complexities. At Sliderock Mountain, however, the section is probably 500 feet or more thick, and at Canyon Camp, perhaps as much as 400 feet thick. The principal gaps in the section occur below the Meade Peak Member and between the Meade Peak and Retort Members. Almost all the thinning of the Permian section in this area takes place in the pre-Tosi part of the section (Cressman and Swanson, 1964, pl. 21), where each pre-Tosi member appears to thin.

The Grandeur Member of the Park City Formation, only part of which is exposed at the sample localities, is probably 100-200 feet thick. The Meade Peak Member of the Phosphoria Formation is less than 10 feet thick; the Rex is 20 feet or more thick; the Franson (Park City) is 50 feet or more thick; and the lower member of the Shedhorn Sandstone is not more than 25 feet thick. The Retort Member of the Phosphoria is well developed and is probably 40 feet or more thick including the prominent chert at its base. The Tosi, well developed at both localities, is 80-100 feet thick. It intertongues with a much thinner unit of the upper member of the Shedhorn Sandstone. The contact with the calcareous mudstone at the base of the overlying Dinwoody Formation appears to be conformable.

The Meade Peak Member contains a 3.5-foot-thick zone of furnace-grade phosphate rock at Sliderock Mountain (lot 1301), but at Canyon Camp (lot 1311) this bed is only 0.5 foot thick. The associated shales also lens out. The Retort Member contains a low-grade phosphate zone (18 percent P_2O_5 of minable thickness in the top 10 feet at each locality but contains no minable zones of furnace-grade rock. The lower part of the Retort Member is faulted out at Sliderock Mountain, but on the basis of Canyon Camp as well as other localities near this area, it probably does not contain very high quality phosphate. At Canyon Camp, however, a 3-foot-thick zone about 15 feet above the base might contain 18 percent P_2O_5, even though the 3.2 feet of strata sampled contains only 17.5 percent P_2O_5.

In the Sliderock Mountain-Green Horn area the strata are overturned and are considerably sheared parallel to the bedding. Gealy (1953, p. 80-83) described the complex folds and faults in the Carboniferous strata north of Sliderock Mountain, at the axial part of the Sliderock Mountain anticline; steep thrust faults farther west (most of which have fairly small displacement); and a thrust fault ½–⅔ mile east of the Permian outcrop, which he traced for more than 8 miles to the north edge of T. 10 S. This last fault cuts only Cretaceous strata at the surface, and the amount of displacement is unknown. Mann's map (1950, pl. 1) does not show this fault.

About 1½ miles south of Ruby Canyon, the small folds mapped by Mann (1955, pl. 1) offset the general trend of the formations to the right approximately half a mile. The small syncline and anticline apparently plunge southeast, and they may die out within a short distance. To the west, Mann showed Precambrian rocks thrust over Carboniferous strata along a fairly steep fault. On the south side of Ruby Canyon he mapped a left-lateral cross fault that strikes west-northwest, offsetting the formations about half a mile. This may be the tear that Gealy (1953) mapped at the north end of the steep thrust which cuts across Cretaceous rocks in T. 10 S.; or it may connect across the syncline with faults mapped on the east limb by Mann (1950, pl. 1) and by Kennedy, as suggested on plate 28A.

About a mile north of Ruby Canyon the Permian and associated formations pass beneath the Green Horn thrust plate. Mann (1950, p. 101) described this thrust as dipping 20°–25° W. and having an easterly displacement of 5,000 feet or less, though by comparing his geologic map against the topographic base, it appears that the dip might be even flatter and the displacement greater; Hadley (1959) believed that the displacement may be several miles. Part of the sharp overturning of the strata in the Ruby Canyon area is most likely due to drag beneath this thrust.

The north-central part of the Ruby Valley syncline is fairly narrow, and the axial part of the syncline is closer to the west limb there than it is farther south. Also, the uplift that formed the Warm Springs anticline in T. 9 S., R. 3 W., has shifted the axis even farther west near Ruby Canyon. Hence, the area underlain by phosphatic rock in the Sliderock Mountain-Green Horn area is rather small. This fact plus the facts that the phosphate is thin and is generally of poor quality results in a low tonnage estimate for phosphate in the area (table 5). The dips of the strata are, for the most part, too steep to allow strip mining of the phosphate deposits, but there may be some deposits which could be strip mined in the small fold structure south of Ruby Canyon.

EAST LIMB OF RUBY VALLEY SYNCLINE

The east limb of the Ruby Valley syncline underlies the top and the west side of the Gravelly Range and most of the upper Ruby River valley. The Ruby River drains most of the synclinal area, but part of the Gravelly Range is drained by tributaries of the Madison River to the east, and the Red Rock River drains the area to the south.

The geologic discussion that follows is based chiefly on the unpublished geologic maps and cross sections of the Monument Ridge and Lower Red Rock Lake quadrangles by G. C. Kennedy (written commun., 1952), the report by Mann (1950), and observations by the author. Also, J. B. Hadley (written commun., 1957) kindly furnished some map data on the distribution of

Permian rocks in the north-central part of the Varney quadrangle, and he showed the author some incomplete exposures of Permian strata near Wigwam Creek.

The east limb of the Ruby Valley syncline does not have large differences in thickness or in character of stratigraphic units, nor is the limb readily divisible into natural geologic blocks on the basis of structural features. Therefore, the east limb is described as a single area, and local details are presented as necessary. For convenience in resource presentation, however, the east limb is divided into three subareas (fig. 184), which are separated in some places by fault zones. These subareas are—

1. *Warm Springs Creek area.*—That area between the steep reverse fault in T. 8 S., R. 2 W., and the Ruby Canyon fault in T. 10 S., Rs. 2 and 3 W., and its possible extension into T. 9 S., R. 3 W.
2. *Black Butte area.*—South from the Warm Springs Creek area to the middle of T. 12 S., Rs. 2, 3, 4, and 5 W.
3. *West Fork Madison River area.*—South from the Black Butte area to the south edge of T. 13 S., Rs. 2-6 W.

The Snowcrest Range is dominated for much of its length by a single sharp, narrow ridge, whereas the Gravelly Range is broad and somewhat rounded. Black Butte, described as a volcanic plug, is 10,545 feet in altitude. A few other peaks reach an altitude of 10,000 feet, but most of the range crest is a little more than 9,000 feet in altitude in the central part and is lower to the north and the south. The east (scarp) slope of the range is rather deeply incised by stream valleys, but the west (dip-slope) side is undulating and has an average gradient of about 500 feet per mile; local relief is generally less than 1,000 feet. The valley of the Ruby River ranges in altitude from about 6,000 feet in Ruby Canyon to nearly 7,500 feet at the drainage divide to the south. Numerous dirt roads and trails furnish ready access to the Gravelly Range.

Precambrian and lower Paleozoic rocks crop out on the east side of the Gravelly Range; upper Paleozoic and lower Mesozoic rocks crop out in the general area of the range crest; and Upper Cretaceous rocks crop out on the west side of the range and in the Ruby Valley area. Carboniferous strata have an aggregate thickness of little more than 2,200 feet, according to Honkala (1949a) and Mann (1950, p. 22–34). These strata are dominantly carbonate rock but include red shale and sandstone in the Amsden Formation and quartzitic sandstone in the Quadrant Formation. Overlying the more than 200 feet of Permian strata is 550–1,500 feet of Triassic and Jurassic strata. The large range in thickness is due primarily to the northward thinning and pinching out of the Triassic formations. The Jurassic section is rather thin in this area. The Lower Cretaceous Kootenai Formation is about 500 feet thick and is overlain by a thick sequence of Cretaceous shales and sands.

The two members of the Park City Formation make up about a third of the Permian section in the Gravelly Range and are much thinner than in the Snowcrest Range, to the west. Most Park City strata belong to the Grandeur Member, which is 50-80 feet thick. The contact with the underlying Quadrant Formation is hard to define and is therefore somewhat arbitrary owing to the numerous beds of carbonate rock interbedded with the sandstone of that formation in this part of the region.

The two phosphatic shale members and the Rex Chert Member of the Phosphoria Formation are very thin in this area. In fact only about half the Retort Member is phosphorite and shale; the rest is chert that underlies the shale and that is arbitrarily included with the Retort because of its logical assignment to the Phosphoria Formation. It could be best compared with the lower chert member that underlies the Meade Peak in part of western Wyoming (Sheldon, in McKelvey and others, 1959, p. 22), but it could be assigned with almost equal logic to either the Rex or the Tosi Chert Members—to the former on the basis of comparison with relations in southeastern Idaho, and to the latter on the basis of comparison with relations near Three Forks, where the Retort tongues out into the Tosi. The Tosi is well developed in the Gravelly Range area and averages more than 50 feet thick; it represents more than half the total thickness of the Phosphoria Formation.

Both the lower and upper members of the Shedhorn Sandstone are well developed in the Gravelly Range. They average about 35 and 50 feet thick, respectively. Part of the upper member appears, at least locally, to have been removed by pre-Triassic erosion.

In the Meade Peak Member, phosphorite 3 feet thick and containing 18 percent P_2O_5 occurs in only the southern half of the east flank of the syncline, and the area of rock of this thickness containing 24 percent P_2O_5 is not much smaller, for most of the phosphate there occurs in beds of 24 percent or better quality. (See pl. 29 and fig. 185.)

The Retort Member is a little thicker than the Meade Peak and contains more total phosphate, but the average phosphate content of the Retort is lower than that of the Meade Peak. The area containing more than 3 feet of 18 percent P_2O_5 rock is larger for the Retort than for the Meade Peak, but that containing 24 percent P_2O_5 rock is much smaller (pl. 29; fig. 185) and is restricted to the vicinity of the Warm Springs sample locality (lot 1300). In the Meade Peak Member the principal diluent is sand, whereas in the Retort Member it is mud.

The east flank of the syncline is characterized by gentle westerly dips (10-15°) in most of the area. Locally, however, the strata are considerably faulted and the dips are steeper. The faults all appear to be steep, and most are probably normal. Some of them, however, are known to be reverse. Stratigraphic displacement on most of the faults is limited to a few hundred feet. Most faults strike north-northeast or west-northwest. The reverse faults belong chiefly to the more northerly group of faults, whose west sides have been moved up.

Two asymmetric anticlines interrupt the general pattern. Both strike west of north, and their steep limbs are on the east. The one of greater uplift—nearly 2,000 feet—is to the north near the axis of the Ruby Valley syncline in T. 9 S., R. 2 W. This structure is breached by Warm Springs Creek, on whose canyon walls the Permian strata were measured (lot 1300). The other structure is at the south end of the Gravelly Range, and the Permian strata are exposed where the axis of the anticline is cut by the West Fork Madison River (lot 1318).

The downdropped block north of the steep reverse fault in T. 8 S., R. 2 W., includes an area of about 15 square miles that is drained chiefly by Wigwam Creek. An incomplete section of Permian strata was measured on the north side of this creek (lot 1481). There, the Retort Member is very thin and does not contain much phosphate; the Meade Peak Member is not exposed, but as its presumed horizon is a thin covered interval, it would also appear to be thin and it probably also contains very little phosphate. Therefore, this entire area is assumed to contain too little phosphate for resource estimation.

The Permian rocks in much of this area are poorly exposed. Their distribution in T. 8 S., R. 2 W., supplied by J. B. Hadley (written commun., 1957), indicates gentle dip and the presence of some minor faults on the east limb of the syncline. Permian rocks on the west limb north of the Romey thrust were seen by the author on the ridge south of Arasta Creek, where they strike north-northeast and dip almost vertically. No phosphorite was seen and a section could not be measured. Much of the north end of the syncline is covered by volcanics.

On the west side of the Warm Springs Creek area, the main axis of the Ruby Valley syncline appears to be offset about half a mile at the left-lateral fault near Ruby Canyon. About a mile north of the canyon, the western part of the syncline is cut off by the Green Horn thrust (Mann, 1950); all rocks of the syncline north and east of that thrust are treated here with the east limb. Two miles farther north in sec. 34 (?), T. 8 S., R. 3 W., Condit, Finch, and Pardee (1928, pl. 12) showed the strata dipping 80° SE., presumably including the Permian. Mann's map, however, shows the Triassic strata as the oldest rocks exposed beneath the Green Horn thrust there, and Condit, Finch, and Pardee's map does not show the thrust. At the crest of the Gravelly Range, Mann mapped Permian strata near the head of French Gulch, southwest of the steep reverse fault in the southwest part of T. 8 S., R. 2 W. From French Gulch the Permian rocks probably extend northwestward along the prominent ridge northwest of Crockett Lake to the place where they are cut off by the Romey thrust in the eastern part of T. 8 S., R. 3 W.

In the trough of the syncline at Warm Springs Creek, east of the Ruby River canyon, is a sharp anticline that is asymmetric toward the northeast; its northeast limb is vertical and its other limb dips about 10°–15° SW. The Quadrant Formation is exposed at the axis of the anticline in the canyon of Warm Springs Creek. Mann's map shows a fault, down several hundred feet on the southwest, that is west of the axis of the fold by several hundred feet. This fold appears to have formed in response to a break in the crystalline basement rocks below the present fault; the southwest side of this break was uplifted nearly 2,000 feet and thus formed an asymmetric fold in the overlying strata as they draped across the displaced blocks. The fault mapped by Mann is believed to represent a subsequent reversal of movement on the original break due to later subsidence of the originally raised block (fig. 186.)

South of French Gulch the Permian strata crop out mostly at the crest of the range. In the northwest quarter of T. 10 S., R. 2 W., the strata are broken by a steep reverse fault that strikes north-northeast, dips west, and has a net displacement of about 1,000 feet, including drag. Although Mann (1950) did not map the full length of this fault, he connects this fault with the one near Crockett Lake. Kennedy (1949) showed the fault to extend several miles farther south as a zone of faults ½-2 miles wide. An apparently similar but smaller fault zone occurs in the southeastern part of T. 10 S. and the adjoining part of T. 11 S., R. 2 W.; the net uplift in this zone is about 500 feet.

A number of faults in this general area strike eastward. These faults have generally small displacement

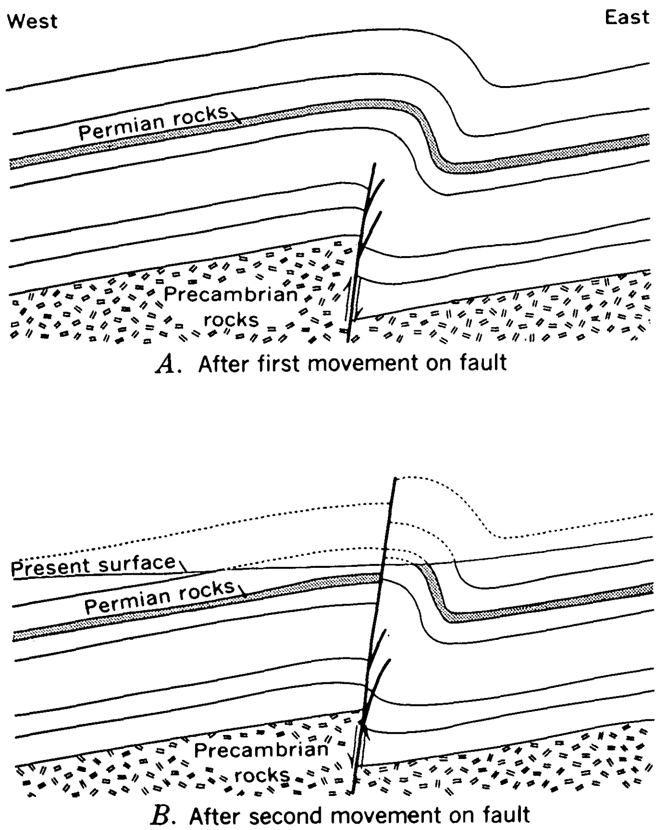


FIGURE 186.—Structural relations at Warm Springs Creek. Presence of a norm a fault west of the anticlinal axis is the result of a reversal in movement.

and most of them appear to have moved up on the north. One fault occurs in the northeastern part of T. 10 S., R. 3 W., and westward its trend changes from west to northwest. This fault may connect beneath the Ruby River valley with the left-lateral fault at Ruby Canyon. This fault separates the Warm Springs Creek and Black Butte resource areas. About 7 miles farther south, near the Beaverhead-Madison County line in T. 12 S., R. 2 W., a fault of similar magnitude has moved up on the north and was traced for several miles east into the Precambrian crystalline rocks that underlie that area.

At West Fork Madison River, south of the fault, the Permian outcrop is offset about 2 miles to the west at an asymmetric anticline which plunges gently north-northwest. A few miles farther south, near the west-central part of T. 13 S., R. 2 W., the Permian strata disappear beneath the alluvial fill of the broad Centennial Valley.

The gentle dips and relatively simple structure and the undulating topography of the Gravelly Range are favorable for phosphate deposits that could be strip mined, particularly in the southern part of the range where the phosphorite is thicker and the haulage would be easier. In general, however, the Tosi Chert Member and the upper member of the Shedhorn Sandstone form a hard thick protective cap over the phosphatic rocks and seriously restrict the tonnage that might otherwise be stripped. Though the local relief in this areas is not very great, the gentle dip of the strata is favorable to a fairly large resource of phosphate above entry level (table 5).

CENTENNIAL MOUNTAINS DISTRICT

General features

The Centennial Mountains are a long, fairly narrow mountain range trending west from the vicinity of Yellowstone Park. The Continental Divide and much of the southern boundary between southwest Montana and Idaho follow the crest. The range is bounded on the north by the flat alluvium-floored Centennial Valley and on the south by the eastern part of the broad Snake River Plains.

The eastern part of the range is the most rugged, having a very steep scarp slope on the north that rises from the floor of the valley at an altitude of a little over 6,600 feet to the range crest at an altitude of more than 9,500 feet; in some places there is difference in altitude of nearly 3,000 feet within a mile. Westward the range is lower and the slopes are less steep, and the range merges into a series of rolling hills in the general vicinity of Monida. From the range crest, the south (dip) slope is much gentler, and gradients average less than 1,000 feet per mile. However, dissecting streams have steep valley sides marked by cliffs formed on resistant strata. The lower slopes are generally timbered, but the upper parts of the range contain broad areas of grassland.

The principal drainage of the Centennial Mountains is southward to the Snake River Plains, where most of the surface water seeps into volcanic rocks and disappears. Locally, however, this water drains into streams flowing north, as Odell Creek. Most of the streams are closely spaced and are small. Winter is usually long in the Centennials, and much of the area is commonly inaccessible before June.

No railroad is near the area of phosphate deposits of the Centennial Mountains, but two branches of the Oregon Short Line Railroad of the Union Pacific Railway system are near the ends of the range. On the west is the main line that connects Butte and Salt Lake City, and on the east is the spur line that connects West Yellowstone to the main line at Idaho Falls. Truck hauls of 20-35 miles from the phosphate area are necessary to reach these railroads, and only secondary roads along both flanks of the range provide access to the railroads. Until recently, the phosphate-bearing eastern part of the range has been accessible only by sheepherders' trails from these dirt roads. In about 1955 a road was constructed to the crest of the range from the Centennial Valley for purposes of phosphate mining, and a poor connection from this road was established to the road along the south side of the range. The phosphate has been trucked to Monida for rail shipment.

Geologic setting

Details on the geology of the phosphate-bearing eastern part of the Centennial Mountains (pl. 28B) were obtained primarily from the maps of Kennedy (1949; written commun., 1952) and Honkala (1953). The author has also studied much of the geology of the phosphate area in detail.

The Centennial Mountains are a long south-tilted fault block. The eastern part of the range is composed primarily of Paleozoic formations. These formations are underlain by Precambrian crystalline rocks that crop out near the fault on the lower slopes of the north side and in the low connection with the Gravelly Range at the northeast. They are overlain chiefly by lower Mesozoic strata that veneer much of the south flank and that, in turn, are overlain by volcanic rocks near the edge of the Snake River Plains. In the western part of the range, only the Upper Cretaceous strata and the associated younger volcanic rocks are exposed.

A prominent fault scarp is exposed at many places along the north base of the range and indicates that the uplift was fairly recent. A number of cross faults divide the range into discrete geologic units. The largest cross fault is near Odell Creek, when it separates the two major segments of the range. Stratigraphic displacement on this fault is at least several thousand feet, with the east side having been raised.

In the eastern half of the range, the Permian rocks are exposed in two principal areas, which are about 4½ miles apart. The area on the west is the larger—about 6½ miles long. It is just east of the fault at Odell Creek and includes the prominent Sheep and Taylor Mountains. This area has been mapped and sampled in detail by the U.S. Geological Survey (Kennedy, 1949, and written commun., 1952; Honkala, 1953; Cressman and Swanson, 1964, lots 1251-1255, 1342-1343.) Phosphate has been mined there fairly recently. Permian strata in this area crop out at the crest of the range and in some of the valleys that drain the area. They strike west-northwest and dip 10°–15° S. The area on the east is 3 miles long; it was mapped by Kennedy (1949), but no Permian strata were measured or sampled. The strata dip about 15° S. beneath the volcanic cover; they are also covered by volcanic rocks to the east. These strata reach the crest of the range at Reas Peak. In the 4½ miles between the east and west areas, the Permian strata are preserved in down-dropped fault blocks and are partly covered by volcanic rock or have been removed by erosion.

Stratigraphy

The Carboniferous formations are less than 1,500 feet thick in the Centennial Mountains, according to Sloss and Moritz (1951, p. 2157, 2163), who measured sections on Arrowhead Mountain (apparently the peak now labelled Taylor Mountain on the Upper Red Rock Lake topographic sheet) and near Odell Creek. Most of this thickness is Mississippian limestone and dolomite; the Quadrant Formation (dominantly sandstone) is only 125 feet thick according to these authors but is about 250 feet thick according to Honkala (1953, p. 9). Permian strata, described later in more detail, are nearly 200 feet thick. Honkala (1953) indicated that about 3,500 feet of Mesozoic strata overlies the Permian. The basal 470 feet of Mesozoic strata is Dinwoody Formation and is overlain by 800 feet of Woodside Formation; both units are Triassic. The Dinwoody Formation is dominantly thin-bedded siltstone (at the base) overlain by flaggy to medium-bedded limestone and sandstone.

The Permian strata range considerably in thickness within their fairly small outcrop area. Part of this range in thickness is due to lateral variation in original thickness of deposits, and part is due to intra-Permian unconformities that indicate local erosion. Most of the range in thickness, however, is due to a post-Permian unconformity (Cressman and Swanson, 1964, pl. 18) representing removal of as much as 75 feet of Permian strata before deposition of Triassic sediments. The maximum thickness of Permian strata at the close of Permian time may have been more than 240 feet, although the present range in thickness is from about 165 feet to 205 feet.

At the base of the Permian, the Grandeur Member of the Park City Formation is 30 feet thick. It appears to overlie the Quadrant Formation conformably, but the great difference between its thickness in this area and its thickness (more than 300 feet) in the Snowcrest Range and Lima areas 30-45 miles away suggests that a large hiatus may be involved. The Franson Member of the Park City is as much as 26 feet thick and intertongues with the lower member of the Shedhorn Sandstone, which is generally as much as 36 feet thick.

Both phosphatic shale members of the Phosphoria Formation are well developed. The Meade Peak Member is as much as 18 feet thick and contains some of the highest quality phosphorite known in Montana.

The member has a rather wide range in both lithology and thickness, however, and is locally absent. Most of the phosphorite is in the lower part of the member but may represent more than half the total thickness. Honkala (1953, p. 10) was unable to find evidence of the member at the west end of the main area—in the general vicinity of Odell Creek. At another locality a little farther east (labelled Confusion Gulch on plate 28B), Meade Peak strata are absent and a conglomerate at that position unconformably overlies the Quadrant Formation. The area in which the Meade Peak Member is absent may be small, perhaps not more than 160 acres; the adjoining areas to the north and the east have features apparently related to this conglomerate. For example, about half a mile to the north at the crest of Sheep Mountain, conglomerate and conglomeratic phosphatic sandstone several feet thick occur beneath the phosphorite; about a mile to the east, phosphatic sandy limestone and (or) calcareous sandstone occur as a prominent interbed in the phosphorite. (See also page 732.) Most of the Meade Peak phosphorite is composed of coarse oolitic grains and organic remains (bone and tooth chips and shell fragments) and is light gray to light tan; quartz grains and carbonate are the principal diluents.

The Retort Member is about 30 feet thick and is composed mainly of fissile to thin-bedded mudstone that has interbeds of fine-grained phophorite in its lower part. These rocks are dark gray to black. The upper part of the member is dominantly cherty siltstone and therefore appears to be gradational with the Tosi Chert Member.

The Tosi Member is locally 50-60 feet or more thick. Near Reas Peak, where the Tosi is 50 feet thick, it is overlain by 37 feet of the cherty quartzitic upper member of the Shedhorn Sandstone; but in the Sheep Mountain-Taylor Mountain area to the west, the Tosi is unconformably overlain by the lower mudstone member of the Dinwoody Formation, which locally has a thin basal conglomerate. Measured sections of the Tosi range in thickness from 15 feet to nearly 60 feet within 3 miles, and in places the Tosi seems to be absent, as near Taylor Creek. The E_2 siltstone unit described by Honkala (1953, p. 12) on top of the chert is now assigned to the Dinwoody Formation.

Structure

The geologic structure within the eastern half of the Centennial Mountains is generally simple, the tilted fault block displaying dips of 15° S. or less over most of the area. Honkala (1953, p. 14) described a few faults in the Sheep Mountain-Taylor Mountain area, but most are small. The largest fault—on Taylor Mountain—has a stratigraphic displacement of about 200 feet, down on the west, and strikes south-southwestward in the direction of dip of the strata. Farther east the faults are generally larger and more closely spaced. The displacement on some faults is indeterminate owing to the unconformable volcanic cover, but, in general, the 4½-mile-wide area west of Reas Peak is downfaulted and is topographically lower than the areas on either side.

In the western half of the range the details of the structure and stratigraphy are not known to the author. However, no rocks older than Late Cretaceous are known to be exposed, so the Permian strata there must be deeply buried.

Phosphate

The Centennial Mountains contain some of the highest quality phosphate in Montana. The main phosphorite bed occurs in the lower part of the Meade Peak Member (pl. 29). It has been extensively explored in the Sheep Mountain–Taylor Mountain area east of Odell Creek. (See Honkala, 1953.) The bed has been strip mined by the J. R. Simplot Co.

Part of the extensive exploration has been necessitated by the lenticularity of the phosphorite bed. Throughout most of the western phosphate field, the phosphatic strata are noteworthy for their lateral continuity in both lithologic character and thickness (McKelvey, 1949, p. 272). In the Sheep Mountain-Taylor Mountain area, however, some marked changes in both thickness and lithology occur within very short distances. A summary of the relations is included here.

In this area the Meade Peak Member is typically composed of a rich basal phosphorite bed, normally about 5 feet thick, overlain by a little mudstone or carbonate rock and a thin but persistent chert that is 1 foot or more thick. The upper half of the member is characterized by alternating thin beds of mudstone, phosphorite, and carbonate rock, and by a persistent bed of phosphorite near the top that in places may be nearly 2 feet thick. Above this, commonly separated by a thin mudstone or carbonate bed, is a persistent bed of phosphatic sandstone 1-2 feet thick that is overlain by chert or cherty carbonate rock. The sandstone bed may be a tongue of the lower member of the Shedhorn Sandstone, but if so, it is unusually phosphatic. The chert above it is probably a tongue of the Rex.

At the range crest in the area between Taylor and Sheep mountains, the main phosphorite bed is generally thick, and locally is as much as 11 feet thick. Commonly, however, a very irregular zone of calcareous gritty sandstone or sandy limestone as much as 4 feet thick occurs at or just below the middle of the bed and divides the bed into upper and lower parts (Honkala, 1953, pl. 6). This parting bed pinches and swells abruptly from 0 to 3 feet within as little as 10 feet laterally, and it is characterized by very sharp but highly irregular contacts with the phosphorite. Locally it contains abundant disseminated phosphate, both as oolites and as abraded fragments of shell, tooth, or bone.

Nearly a mile farther northwest, on the north side of Sheep Mountain, several feet of phosphatic conglomeratic sandstone occur at the base of the Meade Peak Member, and locally (at least) this layer contains enough phosphate to be classed as sandy conglomeratic phosphorite. It is overlain by 3-4 feet of high-quality phosphorite, which here marks the top of the Meade Peak Member, for the phosphorite is overlain by sandstone and carbonate rock at least 15 feet thick.

Two-thirds of a mile to the southwest, in a sharp draw that he identified as Confusion Gulch, Honkala (1953) found no evidence of either the Meade Peak Member or the Grandeur Member of the Park City; however, he did find a massive bed of conglomerate 8 feet thick, overlain by the lower member of the Shedhorn Sandstone. About a mile farther west (lot 1251) the main phosphorite bed is nearly 5 feet thick and is conglomeratic in the basal few inches.

The unusual thickness of the phosphorite at the range crest between Sheep and Taylor Mountains and the peculiar sandstone-limestone parting in the bed are believed to be related in origin to the 8 feet of conglomerate at Confusion Gulch. These relations suggest that a small block was tilted during Meade Peak time, the southwest side having been uplifted above wave base, allowing erosion, and the northeast side depressed somewhat, allowing a greater thickness of sediment to accumulate. Tilting of this small block would appear to have taken place after about one-third of the main phosphorite bed had been deposited. The uplift was sufficient to cause erosion of 30 feet of Grandeur sediment and an unknown thickness of Quadrant strata, although no evidence of the formation of an island was found. The coarse fraction formed by the wave erosion was deposited nearby, probably mostly on the lee side of the uplift, and the finer clastics were carried farther away. Prevailing southwesterly winds would have favored deposition to the northeast. Part of the phosphorite below the parting in the area of abnormal thickness probably represents reworked material derived from the uplifted segment.

About a mile west of Sheep Mountain, Honkala (1953, p. 10) was unable to find float of phosphorite at the Meade Peak position while mapping, though normally, on weathering, phosphorite forms a readily identifiable float fragment. In the absence of outcrops, therefore, Honkala (1953) assumed that phosphorite and perhaps most of the Meade Peak Member are absent from that area. This absence may reflect another area of uplift, perhaps broader but not as high. If such an uplift occurred after partial deposition of the main phosphorite bed, much of the phosporite in the Sheep Mountain-Taylor Mountain area, which is commonly sandy, could be the result of reworking following such uplift.

The phosphorite of the Meade Peak Member in this area is typically coarse grained and light brownish gray. Much of the phosphate occurs as pellets, but oolites and organic fragments are more abundant. Quartz sand is a common diluent, and some beds are calcareous. The light color of this phosphorite indicates the low organic content of the rock, and the low organic content increases the value of the rock for treatment by the acid process.

Two beds of fairly high quality phosphorite (pl. 29) occur in the lower part of the Retort Member. However, these beds average only about 1 foot thick, and they are separated by 2 feet of poorly phosphatic mudstone. As a result, a minable thickness averages only about 20 percent P_2O_5. The phosphorite is finely pelletal and black and probably contains a considerable amount of organic matter.

Over wide areas in the Centennial Mountains, the Permian strata are overlain only by the Dinwoody Formation, which suggests that the Permian strata are possibly amenable to extensive mining by surface methods. However, the principal phosphate bed is as much as 150 feet below the base of the Dinwoody, and the intervening rocks include considerable amounts of chert and quartzitic sandstone that are resistant to erosion. As a result, most of the exposures of the phosphatic zones occur on the scarp face of the range or on the steep walls of creek valleys, and only a comparatively small part of the total area has a sufficiently thin overburden to favor surface mining. Some of the phosphate has already been mined.

The considerable relief of this range with respect to the lowlands to the south—in many places more than 2,000 feet—and the gentle dip of the strata result in a large part of the shaded area shown in figure 187 lying above entry level. Therefore, a large tonnage of rock above entry level might be mined by underground methods (table 6). Furthermore the simple structure of the area would favor a low-cost mining program and would also denote a low spoilage loss from crushing and dilution. The shaded area in figure 187 extends south to lat. 44° 30′. (See pl. 28*B*.)

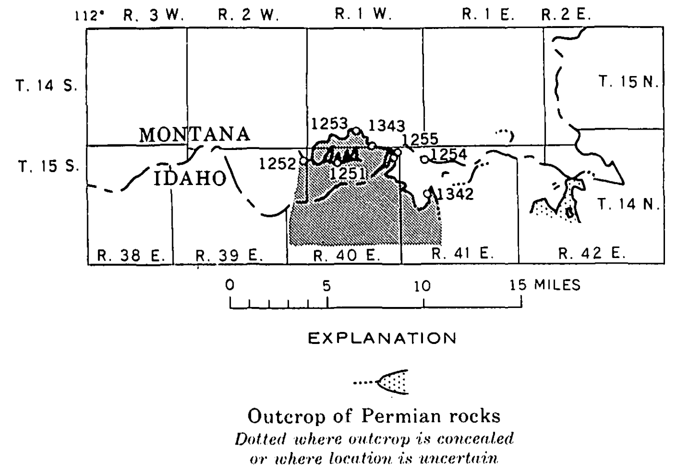


FIGURE 187.—Index to resource block in the Centennial Mountains district. Area for which resource calculations were made is shaded. Circle and number indicate sample locality and lot number.

Evaluation of the phosphate deposits near Reas Peak at the east end of the Centennial Mountains cannot be made owing to lack of data. According to the data gathered by Condit, Finch, and Pardee (1928, p. 206), the Retort Member does not contain minable phosphate. Good quality phosphorite is present in the Meade Peak Member, as judged from an abundance of high-quality float, but thus far no natural or artificial exposures have been observed, and information on thickness is lacking. Limited observations on the south side of Reas Peak indicate, however, that the phosphorite is probably less than 3 feet thick, and is perhaps considerably thinner. The topographic and structural relations here are comparable to those farther west and would indicate a considerable reserve of phosphate, were the bed thick enough to mine.

MADISON RANGE DISTRICT

General features

The Madison Range district is a large synclinal area in the Madison and Gallatin Ranges immediately northwest of Yellowstone National Park (pl. 28C). It is about 45 miles long and 15 miles wide and trends N. 30° W. The Gallatin River crosses the eastern part of the area, and tributaries of the river drain the larger part of the area. The western part of the area is drained by tributaries of the Madison River, which crosses the Madison Range below Hebgen Dam in a sharp canyon at the south edge of the area and flows northward in a broad valley on the west side of the range.

The area is accessible by U. S. Highway 191 along the Gallatin River, State Highway 287 along the Madison River, and by a few short side roads. However, much of the area is accessible only by trail. The area has no railroads, but spur lines to Alder to the west, Norris to the northwest, Gallatin Gateway to the north, and West Yellowstone to the south reach to within 15-35 miles by road, of its boundaries.

Much of this area is very rugged, and except for the numerous rock exposures and a few parks, it is well timbered. Outcrops of most rock units, even the softer layers, are fairly common, and the harder layers commonly make bold cliffs and ridges that are crossed by the streams in sharp canyons. Although the highest peaks reach altitudes of more than 11,000 feet, few outcrops of Permian strata occur above an altitude of 9,500 feet. Nearly all the area is above 6,000 feet in altitude, and local relief is generally 2,000-3,000 feet but locally exceeds 4,000 feet.

Geologic setting

The north end of the Madison Range district was mapped by Swanson (1951), and the east side, by W. B. Hall (written commun., 1957). Map information for the rest of the district was taken largely from Condit, Finch, and Pardee (1928). This district is well within the southwest Montana positive area, and the cover of Paleozoic and Mesozoic strata that unconformably overlies Precambrian crystalline rocks is only about 10,000 feet thick. The Paleozoic strata total about 4,000 feet thick, and the Mesozoic strata, perhaps 5,000-6,000 feet, though the upper half of the Mesozoic strata has been removed from most of the district. Volcanic rocks and associated sediments probably belonging to the Upper Cretaceous Livingston Group are preserved in a small area in the west-central part of the district and are overlain by nearly 2,000 feet of coarse red clastic sediments named by Peale (1896, p. 3) the Sphinx Conglomerate. All that remains of the Sphinx caps Sphinx Mountain. This conglomerate is comparable to the Beaverhead Formation of the Lima region and may once have been continuous with that unit.

Precambrian crystalline rocks underlie the rugged, alpine areas that form the north boundary and much of the west boundary of the district and are exposed in small areas at the south end of the district, near the northwest corner of Yellowstone Park. Intrusive rocks—mostly andesitic sills in the form of Christmas-tree laccoliths within the Cretaceous (Swanson, 1951) —occupy a considerable area north of Sphinx Mountain in Tps. 6 and 7 S., Rs. 1 and 2 E. The east side of the district is covered by the thick series of volcanic rocks that compose much of the Gallatin Range. Tertiary and younger continental deposits occupy the Madison Valley to the west; elsewhere in the district, however, these deposits are restricted to small areas. Mountain glaciation was active during the Pleistocene, chiefly in the areas of crystalline rocks.

TABLE 6.—*Phosphate resources in the Phosphoria Formation, Centennial Mountains district*

[Phosphate resources given in millions of short tons]

Resource block	Bed area [1]			Average member thickness (ft)	Average grade (percent P_2O_5)	Total tons P_2O_5 in block	Rock containing >31 percent P_2O_5					Rock containing >24 percent P_2O_5					Rock containing >18 percent P_2O_5				
	Above entry level	First 100 ft below entry	Total block				Thickness (ft)	Grade (percent P_2O_5)	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)
Retort Phosphatic Shale Member	145.5	12.3	768	6.0	16.0	60											4.0	20.0	55	5.0	250
Meade Peak Phosphatic Shale Member	115.1	10.7	579	13.7	19.4	100	3.5	32.9	35	3.5	150	5.5	28.0	55	5.0	250	8.5	23.2	80	8.0	400
Totals and averages	260.6	23.0	1,347	9.3	18.2	160	3.5	32.9	35	3.5	150	5.5	28.0	55	5.0	250	5.9	21.9	135	13.0	650

[1] Area in the plane of the bedding, in millions of square feet.

The structure of the Madison-Gallatin district is directly related to the movements of large blocks of the crystalline crust underlying the rather thin veneer of Paleozoic and younger strata. The west flank of the southern Madison Range (where some peaks are more than 11,000 feet in altitude), is composed of Precambrian rocks and is bounded on the east by deeply dipping Paleozoic rocks. The latter are commonly overturned, and a steep reverse fault, called the Madison fault by Condit, Finch, and Pardee (1928, p. 189), is present along much of the boundary; these features indicate that some compression from the west accompanied the uplift of the positive block on that side of the district. Farther north, in Tps. 5, 6, and 7 S., R. 1 E., similar relations were noted except that few of the Precambrian rocks are preserved between the upturned Paleozoic strata and the Madison Valley.

A normal fault of large displacement is represented for 45 miles along the west edge of the Madison Range by a prominent fault scarp that reflects movement within the last few hundred years (Swanson, 1938; Pardee, 1950, p. 370-373). Displacement on this fault may exceed 10,000 feet according to evidence obtained east of Ennis by Swanson (1951, and unpub. data); the fault has been a controlling factor in development of much of the topography af the area.

Another large block of crystalline rock cuts across the north end of the district. The block contains many peaks above 10,000 feet and has been uplifted on a large reverse fault that strikes about N. 60° W. and dips steeply to the north. This fault appears to be a continuation of the Gardiner fault mapped by Wilson (1934b) at the north edge of Yellowstone Park; however, because the fault is covered for more than 15 miles by volcanic rocks of the Gallatin Range, its correlation cannot be verified. The Paleozoic and younger strata on the south are turned up sharply against this fault block and are locally overturned. Uplift on this fault was later than that on the Madison fault near the west side of the range, as indicated by structures near the intersection of the two uplifted blocks (Swanson, 1951, p. 9). Detailed structures in Tps. 5 and 6 S., R. 1 E., near Jack Creek east of Ennis also indicate that renewed thrusting from the west followed uplift on the Gardiner fault and caused sharper overturning of the strata and other minor structures.

About 10 miles south of the Gardiner fault and nearly parallel to it is the sharply asymmetric Buck Creek anticline, which has its steep limb on the southwest. This fold indicates similar northeastward tilting of a large block of the crust but with much smaller uplift. The displacement in the crystalline basement rocks probably did not exceed 4,000 feet, and the upper Paleozoic and lower Mesozoic strata apparently were not ruptured but were drape folded.

Near the corner of Yellowstone Park, in Tps. 9, 10, and 11 S., Rs. 4 and 5 E., are a number of folds and associated faults that have not been fully mapped. From the map by Condit, Finch, and Pardee (1928, pl. 12) and the Montana geologic map (Ross and others, 1955), both based on reconnaissance, and from the information supplied by W. B. Hall (written commun., 1957), the structures trend north-northwestward and are asymmetric, mainly toward the east; however, the anticline at Sage Peak is asymmetric toward the south. Outcrops of Mesozoic and older rocks in this area are covered by volcanic rocks south and east of the Wyoming State line (Love and others, 1955).

Stratigraphy

The Carboniferous rocks underlying the Permian are about 2,000 feet thick in the Madison Range district and are dominantly dolomitic limestone. Even the Quadrant Formation at the top of the Carboniferous contains many interbeds of carbonate rock; the Quadrant here is about 200 feet thick, as compared with 400-500 feet thick in the Gravelly Range and more than 2,500 feet thick in the Lima district to the west. Above the Permian strata is 100-250 feet of typical Dinwoody shaly limestone and sandstone overlain in the southern part of the district by red beds as much as 450 feet thick (Condit and others, 1928). Both units are Triassic, and unconformities occur at both the top (Condit, 1918, fig. 14) and bottom of the sequence. The upper unconformity is more distinct and represents a longer time, but angular discordance is not conspicuous at either horizon. The rest of the Mesozoic section is composed of alternating marine and nonmarine rocks, and the upper part contains abundant volcanic material.

The Permian section in this district is composed mostly of Shedhorn Sandstone, although it includes tongues of most members of both the Phosphoria and the Park City Formations (Cressman and Swanson, 1964, pls. 21, 22). The sequence is almost everywhere less than 200 feet thick, and the dominance of hard rocks resistant to weathering results in abundant exposures. The phosphatic rocks, however, are soft here, as they are elsewhere, and most are covered.

In the Permian section below the Retort Member there is much intertonguing of lithologies. The contact between the Quadrant Formation and the Grandeur Member of the Park City Formation has been placed at the horizon dominated by sandstone below and by carbonate rock (chiefly dolomite) above, although carbonate beds are common in the Quadrant and sandstones are common in the Grandeur. The Grandeur attains a maximum thickness of nearly 50 feet. The Meade Peak Member of the Phosphoria Formation is not present, but its position is apparently represented at several localities by a thin sandstone bed that is abnormally rich in phosphate. Above this level the rocks include features characteristic of the Phosphoria, including chiefly phosphate grains in the sandstone beds (pellets, oolites, shell fragments, and spicule fillings) and both phosphate grains and spicules in the chert beds or fragments.

The interval between the Meade Peak horizon and the Retort Member averages nearly 50 feet thick. It contains interbedded sandstone of the lower member of the Shedhorn Sandstone, carbonate of the Franson Member of the Park City Formation, and beds of chert that are probably tongues of the Rex Member.

The Retort Member is 17 feet thick at Shell Canyon near the northwest corner of the district; in other parts of the district it is less than 10 feet thick, and locally is only 2 feet thick. It is characteristically composed of dark mudstone and phosphorite, although these are lighter colored eastward. At the base the member is gradational with the lower member of the Shedhorn Sandstone, and the basal bed is commonly conglomeratic phosphatic sandstone, apparently indicating a condition of overlap. The upper contact is also gradational, and the Retort intertongues laterally with the Tosi Chert Member. Most of the phosphate is in a single bed a few feet above the base of the Retort, and in parts of the district, especially in the northern part, this bed consists of high-grade phosphorite. By inclusion of the adjoining lower grade layers, a minable thickness of furnace-grade quality is obtainable. A thinner and less phosphatic zone generally occurs at the base, and at many localities a thin bed of phosphorite occurs several feet above the main bed, commonly in an upper tongue of Retort above the basal tongue of Tosi.

The Tosi Chert Member is well developed in this district, averaging nearly 50 feet thick on the west side of the district and perhaps 30 feet thick on the east side. The main chert unit is generally thin bedded and has many partings of mudstone in its lower part, where it intertongues with the Retort Member. Upward in the unit the chert layers are generally thicker, and the partings of mudstone, less conspicuous. The upper part of this main unit commonly contains thin beds of the upper member of the Shedhorn Sandstone, and although these two members intertongue to the top of the Permian section, sandstone is the dominant rock above the main chert zone. Locally, the two lithologies are so finely interbedded as to be unidentifiable as separate members.

Phosphate

In much of the Madison Range district, the phosphate rock is neither thick nor rich enough to warrant serious economic consideration (pl. 29). Nevertheless, a zone 3 feet or more thick of furnace-grade rock is present at two localities on the west side — at Shell Canyon and at Indian Creek (lots 1214, 1362) — and the zone at Indian Creek containing more than 18 percent P_2O_5 is nearly 6 feet thick. Phosphate rock containing more than 18 percent P_2O_5 and 3 feet or more thick is known at three localities on the west side of the Gallatin River near the center of the district (Buck Creek, Cinnamon Creek, and head of Sage Creek (Condit and others, 1928)) and at another locality near the south end of the district (at Pulpit Rock, lot 1479). The phosphate rock is less than 3 feet thick near the Gardiner fault on the north and in the Cabin Creek area on the south and presumably also in most of the

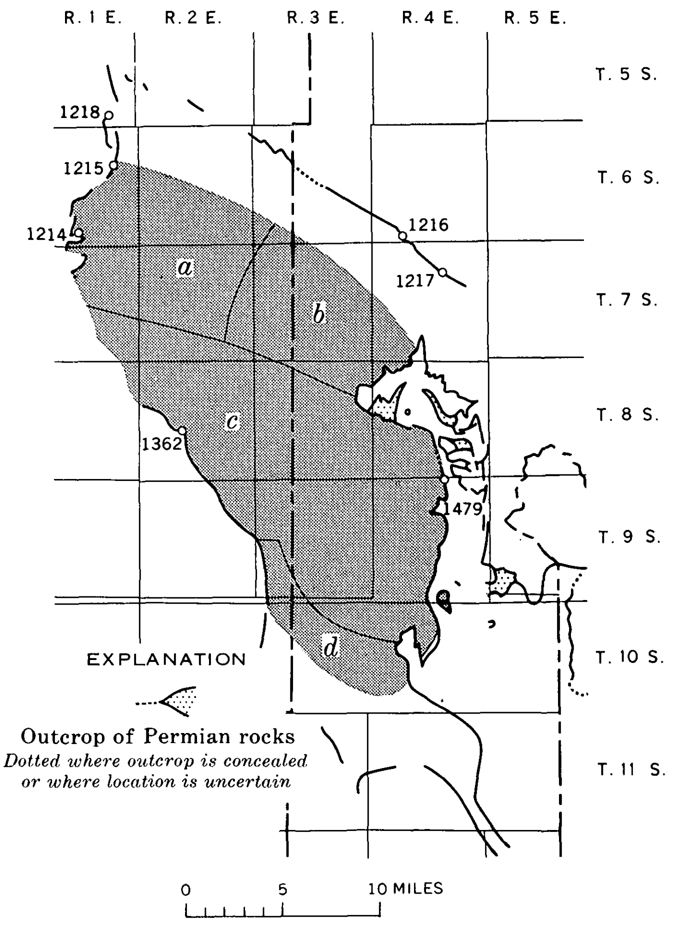


FIGURE 188.—Index to resource blocks in the Madison Range district. Area for which resource calculations were made is shaded. *a*, Cedar Creek–Jack Creek synclinal area; *b*, West Fork Gallatin River synclinal area; *c*, Indian Creek–Taylor Creek synclinal area; *d*, Beaver Creek–Cabin Creek synclinal area. Circle and number indicate sample locality and lot number.

TABLE 7.—*Phosphate resources in the Retort Phosphatic Shale Member of the Phosphoria Formation, Madison Range district*

[Phosphate resources are given in millions of short tons]

Resource block	Bed area [1]			Average member thickness (ft)	Average grade (percent P_2O_5)	Total tons P_2O_5 in block	Rock containing >24 percent P_2O_5					Rock containing >18 percent P_2O_5				
									Tonnage					Tonnage		
	Above entry level	First 100 ft below entry	Total block				Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Above entry level	In first 100 ft below entry level	Total (in block)
Cedar Creek-Jack Creek synclinal area	23.8	2.5	1,756	12.6	8.9	150	3.2	25.9	3.5	0.4	350	3.6	24.6	6.5	0.7	550
West Fork Gallatin River synclinal area	108.5	10.0	1,324	12.3	8.0	100	3.2	24.8	10.0	1.5	250	3.7	19.3	30.0	30.0	400
Indian Creek-Taylor Creek synclinal area	219.7	81.5	4,262	9.9	10.3	350	3.2	26.0	6.0	1.5	500	4.3	19.1	60.0	25.0	1,500
Beaver Creek-Cabin Creek synclinal area	34.6	6.5	597	4.2	14.4	30						3.4	19.7	10.0	2.0	150
Totals and averages	386.6	100.5	7,939	10.5	9.6	630	3.2	25.7	19.5	3.4	1,100	4.0	20.3	106.5	30.7	2,600

[1] Area in the plane of the bedding, in millions of square feet.

area east of the Gallatin River and Sage Creek (pl. 29). Thus, none of that rock is considered to be minable.

The district is rugged and will probably remain remote from transportation. Nevertheless, tonnages of rock of minimum thickness and grade for mining are estimated for a considerable part of the district. The tonnages are computed for four synclinal areas (fig. 188; table 7) : two north of the axis of the Buck Creek anticline (the Cedar Creek–Jack Creek area on the west, and the West Fork Gallatin River area on the east) ; the large central area south of that axis and north of the Sage Creek anticline (the Indian Creek–Taylor Creek area) ; and a small area south of that structure (the Beaver Creek–Cabin Creek area).

The Cedar Creek–Jack Creek area contains a very small tonnage of phosphate above entry level in the folded and faulted zone along the west flank of the Madison Range; the best rock occurs at the south, near Shell and Tolman Creeks. In much of the area the Permian strata are deeply buried beneath Christmas-tree laccoliths (Swanson, 1951) that have invaded Cretaceous strata in an area of nearly 100 square miles. (See geologic map of Montana, Ross and others, 1955, for area dominated by these intrusive bodies.) At the deepest levels of erosion, as in the canyon of Cedar Creek which drains much of the laccolith area, the lowest strata exposed are Cretaceous. The structures in the layers at these levels suggest that the base of the main zone of sills that form the laccolithic masses is not far below (perhaps within 500 to 1,000 ft). The Cambrian to Lower Cretaceous strata exposed along the west side of the range should extend beneath these intrusive bodies, broken only by the dikes that served as feeders. Though the phosphate beneath that area probably could not be mined economically under any conditions, it has been included in the total estimate.

The strata in the West Fork Gallatin River area — on the north flank of the Buck Creek anticline and east of the cross axis at the west boundary of R. 3 E. — dip gently north-northeastward and are broken by a few normal faults of fairly small displacement. Permian rocks containing minable quality phosphate crop out to the southeast near Buck Creek and the Gallatin River. Sample data recorded by Condit, Finch, and Pardee (1928) indicate the presence of about 3 feet of rock containing 18–24 percent P_2O_5. Most of the total phosphate estimated for this area is above the lowest Permian outcrops at the Gallatin River. For the estimation of tonnage above entry, however, data were not projected more than 1 mile from the exposures along the canyon walls that would provide entry.

The large syncline in the central part of the range, here identified as the Indian Creek–Taylor Creek area, is more than 20 miles long and averages perhaps 7 miles wide. Permian rocks crop out near Indian and Shedhorn Creeks on the southwest side of the area and near Buck, Cinnamon, and Sage Creeks and the Gallatin River on the northeast and east. Along the southwest side and along the south flank of the Buck Creek anticline, the Permian and associated strata dip rather steeply and may be overturned north of Indian Creek; but throughout the broad central part of the area, they probably dip very gently. The phosphate rock at Indian Creek on the west side of the range is both richer and thicker than that on the east near the Gallatin River; phosphate rock at the latter locality is only slightly more than 3 feet thick. Exposures near the Gallatin River and near Sage Creek mark the east boundary of the area.

Near the head of Sage Creek in the southern part of T. 10 S., R. 4 E., Condit, Finch, and Pardee, (1928, p. 193) found a little more than 2 feet of phosphate rock containing 30 percent P_2O_5. This was underlain by sandstone and overlain by chert. Although it would represent a grade of 21 percent P_2O_5 at a thickness of 3 feet by including barren wallrock, it would not be feasible to mine. At the upper end of the short canyon of Cabin Creek about 5 miles to the southwest of Sage Peak (sec. 14, T. 11 S., R. 3 E.; measured section described below), the phosphatic shale is nearly 4½ feet thick, including 1½ feet of phosphorite (at the top) underlain by thin beds interbedded with mudstone. Condit, Finch, and Pardee (1928, p. 194) reported 28.4 percent P_2O_5 in the top phosphorite, and they reported only 11 inches of gray calcareous shale below it; the entire zone probably contains about 15 percent P_2O_5. The southern part of the Beaver Creek–Cabin Creek synclinal area thus appears to contain less than 3 feet of rock having more than 18 percent P_2O_5, but the northern part probably contains 3 feet or more of phosphate rock of that quality. Tonnages were computed for that part of the area on the basis of this premise.

Cabin Creek

[Permian strata measured during reconnaissance along cliffs on northwest side of Cabin Creek about ¾ mile above mouth of canyon in NW¼ sec. 14, T. 11 S., R. 3 E., Gallatin County, Mont., by R. W. Swanson in August 1956. Strata are overturned on northeast (down-dropped) side of large reverse fault; they strike N. 20°–60° W. and dip about 40° SW.]

Bed	Thickness (ft)	Description
D–26	2.0+	Carbonate rock, hard, thick-bedded to massive, light-brownish-gray (*IDYR* 6/1).
D–25	9.5	Mudstone and carbonate rock; interbedded and thin-bedded medium-hard light-brownish-gray mudstone and silty carbonate rock. Irregular basal contact.
US–24	2.4	Sandstone, cherty, calcareous, hard, massive, very fine grained, pale-brown (10*YR* 5/2); chert light bluish gray weathered (5*B* 7/1); contains black tarry material like gilsonite.
T–23	4.1	Chert, sandy, hard; thin and wavy bedded to nodular, medium gray (*N* 5/0); sand chiefly as thin interbeds and matrix to nodules, calcareous, very fine grained, very pale brown (10*YR* 7/2).
US–22	68.0	Sandstone, hard; thick bedded to massive cliff former, fine to very fine grained, pale brown (2.5*Y* 6/2) ; contains thin lenses of sandy yellowish-gray (10*YR* 8/1) dolomite, and bottom 20 feet contains lenticular beds and irregular masses of yellowish-gray (10 *YR*7/1) chert. Irregular basal contact.
T–21	46.0	Chert, hard, thin- to thick-bedded, medium-dark-gray (*N* 4/0); upper 20 feet poorly bedded to massive with considerable fine sand as irregular lenses and some concretionary bodies; lower 25 feet thin-bedded chert characteristic of Tosi Member.
Rt–20	0.05	Phosphorite, medium-hard, finely to medium coarsely pelletal, dark-brownish-gray (10*YR* 3/1); locally a shaly parting at top, and basal contact irregular on nodules of bed below.

Cabin Creek—Continued

Bed	Thickness (ft)	Description
Rt–19	0.15	Phosphorite, medium-hard, finely to medium coarsely pelletal, brownish-gray (10*YR* 4/1); contains phosphorite nodules to 1 inch or more diameter.
Rt–18	1.3	Phosphorite, medium-hard, thin- to medium-bedded, medium coarsely pelletal, dark-brownish-gray (10*YR* 3/1); contains small nodules at 0.2 foot below top. Beds 18, 19, and 20 are probably equivalent to the 17-inch bed described by Condit and others (1928, p. 194) which contained 28.4 percent P_2O_5.
Rt–17	0.5	Dolomite, medium-hard; one bed; grayish brown (10*YR* 5/3).
Rt–16	0.35	Mudstone soft, fissile brownish-grey (10*YR* 4/1).
Rt–15	0.2	Phosphorite, argillaceous, medium-hard, very finely pelletal, dark-brownish-gray (10*YR* 3/1).
Rt–14	0.7	Mudstone, soft, moderately fissile, dark-brownish-gray (10*YR* 3/1); contains laminae of phosphate pellets. Gradational basal contact.
Rt–13	0.5	Mudstone, soft to medium-hard poorly bedded and not fissile like beds above and below, brownish gray (10*YR* 4/1).
Rt–12	0.2	Mudstone, soft, very fissile, brownish-gray (10*YR* 4/1); appears sheared. Irregular basal contact.
Rt–11	0.4	Phosphorite, sandy, hard, medium coarsely pelletal, grayish-brown (10*YR* 4/2); sand very fine; contains phosphate nodules up to 3 inches, phosphatic shell fragments, and sponge spicules. Gradational basal contact.
LS–10	5.5	Sandstone, hard, quartzitic, thick-bedded to massive, fine-grained, light-brownish-gray (10*YR* 6/1); contains columnar concretions of sandstone.
LS–9	1.0	Sandstone and carbonate rock; very closely spaced columnar concretions of sandstone in a carbonate matrix; hard fine-grained light-brownish-gray (10*YR* 6/1) sandstone in columns 1–4 inches in diameter and height of bed, some projecting into beds below and above; medium-hard shaly carbonate, weathering out as undercut in cliff. Top and bottom contacts irregular.
LS–8	3.3	Sandstone, hard, massive, fine-grained, light-brownish-gray (10*YR* 6/1). Basal contact gradational.
F–7	3.0	Carbonate rock, cherty, sandy, hard, massive, light-brownish-gray (10*YR* 6/1); upper part conglomeritic, chert irregularly distributed, basal contact irregular.
LS–6	0.8	Sandstone and carbonate rock; columnar concretions of sandstone with carbonate matrix like bed 9 above.
LS–5	2.6	Sandstone, carbonatic, hard, fine-grained, pale-brown (7.5*YR* 6/2); irregular basal contact.
PC–4	2.9	Chert and carbonate rock; nodular to poorly bedded chert with sandy carbonate rock matrix, hard.

Cabin Creek—Continued

Bed	Thickness (ft)	Description
PC–3	9.8	Carbonate rock and chert; nodular chert in hard irregularly and generally poorly bedded carbonate rock that is locally sandy.
PC–2	45.0	Carbonate rock, cherty, hard, thick-bedded to massive, very finely crystalline, yellowish-gray (2.5*Y* 7/2); chert in small nodules to lenticular layers, very pale orange (10*YR* 8/2).
Q?–1	--------	Sandstone and carbonate rock; interbedded 1- to 5-foot layers of hard medium-grained yellowish-gray (2.5*Y* 8/2) sandstone and hard light-gray (N8/0) carbonate rock. Believed to be part of Quadrant Formation.

YELLOWSTONE-GARDINER DISTRICT

General features

East of the southern part of the Madison-Gallatin district is an area equivalent to several townships that lies partly in the northwest corner of Yellowstone Park and partly north of that, in the southern part of Montana (pl. 28D). The area appears from the geologic setting to be an easterly extension of the Madison-Gallatin district. However, it is separated from the Madison-Gallatin district by 6 to more than 15 miles where the older rocks lie buried beneath volcanic rocks chiefly of Tertiary Age.

The southwestern part of the area is drained by the headwaters of the Gallatin River, but the rest of the area is drained by the Yellowstone River (which passes through the northeast side) and by some of its tributaries. Access to the area is gained from the north by U.S. Highway 89 or by a spur of the Northern Pacific Railroad, which extend up the Yellowstone River from Livingston to Gardiner at the north entrance to the park, and from the south by roads through the park. Much of the area is inaccessible by road — especially that within the park, which constitutes about two-thirds of the total area.

This district is mostly in the south end of the Gallatin Range and includes peaks, commonly deeply scarred by glaciers, that rise to a little more than 10,000 feet in altitude. The lowest point, at an altitude of 5,000 feet, is on the Yellowstone River near Cinnabar Mountain, at the north corner. Most of the valleys in the park are above 7,000 feet in altitude.

Geologic setting

The geology of the southern part of the district (south of lat. 45°) is shown on the northern part of the Gallatin sheet of the Yellowstone Park Folio (Hague and others, 1896) and also by the geologic map of Wyoming (Love and others, 1955). The Livingston quadrangle, north of the park was mapped by Iddings and Weed (1894). Wilson (1934b) mapped an area of about 40 square miles along the Gardiner fault at the north. That part of the area within Montana is shown on the geologic map of Montana (Ross and others, 1955).

The phosphatic strata have been sampled and the Permian section measured at two localities — Quadrant Mountain (Condit and others, 1928, p. 186–189) and Cinnabar Mountain (lot 1363). The formations in most of this district dip northeast at low to moderate angles, but they turn up abruptly at the northeast side against the Gardiner fault. The Permian strata are exposed locally along this fault and in the Quadrant Mountain area at the south. In the central part of the syncline, the strata exposed are chiefly Cretaceous; much of this area is overlain by younger volcanic rocks. Numerous andesitic sills and some dikes have been injected into the Mesozoic strata of the Gallatin Range north of Quadrant Mountain, but no large intrusive bodies are known. Precambrian crystalline rocks are exposed north and south of the district. On both the west and the southeast, the sedimentary formations are covered by volcanic rocks of the Yellowstone Park volcanic field, and farther north, by those of the Gallatin Range.

Stratigraphy

The stratigraphy in this district is much like that in the Madison Range district except that the formations are generally a little thinner. Quadrant Mountain, to the south, is the type locality for the Quadrant Formation (Weed, in Hague and others, 1896). The Teton Formation, which included the Permian and Triassic strata, was defined at the same time, but the name has since been abandoned. Redefinition of the formations at this locality has been made by Condit (1918), by Condit, Finch, and Pardee (1928), and by Scott (1935). The strata at Quadrant Mountain were not reexamined in connection with this study, but on the basis of regional correlation, it seems that the 46 feet of dolomitic limestone and gray sandstone placed by Condit, Finch, and Pardee (1928, p. 188) at the top of the Quadrant Formation may be equivalent to the Grandeur Member of the Park City Formation described to the west and south by Cressman and Swanson (1964, pl. 22). These strata would also seem to include the top six beds (Nos. 16–21) described by Scott (1935, p. 1017), which also total 46 feet thick.

If the above tentative correlation is correct, the Quadrant Formation is apparently 196 feet thick at its type locality — on the basis of the section described briefly by Scott (1935). At Cinnabar Mountain the Quadrant is 125–130 feet thick (Scott, 1935, p. 1017; Wilson, 1934a, p. 373) and is composed entirely of sandstone, in contrast to sandstone containing interbeds of limestone, as at Quadrant Mountain.

Condit, Finch, and Pardee (1928, p. 188) identified two phosphate zones in the Permian rocks at Quadrant Mountain; the zones are separated by 38 feet of quartzite to cherty sandstone. The lower zone, apparently a tongue of the Meade Peak Member of the Phosphoria Formation, is 3 feet 2 inches thick, is sandy, and contains 20.1 percent P_2O_5. It overlies 18 feet of "quartzite, gray, phosphatic in upper part" that these authors also assigned to the Phosphoria Formation. The fact that the upper part of the 18-foot quartzite unit is phosphatic and is overlain by sandy phosphorite suggests that the contact between the units is gradational. However, most of the quartzite is not phosphatic, so the quartzite is included in the Grandeur Member of the Park City Formation.

Neither the Rex Chert nor the Franson Member can be identified at this locality, although the "siliceous nodules and ropy masses" suggest an abundance of nonclastic silica in the sediments between the two phosphate zones. Therefore, the entire 38-foot interval between the phosphate zones is assigned to the lower member of the Shedhorn Sandstone. The upper phosphate zone is only 1 foot 2 inches thick and is considered a tongue of the Retort Member.

At Cinnabar Mountain (lot 1363) only 3 feet of the lower member of the Shedhorn Sandstone is present. The contact of that unit with the underlying Quadrant Sandstone is sharp but is no more than a bedding plane. Both sandstones contain grains of orthoclase that is altering to calcite, but the lower member of the Shedhorn Sandstone contains phosphate pellets and shell fragments, diagnostic of the Phosphoria interval. These pellets and fragments are absent below. At the Cinnabar Mountain locality the Retort Member is nearly 13 feet thick (pl. 29), two-thirds of which is phosphorite; at the base the Retort includes 1 foot of fairly coarse conglomerate containing chert and quartzite pebbles as much as 3 inches in diameter in a matrix of sandy phosphorite. All the phosphorite at this locality is composed chiefly of organic fragments, and much of it is sandy. Columnar concretions of ringed chert and of phosphorite are very common.

At both localities the Tosi Chert Member and the upper member of the Shedhorn Sandstone intertongue throughout an interval nearly 40 feet thick; the sandstone tongues are cherty and the chert tongues are sandy. This zone of mixed lithology occurs chiefly just above the Retort Member in the lower part of the Tosi interval and is marked by an abundance of columnar concretions. The upper part of the Tosi interval is dominantly chert but also contains interbeds of sandstone. Above the principal chert zone, the sandstone of the upper member of the Shedhorn is variably cherty; only the lower part of this member remains, as the unit is only 6½ feet thick at Cinnabar Mountain and a little more than 15 feet thick at Quadrant Mountain. At each locality the lower mudstone member of the Dinwoody Formation (present farther west in Montana) is absent and the brown-weathering limestone member of that formation overlies the Shedhorn Sandstone. Thus, an unconformity (represented by strata 100–200 feet thick farther west) apparently occurs at the Permian-Triassic contact in this area, though the strata are apparently otherwise conformable.

The Permian-Triassic contact as here defined is not the same as that designated by Wilson (1934a, p. 372–373) or by Newell and Kummel (1942, p. 990–991). It is based on a correlation of the brown-weathering shaly limestones that overlie the 6½ feet of cherty sandstone with the limestone member of the Dinwoody Formation that is present throughout much of southwest Montana, for this lithology is so typical of the Dinwoody and is so atypical of the Permian. The contact is not based on paleontologic evidence. Kummel (1954, pl. 37, column 10) apparently reached a similar conclusion. Part of this carbonate may contain Permian fossils; if so, that part of the section may be correlative with the Ervay Member of the Park City Formation (Sheldon, in McKelvey and others, 1959, p. 37), which is well developed in the Wind River Mountains region of Wyoming.

Above the Permian sandstone now called the upper member of the Shedhorn Sandstone at Cinnabar Mountain, Wilson (1934a) described 119 feet of chiefly brown-weathering gray limestone. At the top of this section he described 2 feet of "brown and black phosphatic sandstone" underlain by 40 feet of "thinly bedded light gray limestone," which is underlain, in turn, by another 2 feet of sandstone like that above. Field examination revealed that the two sandstone beds are the same unit and that 42 feet of the section are repeated by a near-bedding-plane fault that has several hundred feet of strike-slip displacement. This interval, then, should be considered 77 feet thick. It is overlain by brightly colored beds assigned to the Chugwater Formation.

The 2-foot-thick bed of sandstone described by Wilson (1934a) is dark gray to black, and the black part is commonly mottled with small brownish-gray spots. The sand is fine grained, and it effervesces very readily when tested with dilute hydrochloric acid. Thin-section examination reveals abundant generally poorly rounded quartz grains, numerous chert grains, some well-rounded dense to fairly coarsely crystalline carbonate grains, and numerous light- to dark-brown grains, some of which are phosphate and some of which are a fine-grained poorly anisotropic material tentatively called "argillites." Some grains of altered orthoclase are also present. Coarse-grained calcite constitutes the matrix, and black organic material irregularly distributed throughout the rock is fairly abundant locally.

Most of the phosphate grains are somewhat irregular in shape, and some that were once round have been broken and then partly rerounded, suggesting that the material has been reworked. Many of the phosphate grains are corroded by calcite. Because of the overall stratigraphic relations, it is believed that this bed includes grains derived from Permian and other rocks exposed elsewhere, presumably to the east or northeast, that were reworked by the Triassic sea; this bed should thus be considered part of the Dinwoody Formation. Also, similar grains of phosphate and other rock components having characteristics peculiar to the Phosphoria interval have been found by the author in Jurassic and Cretaceous strata in the Madison Range. Since the Permian and Triassic strata in this region are known to be unconformable, this interpretation seems logical.

Newell and Kummel (1942, p. 991), in the section they measured at this locality, placed "Limestone, dark gray to black, bituminous, oolitic, platy" — presumably the same bed as described above, though no thickness was given — at the top of the Phosphoria Formation. Apparently they followed the placement by Wilson (1934a), for they did not describe any underlying strata. The gypsiferous "gray to olive to yellowish" shales and sandstones above this bed, which these authors identified as Dinwoody, though Wilson included them in the Chugwater, appear to be correlative with the upper part of the Dinwoody Formation in the Madison Range. (See Condit and others, 1928, p. 192, for description of the more than 150 feet of these strata at Indian Creek, where such strata overlie typical Dinwoody limestone.) Kummel (1954, pl. 37) later placed these strata in the Red Peak Member of the Chugwater Formation and placed the underlying strata, which he showed as 60 feet of shale and sand capped by 3 feet of limestone, in the Dinwoody Formation.

At Quadrant Mountain, a more than 60-foot-thick unit above the 15 feet of sandstone, here called upper member of the Shedhorn Sandstone, was described by Condit, Finch, and Pardee (1928, p. 188) as "Limestone, thin bedded, gray, weathers sepia brown; grades up into yellowish sandy shaly beds." They also stated that "*Lingula* shells are plentiful in the limestone." This section appears to be very similar to that at Cinnabar Mountain and further justifies the assignment of the 75 feet of limestone and shale below the 2 feet of black sandstone at Cinnabar Mountain to the Dinwoody Formation, for Condit's studies of the Permian-Triassic boundary relations in northwest Wyoming and adjacent Montana were extensive.

Phosphate

At Cinnabar Mountain almost 9 feet of strata contains almost 20 percent P_2O_5, and the underlying 3 feet, including the 1-foot-thick bed of conglomerate, contains nearly 14 percent P_2O_5 (pl. 29). No beds contain as much as 24 percent P_2O_5. This rock, unlike most phosphorite in the western field, is made up primarily of organic remains, although numerous pellets and oolites are also present. This rock is probably of rather limited areal extent, but its lenticularity cannot be defined on the basis of one exposure. It could cover hundreds of acres of bed area at more than the 3-foot minimum thickness, and, too, it may be far more extensive. Careful examination of the exposures at the top and on the west side of Cinnabar Mountain would give some indication of the conditions to be anticipated.

Tonnage has not been estimated for the Cinnabar Mountain area, even though it may be large. The phosphorite is coarse textured and could probably be beneficiated easily to more than 24 percent P_2O_5. Proximity to rail transportation (0.3 mile from the southeast side of the mountain) makes this rock worth careful consideration.

The Meade Peak Member phosphorite at Quadrant Mountain is 3 feet 2 inches thick and contains 18.7 percent P_2O_5; Retort Member phosphorite is but 14 inches thick and contains 18.7 percent P_2O_5 (Condit and others, 1928, p. 188); no further information is available on the other parts of the district. As neither prospecting nor mining is permitted within any national park, tonnages within Yellowstone Park could not be estimated even if the phosphate there were of greater thickness or of better quality.

SUMMARY OF PHOSPHATE RESOURCES IN SOUTHWEST MONTANA

The Permian rocks in southwest Montana are estimated to contain more than 10 billion tons of P_2O_5 in the Meade Peak and Retort Phosphatic Shale Members (table 8), most of it in the Retort Member. The Retort Member contains about twice the tonnage of acid-grade and low-grade phosphate rock that is present in the Meade Peak Member, but the Meade Peak

TABLE 8.—*Summary of phosphate resources of the Phosphoria Formation, southwest Montana, by district*

[Phosphate resources given in millions of short tons]

District	Bed area [1] [2]			Average member thickness (ft)	Average grade (percent P_2O_5)	Total tons P_2O_5	Rock containing >31 percent P_2O_5					Rock containing >24 percent P_2O_5					Rock containing >18 percent P_2O_5				
	Above entry level	First 100 ft below entry	Total block				Thickness (ft)	Grade (percent P_2O_5)	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)	Thickness (ft)	Grade (percent P_2O_5)	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block
Retort Phosphatic Shale Member																					
Melrose	326	58	2,961	23.4	16.2	918	3.4	31.0	8	6	306	6.8	25.5	116	26	1,165	11.1	21.7	266	50	2,470
Dillon	257	67	5,088	46.0	10.4	1,995						3.3	27.6	25	7	455	10.5	19.8	174	53	4,045
Lima	93	28	1,580	76.5	9.0	950											5.6	21.0	48	14	700
Ruby Valley Syncline	355	84	13,417	45.9	8.2	4,250						3.2	29.0	3	1	150	5.5	19.9	142	32	5,450
Centennial Mountains	146	12	768	6.0	16.0	60											4.0	20.0	55	5	250
Madison Range	387	100	7,939	10.5	9.6	630						3.2	25.7	20	3	1,100	4.0	20.3	106	31	2,600
Total tonnages and average grades	1,564	349	31,753	35.5	9.3	8,803	3.4	31.0	8	6	306	3.8	26.1	164	37	2,870	6.4	20.3	791	185	15,515
Meade Peak Phosphatic Shale Member																					
Dillon	8	4	72	4.3	10.0	15						3.0	25.0	1	1	5	3.5	22.0	1	1	6
Lima	98	29	1,655	23.6	10.7	360						3.1	27.4	19	6	250	6.3	21.4	50	16	850
Ruby Valley Syncline	325	83	13,015	9.4	15.8	1,540						4.6	26.6	76	19	3,100	5.7	19.6	113	30	5,950
Centennial Mountains	115	11	579	13.7	19.4	100	3.5	32.9	35	4	150	5.5	28.0	55	5	250	8.5	23.2	80	8	400
Total tonnages and average grades	546	127	15,321	11.0	13.9	2,015	3.5	32.9	35	4	150	4.7	26.7	151	31	3,605	5.9	20.0	244	55	7,206
Grand total tonnages and average grades	2,110	476	47,074	27.6	9.9	10,818	3.4	31.6	43	10	456	4.1	26.4	315	68	6,475	6.2	20.2	1,035	240	22,721

[1] Tonnage and bed-area figures are rounded to nearest whole number given in district tables.
[2] Area in the plane of the bedding, in millions of square feet.

contains more than twice the tonnage of furnace-grade rock that is present in the Retort.

In that part of the southwest Montana synclinorium within this report area, the Melrose district contains the only acid-grade phosphate rock in the Retort Member (more than 300 million tons), the largest tonnage of furnace-grade rock (more than 1 billion tons), and nearly 2½ billion tons of low-grade rock, but it contains no tonnage of any grade in the Meade Peak Member. The Dillon district contains less than half a billion tons of furnace-grade phosphate rock but more than 4 billion tons of low-grade rock, nearly all of it in the Retort Member. In the Lima district, however, the Meade Peak Member contains a quarter of a billion tons of furnace-grade phosphate rock, and the Retort Member none; and the 1½ billion tons of low-grade rock is almost equally divided between the two members.

In the southwest Montana positive area, the Ruby Valley district contains more than 3 billion tons of furnace-grade rock in the Meade Peak Member but only 150 million tons of that grade in the Retort Member; and it contains the largest tonnage of low-grade phosphate rock in both the Meade Peak and Retort Members (nearly 6 and nearly 5½ billion tons respectively). In the Centennial Mountains district there are 150, 250, and 400 million tons, respectively, of acid-grade, furnace-grade, and low-grade phosphate rock in the Meade Peak Member but only 250 million tons of low-grade phosphate rock in the Retort Member. In the Madison Range district, no tonnages are recognized for the Meade Peak Member, but there are more than 1 billion tons of furnace-grade and more than 2½ billion tons of low-grade rock in the Retort Member. No tonnage was estimated for the Yellowstone-Gardiner district.

In the Meade Peak Member, the tonnages of all grades, as well as the total tonnage of P_2O_5, are much larger in the southwest Montana positive area than in the area of the synclinorium. In the Retort Member, the only high-grade rock occurs in the synclinorium, but the tonnages of furnace-grade and low-grade rock are comparable in the two areas.

As most phosphate mining is now restricted to rock that lies at rather shallow depth, it is noteworthy that the tonnages of such rock are very small compared to the total tonnage present. In general, the tonnage of phosphate rock above entry level in each district is about 5 percent of the total tonnage, and the tonnage within the first 100 feet below entry level is less than one quarter that above this level. Individual geologic blocks may differ considerably from this pattern.

MINING AND TREATMENT OF PHOSPHATE ROCK

Phosphate rock, like many other nonmetallic mineral commodities, is of low value in its raw state. The average value of western phosphate rock sold or used by producers during the 5-year period 1960–64 (Lewis, 1965, p. 836) was $6.48 per long ton; that sold or used in Idaho had a value of $5.40, and that from Montana, Wyoming, and Utah (including a small amount from Arkansas in 1963–64), a value of $8.17. The value of western rock sold or used in 1965 (U.S. Bureau Mines, 1967c, p. 528) was $5.81 per short ton, but data from individual states was not available. The difference in value between the rock from Idaho and that from the other states reflects chiefly the quality of rock mined and the mining method used. The value of the phosphorus contained in the rock sold or used in the western field during 1960–64 was 2.42¢ per pound; that from Idaho had a value of 2.15¢ and that from the rest of the western field 2.78¢ per pound.

Elemental phosphorus and phosphoric acid are the basic products obtained in the treatment of a large part of the phosphate rock mined, and these products are further treated to produce a great many finished products. The average values of the finished products are not available, but according to the data by Waggaman and Ruhlman (1960), the net estimated cost of producing elemental phosphorus by the electric furnace process in 1958 was 11.48¢ per pound, and the estimated cost in 1958 of manufacturing P_2O_5 as phosphoric acid by the sulfuric acid process was 8.48¢ per pound of contained phosphorus. Much of the net value of marketed phosphorus products, therefore, results from the treatment after mining.

Both the methods of mining and the methods of treatment are major considerations in the evaluation of the western phosphate deposits. The mining methods are governed largely by geologic factors that affected the deposits after deposition — particularly the structural and erosional history. The methods of treatment are governed more by chemical factors, which largely reflect the environment of deposition and the subsequent alteration (especially that during weathering).

MINING METHODS

The abundance of western phosphate and the comparatively low price at which high quality phosphate rock from Florida can be delivered to a large part of the United States, including the west coast, make it necessary that the mining of western phosphate rock be done by the cheapest methods that will still insure maintenance of suitable grade. A variety of mining methods are now employed in the western phosphate field, including both surface and underground techniques. (See Ruhlman, 1958; Service and Popoff, 1964, p. 18.) The markedly lower costs of surface mining make such methods particularly attractive, but the number of deposits amenable to surface-mining methods is relatively small. Geologic structure, topography, and character and thickness of overburden are the principal controlling factors to be considered in determining the feasibility of mining by surface means. The long cold winters characteristic of most of the western field generally limit most surface operations to a period of 6 months or less each year.

The type of mining operation most applicable to any one deposit should be determined by a thorough exploration program, by the products that can be produced, and by the types of equipment available, as well as by numerous other considerations. Summaries of such operations have been presented by H. B. Fowler (1949) and by King (1949) for surface mining of phosphate rock in Idaho and Wyoming, and by Service and Popoff (1964, p. 18) for the western phosphate field in general; these summaries indicate that mining needs to be carefully planned and controlled, and also that great flexibility in methods is available to the miner. Only generalized data on comparative costs of surface and underground methods of mining phosphate rock are available; in general, surface methods are estimated to be less than half as costly as underground methods and may be no more than one-fourth as costly. Under ideal conditions, surface mining is used in areas of gentle dip, where large tonnages can be mined from beneath a fairly shallow cover. The maximum stripping ratio is probably somewhere between 5 and 10 to 1, depending largely on the hardness of the overburden but also on facilities for waste disposal and for stockpiling, and on other factors related to an efficient stripping program. Surface mining may also be feasible in some areas of steeply dipping strata (Service and Popoff, 1964, p. 23), so long as the removal of low-grade rock on each side of the phosphatic interval can be kept within the economic limits of a workable stripping ratio and kept consistent with safe practice. Such an area probably occurs most commonly where the strata strike across small- to moderate-sized spurs of a sharply dissected mountain slope.

Surface mining methods are the most practical in both cost and flexibility of operation, and about 60 percent of western phosphate rock is now so mined (Ruhlman, 1958; Service and Popoff, 1964, p. 19). Nonetheless, much phosphate rock in the western field to date (1966) has been mined by underground methods. In the future, mining by underground methods will likely increase, because most of the reserves are not amenable to surface methods. Where the dips are low to moderate and the ground is strong enough not to cave in—during and after actual mining—some form of the room-and-pillar method will probably continue to be the most practical because of the lower costs involved and the greater flexibility of operation. (See Armstrong and McKay (1949) for description of phosphate mining in Montana by this method; see Wideman (1958) for methods employed in the Crawford Mountains, Utah; see Butner (1949, p. 12-18) for a discussion on mining methods; and see Service and Popoff (1964, p. 18-23) for a description of mining methods employed in the western field.) Steeper dips and special problems such as mining where the hanging wall or footwall is soft or the mining of structurally complex rock will probably necessitate more expensive practices. Norris (1944) and Russell (1949) described the underground mining methods employed at Conda, Idaho, where both top-slicing and sublevel-retreat stoping methods were used. (See also Mining World, Oct. 1942.) The extensive use of mine timber required by such methods, either for support provided by stulls and by square setting or for flooring to control dilution, is certain to increase the cost of mining.

Most underground mining in the western field has been restricted to rock above entry level, thereby eliminating the cost of hoisting the ore, as well as avoiding many water control, air circulation, and other problems. A large part of the phosphate mined in the Garrison-Avon district in Montana, however, has been recovered from below entry level. (See particularly Armstrong and McKay, 1949; Popoff and Service, 1965.)

Low-cost methods, utilizing new types of equipment which would accelerate or simplify procedures and increase recovery, need to be developed to reduce mining costs. The long-wall type pneumatic vibrating-blade planer developed by the U.S. Bureau of Mines (Howard, 1956; Service and Howard, 1959; Anderson, 1962) is an example of new equipment that may be significant in lowering costs and conserving resources.

BENEFICIATION

Until recent years most phosphate produced from the western field was utilized without beneficiation. The small margin between cutoff grade and minable grade in many deposits, however, requires special mining practiecs that may increase mining costs. To offset the cost increase and to insure a more uniform and satisfactory grade for treatment, several types of beneficiation are now used (Service and Popoff, 1964, p. 23); these techniques also make possible the use of subgrade ores, and thereby greatly increase the minable reserves of many deposits. The washing plant at Conda, Idaho (Caro, 1949), is a good example. Laboratory testing of beneficiation methods has also been conducted by the U.S. Bureau of Mines (Stickney and Wells, 1955). Recently, the San Francisco Chemical Co. (Dayton, 1958; Engineering and Mining Journal, 1960, no. 5, p. 85) installed flotation and calcining plants at Leefe, Wyo., to upgrade the lower quality phosphatic shales that underlie their main ("A") bed at the top of the Meade Peak Member. The mines are at Leefe and in the nearby Crawford Mountains of Utah. "The San Francisco-Stauffer Chemical Co. joint development of the Vernal [Utah] * * * deposit included plans for a beneficiation plant and a 35,000-kw electric furnace" (Ruhlman and Tucker, 1960, p. 840). The Montana Phosphate Products Co. treats the ore from its Douglas mine at a 300,000-ton-per-day flotation plant (Service and Peterson, 1967, p. 52). Beneficiation not only increases the P_2O_5 content, but makes practical the removal of some objectionable impurities, such as part of the iron, aluminum, and carbonaceous matter that are present. Some beneficiation is accomplished by calcining to remove carbonaceous matter before making phosphoric acid by the wet process, as at Anaconda, Mont. (Caro, 1949).

The type of the cement or bonding material in the rock is a major factor to the success of beneficiation practices. Some cementing material, such as carbonate, is softer than the apatite and is likely to break free on crushing and grinding. Such breakage is particularly apt to occur if the cement merely fills the voids between the grains; however, if it penetrates significantly into the grains, the very fine grinding required for separation into clean particles would probably cause an excessive loss of phosphate as fines during a washing process. Silicified phosphorite probably would not be as amenable to beneficiation, for the apatite particles would not be as apt to break free during grinding, and the greater hardness of the ore would cause greater wear to the grinding equipment, thus decreasing the life of the equipment. Phosphatic strata close to an intrusive have probably been metamorphosed and may not respond well to those beneficiation methods that would be successfully used on unmetamorphosed rock.

TREATMENT METHODS

The methods of treatment used now and probably in the future in the western phosphate field are major factors to be considered in appraising the value of the phosphate deposits. These methods are therefore summarized, with particular emphasis placed on the type of energy source required and on the character of phosphate rock that would be utilized in them. Reports by Waggaman and Bell (1950a, b), Bell and Waggaman (1950), and Waggaman and Ruhlman (1960) present additional data on the processing of phosphate rock. The principal methods of treatment in use in the western phosphate field are described by Service and Popoff (1964, p. 34).

Source of energy

A large source of energy is required to make almost any product from phosphate rock. Most wet-process methods of treatment use sulfuric acid because it is inexpensively produced in large scale (Waggaman and Bell, 1950a; Waggaman and Ruhlman, 1960), though other acids could presumably be used (Lewis and Tucker, 1962, p. 990), and the use of nitric acid might provide an additional source of plant food. The thermal process requires either electrical energy or coke for furnace operation. Availability of these sources of energy in fairly large supply in or near the western phosphate field has favored the growth of the western phosphate industry.

Most of the sulfuric acid is produced as a byproduct from smelters that treat metalliferous sulfide ores. Much of the potential sulfuric acid from this source is already being used to treat phosphate rock, but the wet method could be considerably expanded by producing more acid at those plants now operating below capacity. Acid is much more costly to ship than either raw phosphate rock or bagged phosphate fertilizer; hence, most processing by the wet method is done at or near the acid recovery plant. The Simplot Co. phosphate fertilizer plant at Pocatello, Idaho, produces sulfuric acid by use of modern equipment that utilizes elemental sulfur derived from sour gas (Ruhlman and Tucker, 1960, p. 840). The difference in shipping costs between dry sulfur and wet acid is primarily responsible for the conversion to such a high-quality energy source.

The blast furnace has not been used to treat western phosphate rock. Jacob (1953, p. 156) reported that the last blast furnace to operate in Tennessee closed down in 1938. The electric furnace, however, has become an integral part of the western phosphate industry in recent years, mainly because of the availability of low-cost hydroelectric power.

Processes

In the wet process, finely ground high-grade phosphate rock is treated with sulfuric acid to make either single or triple superphosphate or phosphoric acid. (See Waggaman and Bell, 1950a, p. 272; Waggaman and Ruhlman, 1960, p. 11.) Single superphosphate is made by adding about five parts of 65 percent H_2SO_4 (or 51.7° Baumé) to six parts of phosphate rock containing 31 percent P_2O_5. The two react quickly and form a monocalcium phosphate and hydrated calcium sulfate mixture that normally contains a little less than 20 percent available P_2O_5. Manufacture of phosphoric acid requires about 50 percent more sulfuric acid—about five parts acid to four parts phosphate rock—and yields phosphoric acid and hydrated calcium sulfate. (See p. 764 for discussion of synthetic gypsum.) After the calcium sulfate has been filtered off and the phosphoric acid has been concentrated to proper strength by evaporation, this acid is mixed with raw phosphate rock to produce triple superphosphate, which contains about 45 percent available P_2O_5, or it is combined with either ammonia or potash to produce other concentrated fertilizers. Both types of superphosphate must be aged or cured, about 1 month. During this aging the acid reaction becomes complete, and the excess moisture is lost.

The thermal reduction method (Waggaman and Bell, 1950a; Burt and Barber, 1952; Waggaman and Ruhlman, 1960, p. 4) utilizes either fuel coke or electric power to smelt a mixture of phosphate rock (phosphatic shale containing about 24 percent P_2O_5), carbon (coke, coke breeze), and a siliceous flux at about 1,600°C. The phosphate mineral is decomposed; the phosphorus is volatilized, condensed, and collected under water; and the calcium silicate slag and the ferrophosphorus are tapped separately from the furnace. The residual gases, which contain chiefly carbon monoxide from the coke reduction, are used in the kiln as part of the fuel needed to nodulize the charge before furnace treatment. Much of the fluorine remains in the slag, but some is volatilized and collected in the phosphorus condensing water as fluosilicic acid, where it is neutralized by the addition of soda ash.

Phosphate rock charge

Suitable raw material for treatment by either the wet process or the thermal reduction method must not only contain minimum amounts of P_2O_5 but must have certain other chemical characteristics as well. By present practice, acid-grade rock must have a minimum of 31 percent P_2O_5, a combined iron and aluminum oxide content of not more than 5 or 6 percent, a low content of carbonate minerals, and, preferably, a low content of organic matter. Larger amounts of iron and aluminum oxides are undesirable because of the resulting poor physical condition of the product (Bridger, 1949); carbonate minerals consume and thus waste acid; organic matter appears to prevent the complete solution of the phosphate mineral; and both alumina and organic matter interfere with filtration. All these materials, as well as the moisture, represent dead weight when raw rock is shipped to the treatment plant, and those materials not removed by treatment represent dead weight when the finished product is shipped. Silica, the dominant impurity in most western phosphate rock, remains mostly undissolved in the wet-process manufacture of phosphoric acid and is filtered off with the calcium sulfate.

In the furnace treatment of phosphate rock the variables that must be balanced for each operation—such as the furnace type (blast or electric) and design; the physical and chemical properties of the phosphate rock; the type, size, and proportion of the reducing carbon; and the power load, voltage, and electrode current—are so numerous that the character of phosphate rock required for successful furnace treatment is impossible to specify in advance (Burt and Barber, 1952; Stout, 1950). The results of experimental work by the TVA, as well as the available data from other plants, however, yield some helpful guides.

Furnace-grade rock should contain a minimum of about 24 percent P_2O_5 (somewhat variable depending upon the balance of other constituents in the rock), a SiO_2/CaO weight ratio of about 0.75 (0.7-0.8, Burt and Barber, 1952, p. 248; Waggaman and Bell, 1950b, stated that "It should not be less than 1:1.1 [0.9] and may be higher"), less than 7 percent Al_2O_3 and probably a smaller quantity of FE_2O_3. Combined Al_2O_3 and Fe_2O_3 should probably not exceed 7 percent. The iron in the charge (generally either ferric oxide compounds or iron sulfide) is reduced in the furnace and combines to form ferrophosphorus, which generally contains 20-26 percent phosphorus. This collects at the bottom of the furnace beneath the slag and is tapped separately from the slag. Most of the vanadium, chromium, and nickel and much of the manganese in the charge are recovered in the ferrophosphorus and many constitute 10-15 percent of it. According to Burt and Barber (1952), excessive iron in the charge not only ties up a large amount of phosphorus in a form difficult to recover, but, because the iron is reduced at relatively low temperatures, also causes increased electrical conductivity of the charge. The increased electrical conductivity in turn results in higher furnace-gas temperature and greater dust concentration in the gas and utilizes, without benefit, a significant part of the energy needed for furnace operation (about 1 percent for rock containing 3.3 percent Fe_2O_3).

The alumina present in the charge combines with the lime and silica and is almost completely recovered in the slag. A moderate content of alumina may be beneficial in reducing the viscosity of the slag by acting as a flux, thereby lowering the SiO_2/CaO weight ratio, and by promoting better separation of slag and ferrophosphorus. Melting temperature of the charge decreases as alumina content increases (up to about 11 percent alumina), but like the Fe_2O_3, a large content of Al_2O_3 results in higher furnace-gas temperatures and consequent precipitator operating difficulties.

A well-balanced electric furnace charge would utilize phosphate rock of about 24-25 percent P_2O_5. This content represents about 62-64 percent of apatite, which would contain 34-36 percent CaO and would require approximately 26 percent SiO_2 as flux (fig. 189) at a SiO_2/CaO ratio of 0.75 (about 32 percent SiO_2 at a ratio of 0.9). The remaining 10-12 percent of the charge would include chiefly Al_2O_3, Fe_2O_3, carbonaceous matter, and perhaps some carbonate. The lime or magnesia in carbonate requires an increase in silica flux, but this increase influx required by the lime would be nearly offset by the alumina present. A content of 27½ percent P_2O_5 and sufficient flux at a ratio of 0.75 to combine with the lime in the apatite (almost 30 percent SiO_2 or combined SiO_2 and Al_2O_3) would represent 100 percent of the furnace charge and would not allow for any iron or carbonate minerals or other impurities. A content of 26 percent P_2O_5 plus adequate flux would represent 100 percent of the charge if the ratio were as high as 0.9. Rock containing 30 percent P_2O_5 (76.8 percent apatite) would contain 43 percent CaO and would require 32 percent SiO_2 at a ratio of 0.75 (total, 109 percent); SiO_2 would thus dilute the ore, and the resultant charge would contain 27.5 percent P_2O_5 (70.5 percent apatite) and 29.5 percent SiO_2. Further adjustment would have to be made for other constituents.

These proportions are obtained by using the P_2O_5/CaO ratio of 0.7, determined from the composition of francolite reported by McConnell (1938) and by multiplying the percentage of P_2O_5 by 2.56 to determine total phosphate mineral content. The P_2O_5/CaO ratio is 0.685 in the francolite analysis by Ellestad (reported by Gruner and McConnell, 1937); this amount would require slightly more SiO_2 for flux. The phosphate-mineral factor would be 2.65 for the francolite analysis of Ellestad, and it would be 2.37 for fluorapatite; hence, the factor used (2.56) may be considered realistic, and it reflects a P_2O_5 content in the pure

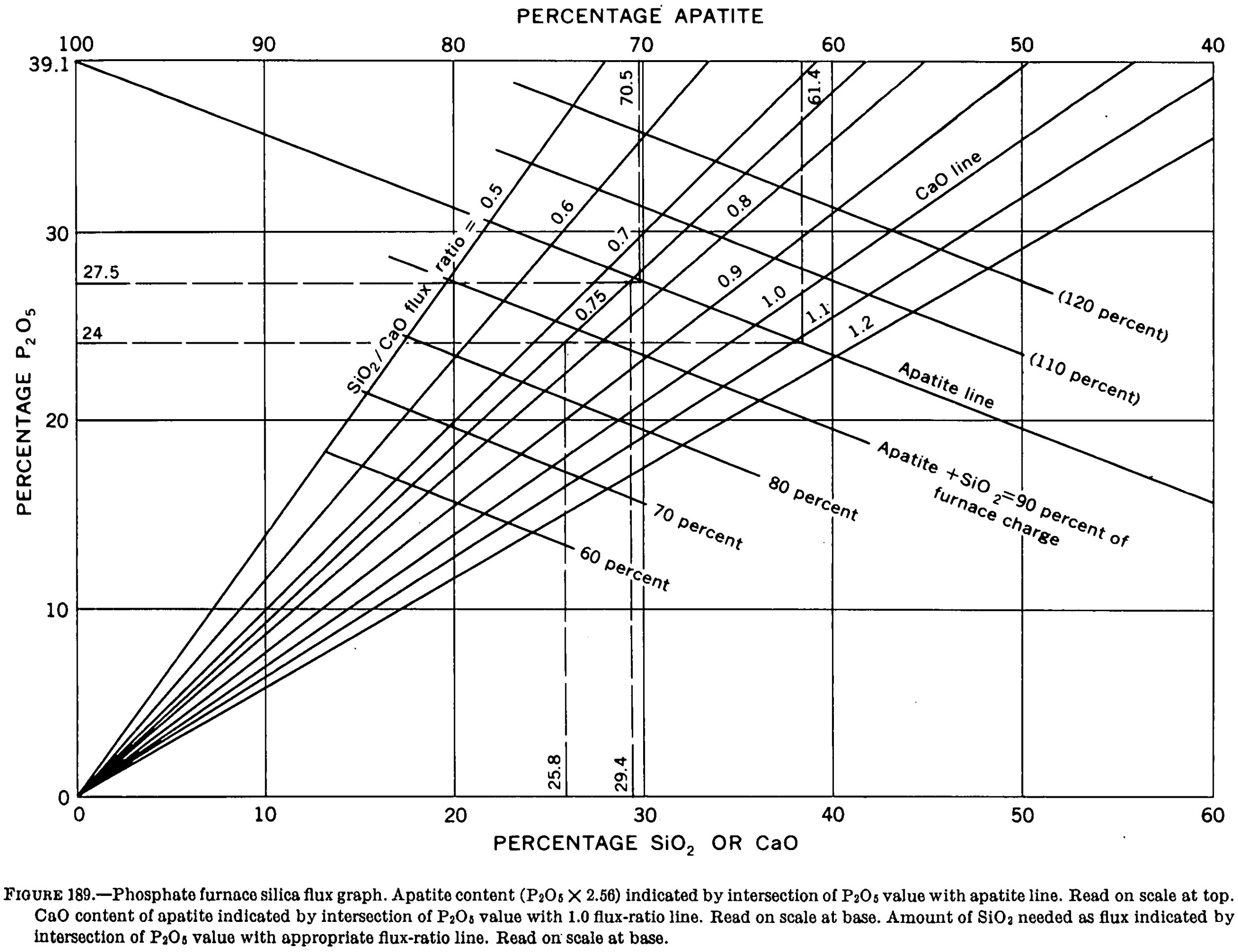


FIGURE 189.—Phosphate furnace silica flux graph. Apatite content ($P_2O_5 \times 2.56$) indicated by intersection of P_2O_5 value with apatite line. Read on scale at top. CaO content of apatite indicated by intersection of P_2O_5 value with 1.0 flux-ratio line. Read on scale at base. Amount of SiO_2 needed as flux indicated by intersection of P_2O_5 value with appropriate flux-ratio line. Read on scale at base.

mineral of 39.1 percent. An increase in the factor used would result in increased amount of silica required for flux, but the difference in silica requirements for factors 2.56 and 2.65 is only 2 percent. The effect of the organic matter (present in almost all western phosphate rock) on furnace treatment practice is not available, but combustion of volatile hydrocarbons would undoubtedly occur and would be favorable to nodulization in the kiln. Any carbon remaining would probably aid in the reduction of iron and phosphorus, although such benefits would probably be small.

Calcium metaphosphate (Brosheer, 1953; Waggaman and Bell, 1950b; Waggaman and Ruhlman, 1960) is a highly concentrated fertilizer that is soluble in neutral ammonium citrate solution but not in water; also it is efficient on acidic and neutral soils but not on alkaline soils. It is produced at a temperature of about 1,100°C by burning elemental phosphorus (to form phosphorus pentoxide) near the bottom of a furnace containing high-grade phosphate rock; the molten metaphosphate that results is collected as a slag and cooled rapidly to a glass to avoid crystallization. No metaphosphate is being made in the western field. The high content of available P_2O_5 (about 65 percent) results in economical shipping, but phosphate production requires a source of elemental phosphorus.

Most sedimentary phosphate contains about 1 part of fluorine for every 10 parts of P_2O_5. The fluorine fixes, or ties up, the phosphorus in a rather insoluble form, thus helping to preserve the phosphate deposits from weathering but also making the raw phosphate rock a poor fertilizer. Defluorination of phosphate rock makes a fertilizer product suitable for acid soils and also a nontoxic animal-feed supplement (Waggaman and Bell, 1950a, p. 274; Hall and Banning, 1958). The process involves either sintering the rock or fusing it with silica at a temperature of 1,400°C or higher while exposed to water vapor. Removal of the fluorine and the organic matter results in a small increase in the P_2O_5 content. In the process developed by the U.S. Bureau of Mines for treating western phosphate rock (Hall and Banning, 1958, p. 43), the vanadium—which can be toxic in an animal-food supplement—and various other impurities are first removed by desliming the coarsely ground (35-mesh) rock. The fluorine may be recovered from the gases in the form of synthetic cryolite that is of an acceptable grade.

Defluorinated stock-food supplement is made at Garrison, Montana, by Rocky Mountain Phosphates, Inc., by mixing phosphate rock, sulfuric acid, and phosphoric acid, and then heating the mixture in a rotary kiln (Crowley, 1962, p. 3; Service and Popoff, 1964, p. 46).

URANIUM RESOURCES

Uranium is generally present in marine phosphorite (McKelvey, 1956). Its occurrence in the Phosphoria Formation of the western phosphate field is summarized in a report by McKelvey and Carswell (1956). The geochemistry of uranium in phosphorite is treated in some detail in a report by Altschuler, Clarke, and Young (1958) and, with particular reference to the western phosphate field in a report by Sheldon (1959). Much of the discussion that follows is based on these reports.

In southwest Montana, uranium is present in almost all samples collected from the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation, but in all samples the amount of uranium present is very small, averaging roughly 1 part for each 3,000 parts of P_2O_5. Of the more than 600 samples from these shale members that were analyzed both chemically and radiometrically for uranium, less than 8 percent contain 0.01 percent or more uranium, and of the more than 300 other samples that were analyzed only radiometrically, all but a few were found to contain 0.004 percent or less equivalent uranium (eU). The data from these analyses were given by Cressman and Swanson (1964).

Despite the low uranium content of the phosphatic strata, the uranium represents a potential byproduct from the treatment of high-quality phosphorite, which is richest in uranium; uranium distribution is described for the principal phosphate zones. Certain inconsistencies in distribution of uranium in relation to that of phosphate are noted because of their significance in geologic history.

Altschuler, Clarke, and Young (1958) credited Strutt (1906, 1908) with pointing out that thorium is virtually absent in sedimentary apatite, and they presented analyses of Florida phosphorite that bear this out. Most radioactivity in the marine phosphorites is therefore attributable to uranium and its daughter products. In radioactive materials in which uranium is the source of the activity, equilibrium (generally indicated by identical radiometric and chemical uranium values and "attained*** when all the daughter products decay at the same rate that they are produced from the parent isotope" — (Rosholt, 1959), is established within a period of about 1 million years (fig. 190). Thereafter, U and eU values will be the same unless disturbed by subsequent events. In fact, 95 percent equilibrium, which falls well within the range of identical U and eU reports for most of the phosphatic shale samples, is attained in about 320,000 years, and 75 percent equilibrium is attained in half that time.

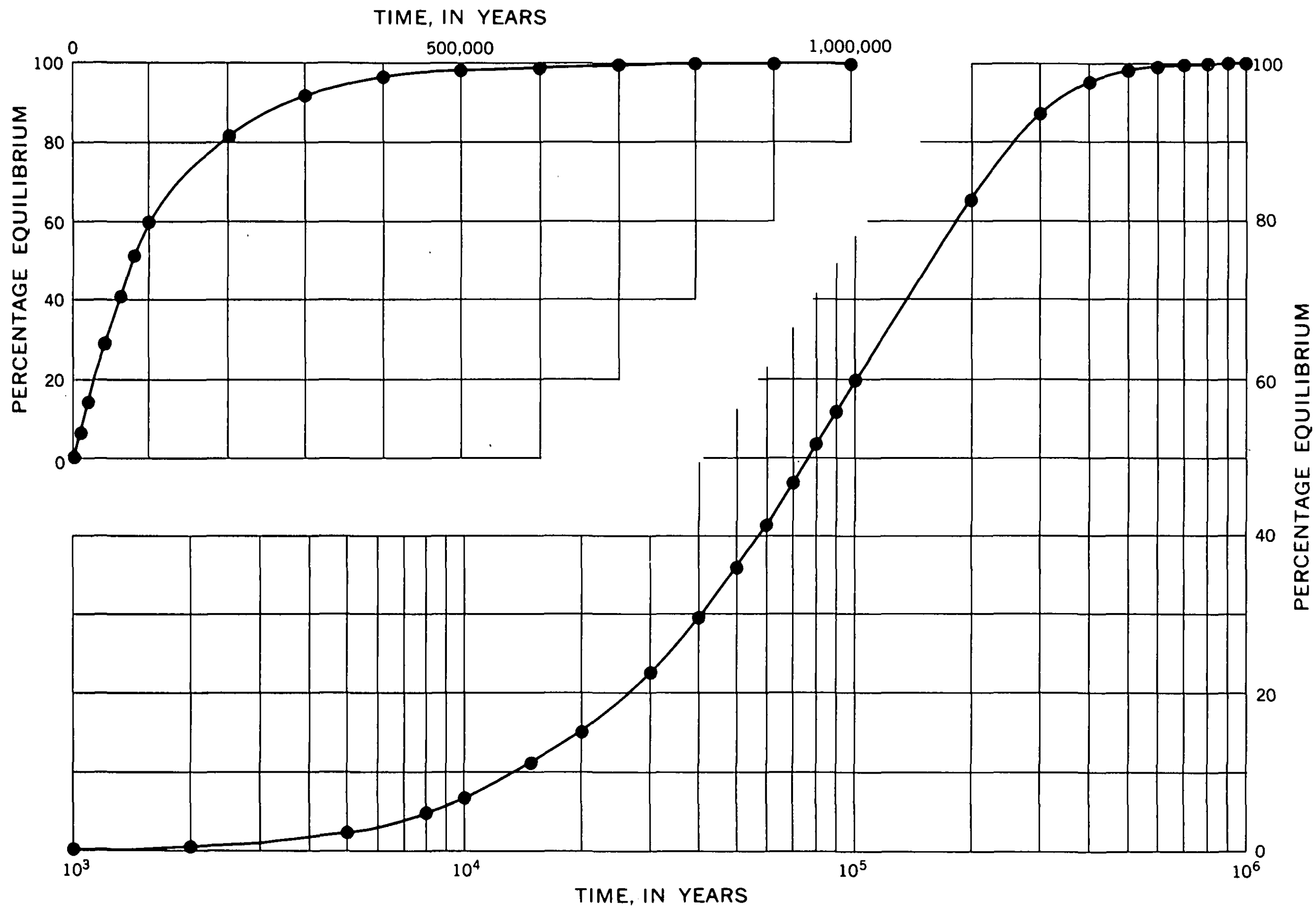


FIGURE 190.—Time-equilibrium curve for radioactive decay of uranium, on both simple cross-sectional (above) and semilogarithmic (below) base (after Kovarik, 1931).

From this equilibrium curve we find that only those geologic events involving redistribution of uranium or its daughter products in the last 160,000–320,000 years might be recognizable in the average Phosphoria sample by the differing values of U and eU. Thus, weathering occurring as late as middle Pleistocene, or much more recently than "as late as early Tertiary time" (Sheldon, 1959, p. 91), could have been effective on Phosphoria rocks without the evidence being recognizable by lack of equilibrium.

McKelvey and Carswell (1956) noted several evidences of the migration of uranium in phosphatic shales of the Phosphoria Formation, some migration occurring today and probably responsible for much of the small difference between eU and U contents that is characteristic of Phosphoria samples. But many of the surface and near-surface Phosphoria strata have been subject to weathering and to uranium migration since middle or possibly early Tertiary time. This earlier migration is recognizable today only by abnormally high or abnormally low uranium content; by the presence of secondary uranium minerals, which are sparse in these rocks; or, indirectly, by other attributes of the rocks and their physical environments that reflect a history which probably involved the redistribution of uranium. Radioactive equilibrium is to be expected, therefore, in Phosphoria rocks as a whole. Small differences in U and eU should be anticipated, however, in samples from those areas where leaching and reprecipitation are believed to be in progress.

URANIUM CONTENT OF PHOSPHORIA STRATA

Sheldon (1957) studied the physical chemistry of the environments of deposition of the Permian rocks of northwestern Wyoming, using primarily the work of Krumbein and Garrels (1952) on acidity and redox potential. He correlated the rock types and rock sequences with the transgressions and regressions of the sea and with the probable pH (above or below 7.8) and Eh (above or below zero) of the environment of sedimentation. Based on principles first defined by Kazakov (1937) and later applied with modifications by McKelvey (McKelvey, Swanson, and Sheldon, 1953) to the Phosphoria, Sheldon (1957) showed that these controls were operative in an area near the outer edge of the platform where phosphate, carbonate, and silica in solution were supplied by cold marine currents, rising from the geosyncline to the west, while clastic sediments were supplied from low-lying areas on the north and the northeast. Extending this concept further, Sheldon (1959) analyzed the distribution of uranium in the phosphatic shales of the Phosphoria Formation and showed for northwestern Wyoming that the phosphatic sediments deposited in an environment of low Eh are richer in uranium and that the pH of the environment could not be shown to affect the concentration of uranium.

In many respects the distribution of sediments in southwest Montana is comparable to that in northwest Wyoming, the major differences being that the geosyncline to the west cannot be so well defined and that clastic sediments were supplied from both the northeast and the northwest. The similarity in the characteristics of the phosphatic shales is marked, and the distribution and content of uranium is comparable in most respects. Thus, the scatter diagram showing U and eU of 627 phosphatic shale member samples from southwest Montana (fig. 191) is similar to that presented by Sheldon (1959, fig. 12) for Wyoming.

This similarity occurs despite the fact that the fluorimetric values determined prior to 1949 are consistently low. (See Cressman and Swanson, 1964, p. 280, written commun. from Z. S. Altschuler and F. S. Grimaldi, 1951.) This point about low values is significant because more than half (53 percent) of the samples represented in figure 191 were collected in

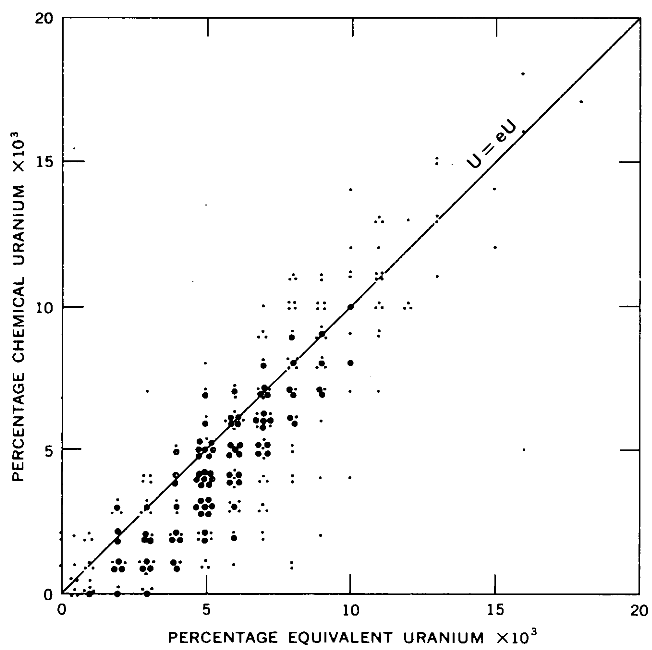


FIGURE 191.—Comparison of chemical and equivalent uranium contents of samples from the Meade Peak and Retort Phosphatic Shale Members of the Phospheria Formation, southwest Montana. Large dots represent five samples.

1947–48. The samples from these two years include 75 percent of all samples having differences between U and eU of 0.003 or more and 68 percent of all samples having a difference of 0.002. Ninety-seven percent of the samples having differences of 0.002 or more for these years have values for eU that are greater than the values for U. The discussion that follows is therefore based primarily on the eU content of the samples. A few samples for which gross differences between U and eU were reported probably involve analytical or clerical error.

A basic concept of the Phosphoria studies has been that uranium varies in almost direct proportion to the phosphate content (McKelvey, 1956, p. 479). It was discussed by Sheldon (1959), who cited evidence to support this conclusion. The concept is substantiated by the data shown on the scatter diagram in figure 192. This diagram of nearly 950 samples displays a fairly large spread of dots; nonetheless, a definite correlation exists between the eU and the P_2O_5 contents. A significant part of this spread, particularly that spread due to low eU values relative to the P_2O_5 content, is believed to have been caused by events that occurred long after deposition. These events are discussed separately in a later section.

Sheldon (1959) classified the Permian rocks of Wyoming according to the probable pH and Eh of their depositional environment as follows:

(a) Rocks that contain benthonic fossils (phosphatic brachiopods or gastropods) or are light colored (color value > 5); assumed to have been deposited in an oxidizing environment (Eh > 0).

(b) Dark-colored rocks (value < 4) that contain authigenic pyrite and lack attributes of classification a; deposited in a reducing environment (Eh < 0).

(c) Rocks that contain less than 20 percent carbonate; assumed to have been deposited in environment having lower pH than environment of group d.

(d) Rocks that contain more than 20 percent carbonate.

Color is used as a rough index of the quantity of organic matter present. Organic matter was deposited with the sediments; hence, its presence indicates a reducing environment. In marine water, a pH above 7.8 favors the deposition of carbonate and a pH between 7.0 and 7.8, of apatite. When carbonate and apatite coprecipitate, (pH above 7.8) the ratio is high in favor of carbonate (Krumbein and Garrels, 1952). When the pH is below 7.8, rich phosphorite can be

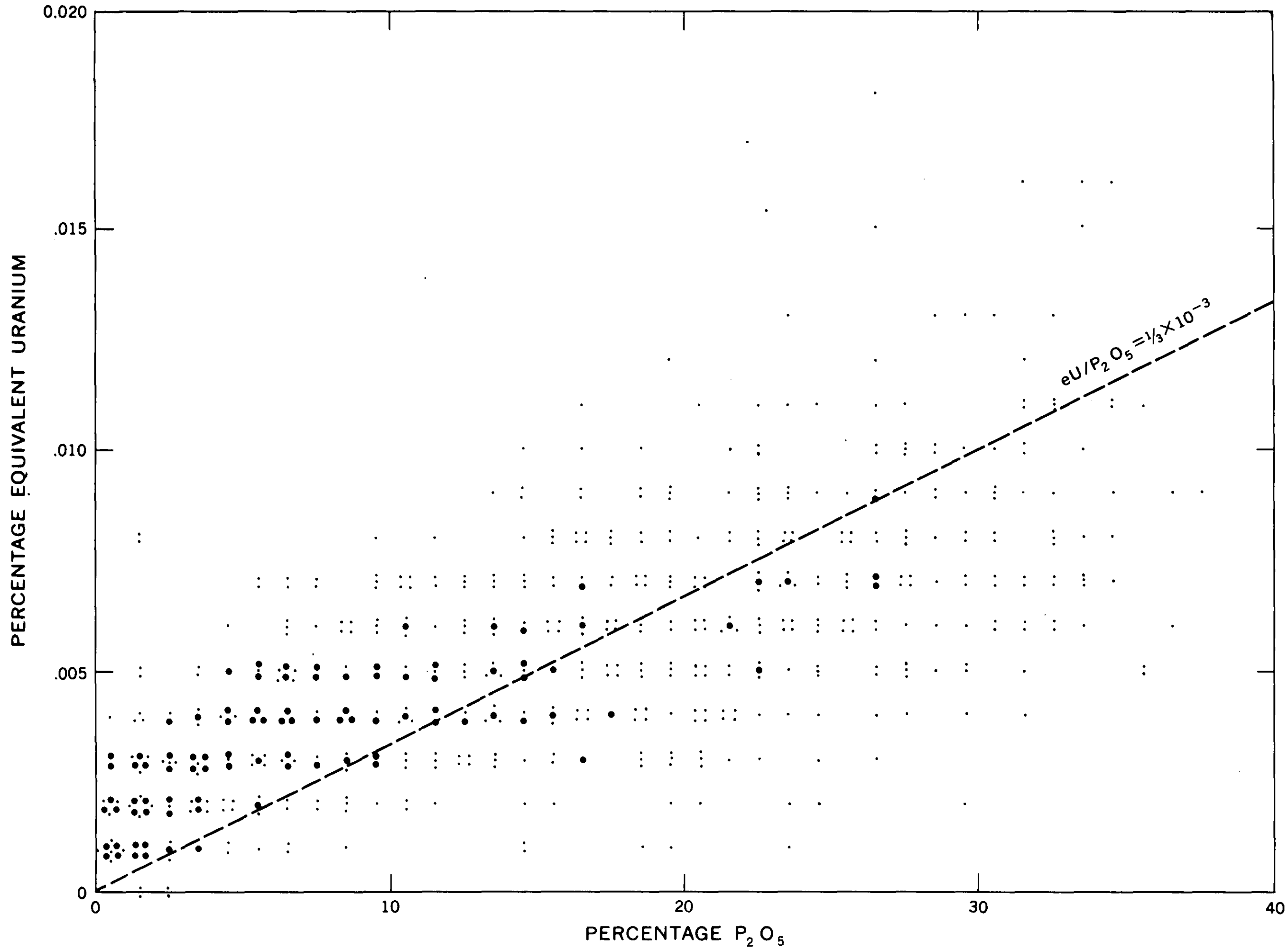


FIGURE 192.—Comparison of eU (equivalent uranium) and P_2O_5 contents of all samples from the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation, southwest Montana. Large dots represent five samples.

deposited because the sediment is not flooded with carbonate.

Sheldon's analysis of the relation between the uranium content and the depositional environment utilized data from 146 samples chosen because they represented single lithologies and included analyses for both U and eU which differed by no more than 0.002 percent (to avoid reporting analytical errors or those samples out of equilibrium). The samples were divided into four classes according to the Eh (above or below zero, as indicated by color) and pH (very roughly, above or below 7.8, as indicated by more or less than 20 percent carbonate mineral) of the depositional environment. For each class, the content of U for each sample was plotted against that of P_2O_5. Sheldon found that the higher values for U occur in rocks deposited in the reducing environment, but that the pH of the environment, as so determined, had little effect on the uranium content.

Similar plots for 436 samples from southwest Montana are shown in figure 193, except that eU is used instead of U, for the reasons just explained, and that rocks having color values of 4 or 5 are not excluded, for these data on many of the samples were not available when the diagram was prepared. Also, the original color of the rocks has been variably modified (generally made a lighter color) by weathering, which has been very extensive in some places, so there is reason to question the result that would have been achieved by systematic elimination of rocks having color values of 4 or 5, despite the possible desirability of such elimination. Direct comparison with Sheldon's figure 13, therefore, is not possible. The author believes, however, that the gross distributional pattern is little affected by these exceptions and that a general comparison is accordingly well justified. The samples of Eh $>$ 0, pH $>$ 7.8 (light-colored rocks containing

359-218 O—70——7

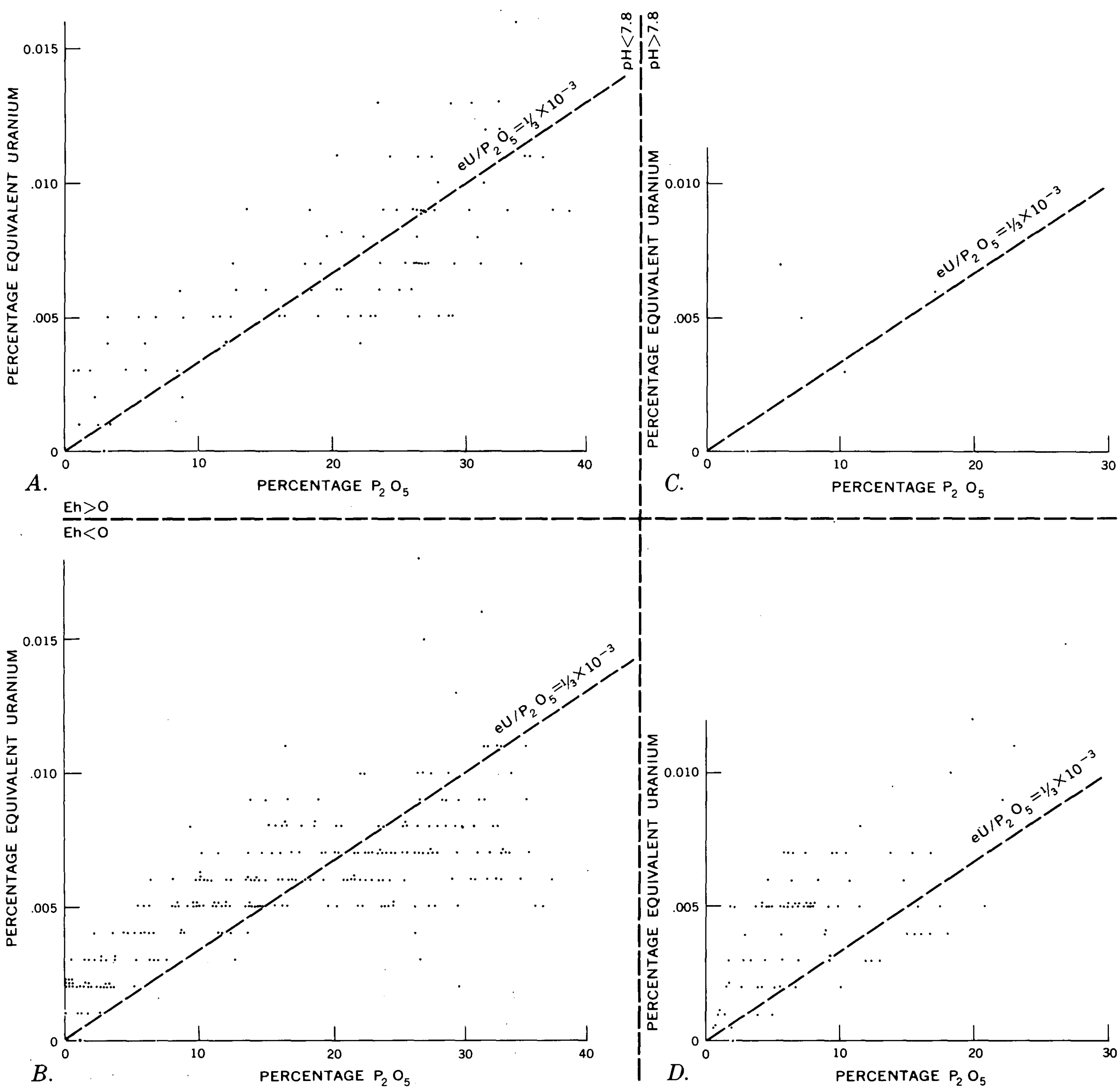


FIGURE 193.—Comparison of eU and P_2O_5 in phosphatic shale member samples from southwest Montana according to probable environments of deposition (Eh > or < 0, and pH > or < 7.8).

> 20 percent carbonate) were too few to be significant; the other three diagrams show distribution patterns that are similar. As in figure 192, these diagrams show an eU content greater than the ratio $eU/P_2O_5 = \frac{1}{3} \times 10^{-3}$ for samples containing less than 15–20 percent P_2O_5, and a content generally averaging less than that ratio for more phosphatic samples (the fitted lines of Sheldon's (1959) fig. 14 approximately coincide with this ratio). Figure 193*B* is particularly noteworthy in this respect and contrasts most strongly with Sheldon's figure 13*B*, where the richly phosphatic samples are also richest in uranium. The diagrams shown in figure 193 involve some bias due to the analytical bias for samples collected in 1947 and 1948. Also, about one-third of the phosphatic shale samples from Montana were analyzed for eU but not for U so are omitted from figure 193; most of the unanalyzed samples are low in both U and P_2O_5. This low content of U and P_2O_5 is particularly significant in the carbonatic samples (pH > 7.8) and largely accounts for the paucity of samples

in figure 193*C*. The fact that Montana is a sandier province than Wyoming is also significant.

The results shown in figure 193 do not fully correspond to Sheldon's, for the samples of Eh > 0 and $P_2O_5 > 20$ percent have a higher eU content than those of comparable phosphate content and Eh < 0. For the less phosphatic samples, figure 193*A* and *B* are fairly similar to Sheldon's, although figure 193*B* shows a greater proportion of the total number of samples tested. The two studies are not strictly comparable, however, because many of the samples of high phosphate and low uranium content from Montana are believed to reflect special geologic events (such as hydrothermal leaching) that were subsequent to the deposition of the sediments. These events are discussed later as parts of the district descriptions.

The phosphate in the Phosphoria Formation probably derived its uranium from a very dilute solution. (See Sheldon, 1959, p. 86, for a discussion of present ocean content, 1.1–3.3 $\times$ 10^{-6} g U per liter.) That the uranium was derived from dilute solution may be the reason that all the phosphorite in the Phosphoria Formation seems to be undersaturated in uranium. For example, the highest eU content reported from Phosphoria samples is 0.065 percent (Thompson, 1953), and few samples contain as much as one-third that amount. But G. W. Moore (1954) has shown that, in a 19-day period, a sample of phosphate rock from Cokeville, Wyo., absorbed 63 percent of the uranium from a solution of uranyl sulfate, thus increasing the uranium content of the rock from 0.028 to 0.11 percent. Altschuler, Clarke, and Young (1958) reported that a pebble of mineralogically similar apatite from Florida contained 0.25 percent U, or about 20 times more than the normal uranium content of unweathered pebbles.

In figures 192 and 193, it is readily apparent that the samples having low phosphate content are generally more radioactive, as compared with the ratio $eU/P_2O_5 = \frac{1}{3} \times 10^{-3}$, than the more phosphatic ones. This characteristic appears to be unrelated to the content of organic matter, which is reflected in the darkness (or lightness) of the samples (Eh < 0 or > 0 in fig. 180). On first impression, it seemed that those sediments having a lower phosphate content were able to extract a greater quantity of uranium (relative to phosphate content) from the dilute marine waters and thereby more closely approach saturation than the more phosphatic sediments. Sheldon (written commun., 1961) suggested, however, that some other component of the rock, such as thorium or potassium or uranium not in phosphate, may be responsible. But as previously stated (p. 748), thorium is very scarce in sedimentary apatite and therefore is probably not responsible for the fairly consistent high ratio of uranium to phosphate in the rocks low in phosphate content.

Data on potassium are available for only two samples from Montana. One sample contains too much phosphate and uranium for the radioactivity effect of potassium to be separately identified. The other sample, a mudstone containing 7.9 percent Al_2O_3 and 3.15 percent K_2O, contains more eU (0.004 percent) than would be expected from the 2.81 percent of P_2O_5 present. Much of the potassium in normal marine sediments occurs in the clay minerals. Some also occurs in glauconite, but the distribution of glauconite is not sufficiently widespread to account for very much of the potassium in the phosphatic shale members.

According to Lapp and Andrews (1948, p. 119), the radioactive isotope K^{40} constitutes 0.012 percent of natural potassium (about 1 atom in every 8,500). A 10-minute test of potassium carbonate in a lead-chamber Geiger counter indicated that this salt, which contains 65 percent K_2O, contains 0.029 percent eU, or 0.00046 percent eU for each percent K_2O. Thus, in a sample containing 4 percent K_2O, about 0.002 percent eU would be attributable to potassium and not to uranium. To test this against data for the Phosphoria (fig. 194), the eU contents were compared with the K_2O and P_2O_5 contents of Meade Peak Member samples from Coal Canyon, Wyo. (McKelvey, Smith, Hoppin, and Armstrong, 1952, lot 1201) and Braser Canyon, Utah (McKelvey, Smith, Kinney, and others, 1952, lot 1203). This comparison indicated fairly clearly that a small amount of radioactivity is due to potassium. Further comparison of the K_2O contents with the lithologies of the samples from Coal and Brazer Canyons, as noted in the above reports, showed that the mudstones contain an average of nearly 2½ percent K_2O_5, whereas the phosphorites, carbonate rocks, and cherts each contain about 1 percent K_2O, and that the argillaceous phosporites and carbonate rocks contain more K_2O than the nonargillaceous varieties.

SOLUTION AND REPRECIPITATION OF URANIUM

Some uranium is removed from phosphatic rocks by circulating ground water, as during the normal weathering cycle. Evidence of solution and transportation of uranium during weathering in the western phosphate field was noted by McKelvey and Carswell (1956), who cited the thin coatings of tyuyamunite on joints in the phosphate mines of the Crawford Mountains area, northern Utah, the abnormally high uranium content of mine waters, and the increase in uranium content with depth below an old erosion

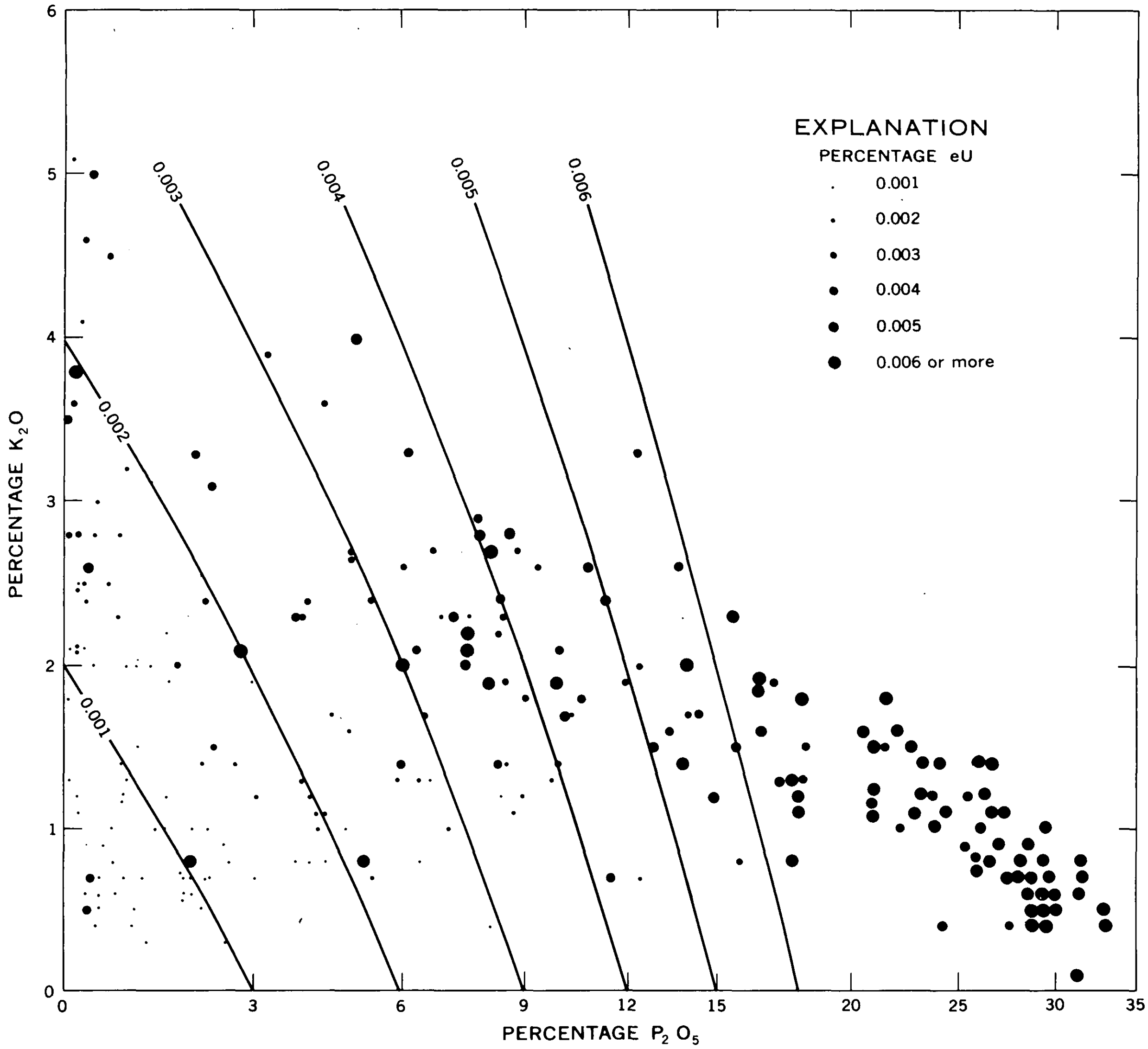


FIGURE 194.—Relation of eU to P_2O_5 and K_2O in the Meade Peak Phosphatic Shale Member of the Phosphoria Formation at Coal Canyon, Wyoming (lot 1201) and Brazer Canyon, Utah (lot 1203). Lines show radioactivity expected on basis of $eU/K_2O = \frac{1}{2} \times 10^{-3}$ and $eU/P_2O_5 = \frac{1}{3} \times 10^{-3}$.

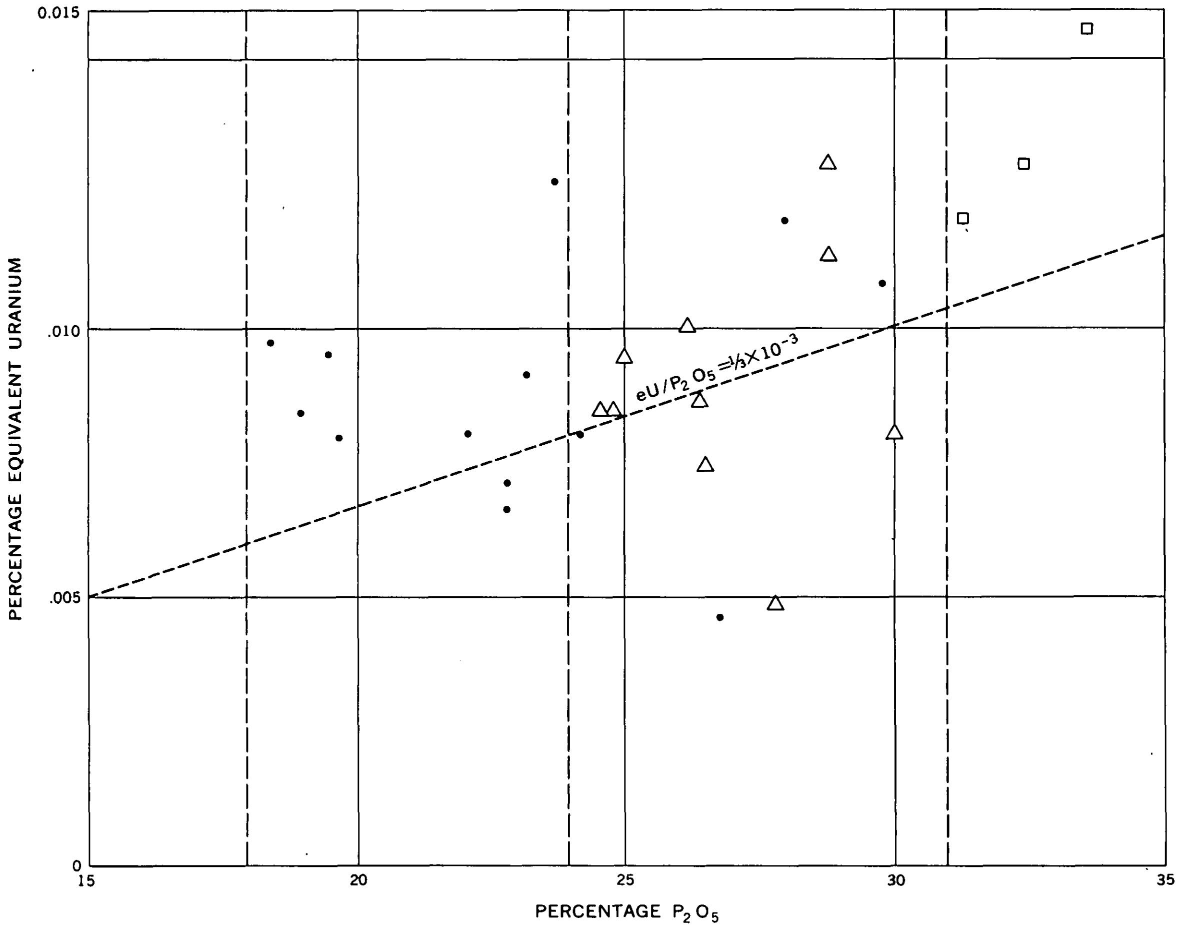
surface in a rugged part of westernmost Wyoming. Altschuler, Clarke, and Young (1958) presented conclusive evidence of both leaching and enrichment of uranium in Florida phosphorites that is much more extensive than that recognized anywhere in the western phosphate field.

Uranium is also believed to be leached by heated connate or ground waters moving toward or away from magma bodies during periods of igneous activity. (See discussion of Melrose district, p. 756). Uranium leached in this manner probably has moved out of the system (structure) under study, and the only indication of the leaching of uranium is the abnormally low uranium content of the phosphorite.

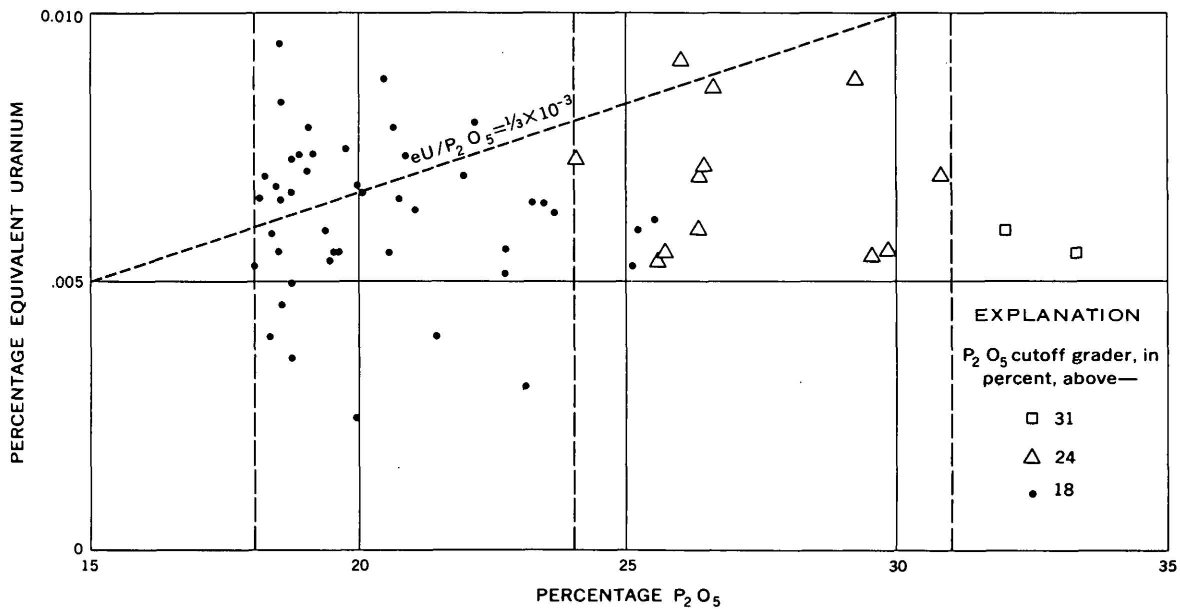
Movement of uranium by solution and reprecipitation from cold ground water appears to have been significant in parts of southwest Montana and to be responsible for many of the abnormally low and high uranium contents of the phosphate zones shown in figures 195 and 196. The intensity and depth of leaching and enrichment are functions of the erosional and weathering history of the area as well as of the texture and the structure of the rocks. Exact definition of individual factors is difficult, but, in general, uranium appears to have been leached from phosphorite near the outcrop and to have been redeposited in phosphorite at shallow to moderate depths.

URANIUM IN PHOSPHATE ZONES

In the phosphate zones of minable thickness and grade in the Meade Peak Member, the uranium content ranges from 0.005 to 0.015 percent (fig. 195A)



A. Meade Peak Member



B. Retort Member

FIGURE 195.—Equivalent uranium and P_2O_5 contents of phosphate zones in Meade Peak (*A*) and Retort (*B*) Phosphatic Shale Members of Phosphoria Formation, southwest Montana, that are 3.0 feet or more thick and that are above cutoff grade (18, 24, or 31 percent P_2O_5, shown by vertical dashed lines).

and averages about 0.009 percent. The difference between the average contents of eU and U is 0.002 or less for all zones, and the only zones having a difference of more than 0.0015 were sampled in 1947 or 1948, so all the zones are considered to be in approximate equilibrium. The average deviation of eU relative to the ratio $eU/P_2O_5 = 1/3 \times 10^{-3}$ for these zones is $+ 0.86 \times 10^{-3}$. The average eU content is thus nearly 0.001 percent higher than would be expected from that ratio.

In the comparable zones of the Retort Member, however, the uranium content ranges from 0.003 to 0.012 percent (fig. 195*B*) and averages about 0.006. The difference between average contents of eU and U is 0.0015 percent or more in 16 (or nearly one-third) of the zones; however, 14 of these zones were sampled in 1947 or 1948. Probably most of these Retort zones can be considered to be nearly in equilibrium. The average deviation of eU relative to the ratio $eU/P_2O_5 = 1/3 \times 10^{-3}$ for the zones in the Retort Member, however, is $- 0.98 \times 10^{-3}$, so the average eU content is nearly 0.001 percent lower than expected from the given ratio.

Meade Peak Member phosphate zones thus contain an average of nearly 0.002 percent more uranium (relative to P_2O_5) than the comparable zones of the Retort Member. This higher uranium content can probably be attributed partly to primary differences, although according to the environments of deposition, as defined by Sheldon (1959), the Retort Member represents the more reducing of the two environments, and should also be the richer in uranium. But the principal difference between the two members is believed to be due to secondary factors that have caused the redistribution of uranium long after the sediments were deposited. These factors are discussed in the district descriptions that follow.

MELROSE DISTRICT

The Melrose district contains the richest phosphate of the Retort Member of southwest Montana (fig. 196), but the uranium content of most samples from this district (fig. 196*A*) is surprisingly low, averaging only 0.0052 percent eU, with 20.1 percent average P_2O_5 content. As noted in the preceding description of the geology of the Melrose district (page 687), the area lies at the southwest corner of the Boulder batholith (pl. 27*A*), and the numerous smaller bodies of plutonic rocks exposed in this area probably represent cupolas related to the batholith. Three of the seven sample localities in this district (lots 1239, 1240, and 1404) are close to intrusive rocks. In fact, the Mount Humbug locality (lot 1404) is in a roof pendant in the main area of the batholith; and the other two localities, in the Maiden Rock mine, are not more than half a mile from a very small stock and are less than 2 miles from a somewhat larger stock to the south.

Samples from the three localities near intrusives (pl. 27*A*) are generally lower in uranium content than those from the other localities (fig. 197). Of the phosphate zones plotted in figure 196*A*, the six containing more than 24 percent P_2O_5 and less than 0.006 percent uranium represent these three localities.

The low uranium content of the phosphorite near intrusive rocks may well be directly related to the presence of those intrusive rocks, for the range in the Eh and pH of the depositional environment within this district was probably too narrow to have caused any significant variation in uranium content. To explain this relationship, the author suggests that the ground water in the Permian strata became heated as the intrusives invaded the area and that the uranium in these strata was more soluble in hot water than in cold water. As the intrusive magma approached, the water probably moved out of these strata carrying the dissolved uranium with it.

The igneous activity took place in Late Cretaceous and early Eocene time. Later, the area was deeply eroded. Middle Tertiary weathering was fairly extensive in the area, and some uranium possibly was leached at that time. Weathering is not as apparent at the three localities containing the least amounts of uranium as it is at the other localities in the district, however, for two of these three localities are some distance underground, and the third is in a high, rugged part of the district.

No information on uranium from a large part of the Melrose district is available; most sample localities are in a small area near Canyon Creek. In computation of the uranium resources for the district (table 9), therefore, a rather low uranium-content factor was applied to all geologic blocks.

DILLON DISTRICT

The Dillon district was also affected by extensive igneous activity, which was approximately synchronous with that farther north. Most of the phosphatic strata in the Dillon district are farther removed from intrusive igneous rocks than are those in the Melrose district; however, the band of strata in the northwestern part of the district is fairly close to the large pluton for a strike length of 15 miles. Myers (1952) reported that contact metamorphism has occurred near all the intrusives he mapped, particularly near the main pluton, which locally cuts out part of the Permian sequence; Carboniferous carbonates, where

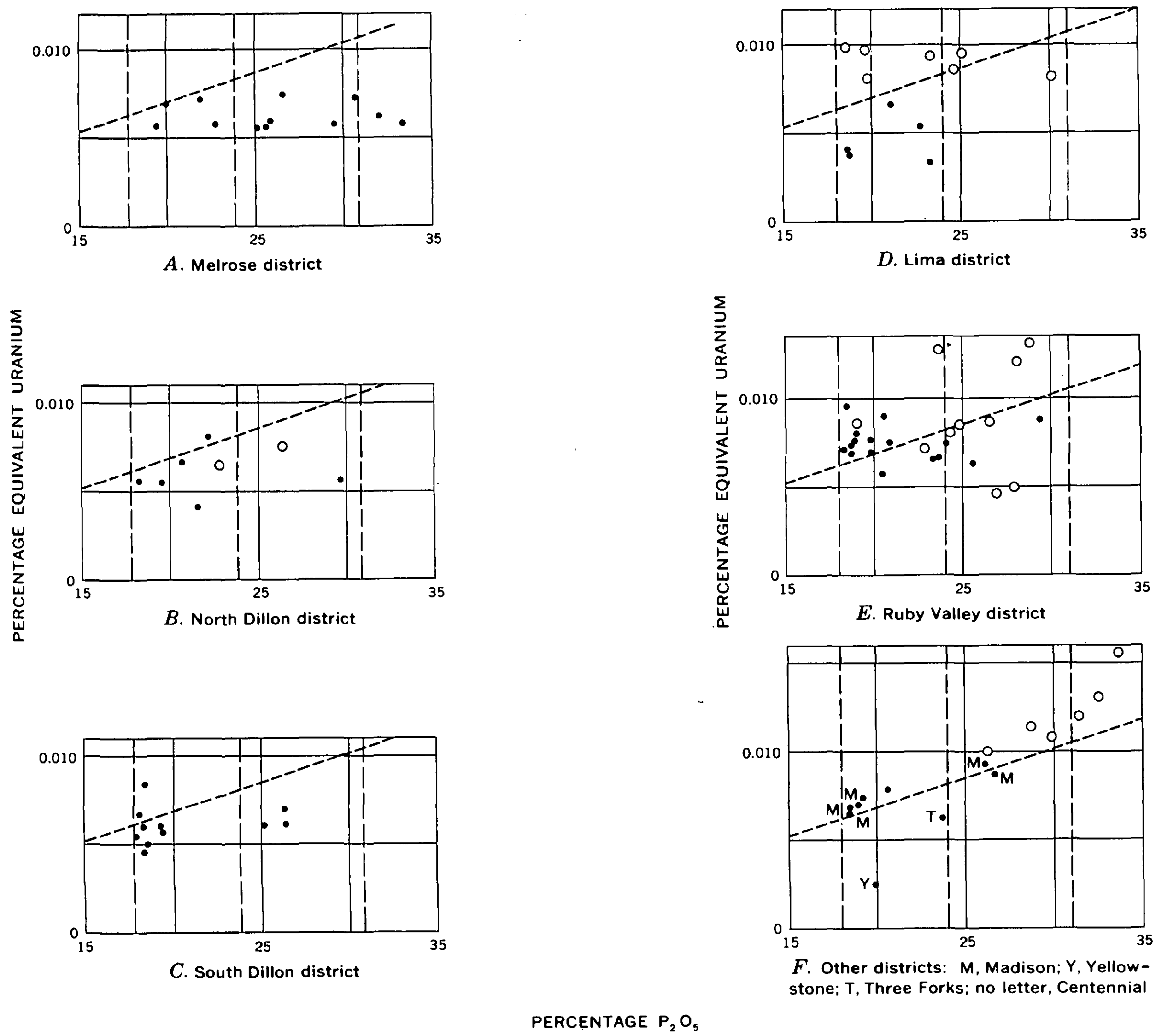


FIGURE 196.—Comparison, by districts, of equivalent uranium and P_2O_5 contents of phosphate zones in southwest Montana that are 3.0 feet or more thick and above cutoff grade (18, 24, or 31 percent P_2O_5), as shown by vertical dashed lines. Circles, Meade Peak Phosphatic Shale Member; dots, Retort Phosphatic Shale Member of Phosphoria Formation. Dashed line, $eU/P_2O_5 = 1/8 \times 10^{-3}$.

preserved, are commonly altered to marble. The Greenstone sample locality (lot 1250) is near the south end of the main-intrusive contact zone (pl. 27*B*) and about half a mile from the contact. The phosphate zones at this locality are fairly low in uranium, averaging less than 0.005 percent eU. Thermal waters may have leached part of the uranium from these zones in much the same way as was suggested in the discussion of the Melrose district.

The phosphate zones at Cave Creek (lot 1257) are 5 miles south of the Greenstone locality and are well removed from the main intrusive mass but are within 2 miles of small plugs. Small sills were noted in the Retort Member at the sample site, and leaching by thermal waters has probably occurred thus accounting for the low uranium content.

The sample sites near Big Hole Canyon are well removed from the McCarthy Mountain stock and do not appear to have been affected by it. Near the intrusive, however, the uranium has probably been leached.

Most of the Dillon district had a long and complex Tertiary history, as shown by the great diversity and wide distribution of the Tertiary rocks. Some periods of weathering have been prolonged, and some of the remaining Permian strata are believed to have undergone several weathering cycles. If so, the average uranium content of the various phosphate zones should be somewhat greater at depth than at the surface,

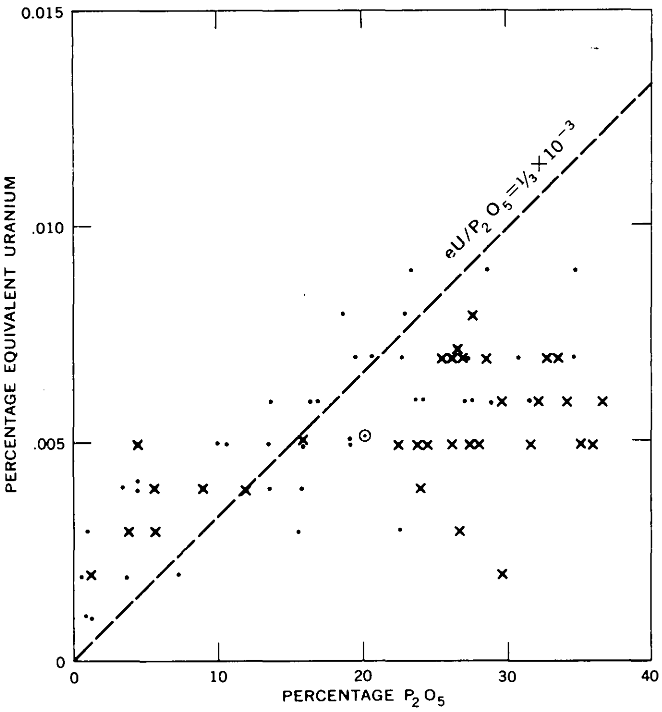


FIGURE 197.—Comparison of equivalent uranium and P_2O_5 contents of samples from the Melrose district. Dots represent samples from lots 1237, 1238, 1359, and 1366 (far from intrusive rocks); x, samples from lots 1239, 1240, and 1404 (close to intrusive rocks); and circled dot, average.

where the zones were sampled. In calculating the resources in table 10, however, no adjustment for an increase of uranium content with depth was made.

LIMA DISTRICT

Phosphate zones were identified at each of the four sample localities in the Lima district. The uranium content of the seven zones that represent the Meade Peak Member average 0.009 percent eU, whereas those of the five zones from the Retort average 0.0045 percent eU (fig. 196*D*). The low uranium content of the zones in the Retort Member and the comparatively high uranium content of those in the Meade Peak Member is not easily explained; they may reflect in part the long and rather complex erosional and weathering history of this area.

The character of the sediments in the two members differ in that the Retort is finer grained, thinner bedded, darker, and richer in organic matter. However, these differences in character of sediments are difficult to correlate with the uranium content. In fact, according to the principles defined by Sheldon (1959), the darker Retort sediments should contain more uranium. In the southern part of the Dillon district and in the northern part of the Lima district, Condit (1919) found the Retort Member to be fairly rich in oil; but the uranium contents of the phosphate zones in both areas are low. The two components may have an inverse relationship, or there may be none, for graphic comparison of the two showed no distinct pattern of distribution. The resources given in table 11 reflect the higher uranium content of the Meade Peak Member and the lower content of the Retort Member.

RUBY VALLEY DISTRICT

The uranium contents of many of the phosphate zones in this district, with noteworthy exceptions, are near the ratio $eU/P_2O_5 = 1/3 \times 10^{-3}$ (fig. 196*E*). At Landon Ridge (lot 1361) the uranium content of the Meade Peak Member is only about half that normally expected from this ratio. This locality is near the south end of the Gravelly Range and is only a few hundred feet higher than the broad flat Centennial Valley. Tertiary and younger continental deposits of varied type and age unconformably overlie the bedrock of the Gravelly Range and reflect several periods of erosion and weathering. In the low rolling hills near the Centennial Valley, probably only a minor amount of erosion has occurred since the mid-Tertiary

TABLE 9.—*Uranium in phosphate resources in the Retort Phosphatic Shale Member of the Phosphoria Formation, Melrose district*

[Grade, in percent uranium; tonnage, in short tons]

Geologic block	Uranium in phosphate rock containing >31 percent P_2O_5				Uranium in phosphate rock containing >24 percent P_2O_5				Uranium in phosphate rock containing >18 percent P_2O_5			
	Grade	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)	Grade	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)	Grade	Tonnage: Above entry level	Tonnage: In first 100 ft below entry level	Tonnage: Total (in block)
Highland Mountains area	0.005	65	20	300	0.005	150	70	800	0.005	250	90	1,000
Mount Fleecer-Jerry Creek area	.005	200	150	8,000	.005	400	250	15,000	.005	550	350	20,000
Wise River-Johnson Creek area	.005	100	100	7,500	.005	250	200	15,000	.005	350	350	20,000
Quartz Hill syncline					.003	300	45	3,500	.003	600	100	7,000
Big Hole syncline					.003	900	150	7,000	.003	1,500	250	15,000
Cattle Gulch syncline					.006	1,500	250	6,000	.006	3,500	700	20,000
Trusty Lake syncline					.006	2,000	200	7,000	.006	6,500	600	25,000
Trapper Creek syncline									.004	800	80	10,000
Total tonnages and average grades	0.005	365	270	15,800	0.005	5,500	1,165	54,300	0.005	14,050	2,520	118,000

TABLE 10.—*Uranium in phosphate resources in the Phosphoria Formation, Dillon district*

[Grade, in percent uranium; tonnage, in short tons]

Geologic block	Uranium in phosphate rock containing >24 percent P_2O_5				Uranium in phosphate rock containing >18 percent P_2O_5			
		Tonnage				Tonnage		
	Grade	Above entry level	In first 100 ft below entry level	Total (in block)	Grade	Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member								
Northern Dillon district								
Browns Lake–Lost Creek area					0.004	1,500	85	8,500
Last Creek–Willow Creek syncline					.004	250	75	10,000
Birch Creek–Cave Gulch area	0.005	150	45	4,500	.004	350	150	15,000
Frying Pan complex area	.005	150	50	7,500	.004	400	150	20,000
McCarthy Mountain area					.006	200	200	30,000
The Hogback syncline					.007	550	300	5,000
Beaverhead Rock–Hogback area					.006	600	650	60,000
Total tonnages and average grades	0.005	300	95	12,000	0.005	3,850	1,610	148,500
Southern Dillon district								
Peterson Flat syncline	0.006	200	70	4,500	0.005	300	100	7,500
Cedar Creek syncline	.006	350	100	2,000	.005	550	150	3,000
Henneberry Ridge syncline					.005	250	150	6,000
Dalys Spur area					.005	60	20	3,000
Small Horn Canyon area	.004	450	100	4,500	.004	2,500	650	30,000
Total tonnages and average grades	0.005	1,000	270	11,000	0.004	3,660	1,070	49,500
Grand total tonnages and average grades, Retort Member	0.005	1,300	365	23,000	0.005	7,510	2,680	198,000
Meade Peak Phosphatic Shale Member								
The Hogback syncline	0.007	70	35	350	0.007	75	40	400
Grand total tonnages and average grades, Dillon district, both members	0.005	1,370	400	23,350	0.005	7,585	2,720	198,400

TABLE 11.—*Uranium in phosphate resources in the Phosphoria Formation, Lima district*

[Grade, in percent uranium; tonnages, in short tons]

Geologic block	Uranium in phosphate rock containing >24 percent P_2O_5				Uranium in phosphate rock containing >18 percent P_2O_5			
		Tonnage				Tonnage		
	Grade	Above entry level	In first 100 ft below entry level	Total (in block)	Grade	Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member								
Little Water Canyon area					0.005	1,000	200	10,000
Little Sheep Creek area					.006	500	350	8,500
East end of Lima district					.006	850	250	20,000
Total tonnages and average grade					.006	2,350	800	38,500
Meade Peak Phosphatic Shale Member								
Little Water Canyon area	0.008	850	150	8,000	0.007	1,500	250	15,000
Little Sheep Creek area	.009	550	350	8,000	.009	1,000	750	20,000
East end of Lima district	.010	300	100	6,000	.010	1,500	450	45,000
Total tonnages and average grades	0.009	1,700	600	22,000	0.009	4,000	1,450	80,000
Grand total tonnages and average grades	0.009	1,700	600	22,000	0.008	6,350	2,250	118,500

weathering cycles; therefore, much of the rock leached of uranium at that time is probably still present, thus accounting for the low uranium content of the samples from lot 1361. Furthermore, the phosphate would have been enriched during that weathering by the removal of carbonate and organic matter; so, even if no uranium had been leached, the U/P_2O_5 ratio would be slightly lower than that of fresh rock.

At Hogback Mountain (lot 1299) the uranium content of the phosphorite in the Meade Peak Member is abnormally high—as much as 0.013 percent in rock containing 28.8 percent P_2O_5. The samples were taken from the east, or scarp, slope of the mountain about 500 feet below the peak. Although the distance of a middle Tertiary weathering surface above this peak cannot be accurately judged, it was probably not many hundreds of feet. The Quadrant Sandstone now forms the top of the mountain and probably projected above the general level as a ridge during Tertiary time. Thus, the surface underlain by the slightly less resistant Permian strata may have originally been no more than a few hundred feet higher than the present outcrop. These rocks, therefore, could very well have been in the zone of enrichment that underlay the leached zone which was developed during that weathering. Furthermore, of the 88 samples of the phosphatic shale members in southwest Montana in which uranium is higher than eU (9 percent of all samples), 29 samples, or 33 percent, came from the Hogback Mountain locality (sampled in 1949). This in turn, suggests that some disequilibrium related to that enrichment still persists. The disequilibrium may be partly the result of enrichment during the last 250,000 years due to the further migration of uranium that was first concentrated at a higher horizon during the Tertiary.

In calculation of the uranium resources of the Ruby Valley district, as given in table 12, some allowance was made for these areas of leaching and enrichment. However, the grades noted are probably a little low for much of the areas they represent.

TABLE 12.—*Uranium in phosphate resources in the Phosphoria Formation, Ruby Valley district*

[Grade, in percent uranium; tonnage, in short tons]

Geologic block	Uranium in phosphate rock containing > 24 percent P_2O_5				Uranium in phosphate rock containing > 18 percent P_2O_5			
	Grade	Tonnage			Grade	Tonnage		
		Above entry level	In first 100 ft below entry level	Total (in block)		Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member								
West limb								
Wadhams-Sawtooth area					0.006	1,000	350	70,000
Sawtooth-Hogback area					.006	3,000	450	50,000
Sliderock-Green Horn area					.007	750	150	20,000
Total tonnages and average grade					0.006	4,750	950	140,000
East limb								
Warm Springs Creek area	0.008	250	30	7,000	0.006	2,500	400	20,000
Black Butte area	.008			5,000	.007	550	250	100,000
West Fork Madison River area					.007	1,000	450	100,000
Total tonnages and average grades	0.008	250	30	12,000	0.007	4,050	1,100	220,000
Grand total tonnages and average grades, Retort Member	0.008	250	30	12,000	0.006	8,800	2,050	360,000
Meade Peak Phosphatic Shale Member								
West limb								
Wadhams-Sawtooth area					0.008	900	300	70,000
Sawtooth-Hogback area	0.008	2,000	300	40,000	.008	2,500	400	55,000
Sliderock-Green Horn area	.008	150	25	8,000	.007	200	50	10,000
Total tonnages and average grades	0.008	2,150	325	48,000	0.008	3,600	750	135,000
East limb								
Warm Springs Creek area					0.007	800	150	9,000
Black Butte area	0.006	2,000	300	70,000	.004	1,500	300	65,000
West Fork Madison River area	.005	1,000	500	80,000	.004	850	400	95,000
Total tonnages and average grades	0.005	3,000	800	150,000	0.004	3,150	850	169,000
Grand total tonnages and average grades, Meade Peak Member	0.006	5,150	1,125	198,000	0.005	6,750	1,600	304,000
Grand total tonnages and average grades, both members	0.006	5,400	1,155	210,000	0.006	15,550	3,650	664,000

CENTENNIAL MOUNTAINS DISTRICT

Both shale members in the Centennial Mountains contain beds of high-quality phosphorite, but the beds in the Retort Member are separated by low-grade shale that causes the phosphate zone to be of rather low quality. The eU content of the phosphate zones of both members is a little higher than the ratio $eU/P_2O_5 = 1/3 \times 10^{-3}$, and is significantly higher for some zones in the Meade Peak Member. This higher content is particularly noteworthy, for the Meade Peak phosphorite is abnormally light colored, thick bedded, and coarse textured (including abundant oolites and tooth and shell fragments), and it contains a considerable amount of sand and carbonate. All these features are typical of the platform environment of deposition. The high content of uranium is surprising, therefore, because in Wyoming Sheldon (1959) found that the rocks that reflect an oxidizing environment of sedimentation are low in uranium.

The high uranium content of the Meade Peak Member in the Centennial Mountains is very possibly a result of the post-Laramide tectonic and weathering history of the area. The range is now a tilted fault block characterized by gentle southward dip, almost no folding, and a generally simple and open-textured fault pattern. However, at the close of the Laramide orogeny the area apparently lay on the gentle west flank and near the south end of a large anticlinal structure that occupied the area between the Madison Range syncline on the east and the Ruby Valley syncline on the west. Subsequent erosion apparently planed the strata down to the Carboniferous and locally to even lower horizons near the site of the present north (scarp) face of the central part of the range, leaving progressively younger strata to the south and southwest (based partly on unpublished data of G. C. Kennedy). Middle Tertiary volcanic rocks and, possibly, continental deposits overlapped these older strata from the south (Snake River Plains area). Uplift by block faulting probably began during late Tertiary time, for the range supported small glaciers on its north (scarp) face during the Pleistocene. Some uplift has occurred fairly recently, as shown by modern scarps, interrupted drainage, and associated landslides. The abruptness of the scarp slope also indicates the recency of the uplift.

During the Tertiary weathering cycle, or cycles, the uranium in the Permian strata was probably leached from the outcrop areas and redeposited in phosphatic rocks at shallow depth. The uplift of the range by block faulting undoubtedly interrupted the process and led to the removal of leached rocks by erosion, leaving uranium-enriched phosphorite at the present outcrop. Thus, the phosphorite in the Centennial Mountains includes rock that is believed to have been enriched in uranium by middle Tertiary weathering and that is near the present outcrop of the strata, as well as fresher rock farther downdip that would presumably contain less uranium. The table of resources (table 13) shows the estimated mean grade of both types of rock.

MADISON RANGE DISTRICT

In general the Permian rocks of the Madison Range are not as weathered as those in most of the other parts of southwest Montana owing to the recency of the uplift. The areas of Permian outcrop are generally rugged, having deeply incised valleys and dominantly steep slopes. The uranium content of the exposed phosphorite has apparently been affected by limited leaching only during the present erosion and weathering cycle and is thus not very different from that in the deeply buried phosphorite. The grades given in table 14 reflect this condition.

YELLOWSTONE-GARDINER DISTRICT

No data are available on the uranium content of the phosphorite at Quadrant Mountain in Yellowstone National Park, but the phosphorite is of low grade, and presumably the uranium content is correspondingly low. At Cinnabar Mountain, just north of the park, the phosphorite is not much richer, and the

TABLE 13.—*Uranium in phosphate resources in the Phosphoria Formation, Centennial Mountains district*

[Grade, in percent uranium; tonnage, in short tons]

Geologic block	Uranium in phosphate rock containing >31 percent P_2O_5				Uranium in phosphate rock containing >24 percent P_2O_5				Uranium in phosphate rock containing >18 percent P_2O_5			
		Tonnage				Tonnage				Tonnage		
	Grade	Above entry level	In first 100 ft below entry level	Total (in block)	Grade	Above entry level	In first 100 ft below entry level	Total (in block)	Grade	Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member									0.005	2,500	250	15,000
Meade Peak Phosphatic Shale Member	0.012	4,000	400	20,000	0.010	5,500	500	25,000	0.009	7,500	700	35,000
Total tonnages and average grades	0.012	4,000	400	20,000	0.010	5,500	500	25,000	0.007	10,000	950	50,000

uranium content is very low (average grade is 0.0025 percent eU). This phosphorite characteristically contains an abundance of shell fragments and related organic remains, and McKelvey and Carswell (1956) noted that such rocks "are generally less uraniferous than pellet phosphates of the same P_2O_5 content." (See also Sheldon, 1959.) No resources were computed for this area.

SUMMARY OF URANIUM RESOURCES IN SOUTHWEST MONTANA

All the phosphatic rocks of Permian age in southwest Montana contain uranium, but the uranium content of much of the acid-grade and furnace-grade phosphate rock is lower than that for comparable rock in other parts of the western phosphate field. The uranium content of the low-grade rock is about normal, approximately 0.001 percent U for each 3 percent P_2O_5. The low uranium content of much of the phosphate rock seems to be related to leaching under hydrothermal conditions long after deposition of the sediments.

More than 1¼ million tons of uranium is estimated to be present in the low-grade phosphate rock of both phosphatic shale members (table 15). One-third of this is in the Meade Peak Member, and two-thirds is in the Retort Member. More uranium is present in the furnace-grade and acid-grade phosphate rock of the southwest Montana positive area than of the synclinorium. The most uraniferous rocks occurs in the Meade Peak Member of the Centennial Mountains and Lima districts, but the tonnages in these districts are not very large due to the relatively small tonnages of phosphate rock.

A summary of the uranium resources for all districts in southwest Montana is given in table 15.

TABLE 14.—*Uranium in phosphate resources in the Retort Phosphatic Shale Member of the Phosphoria Formation, Madison Range district*

[Grade, in percent uranium; tonnage, in short tons]

Geologic block	Uranium in phosphate rock containing >24 percent P_2O_5				Uranium in phosphate rock containing > 18 percent P_2O_5			
		Tonnage				Tonnage		
	Grade	Above entry level	In first 100 ft below entry level	Total (in block)	Grade	Above entry level	In first 100 ft below entry level	Total (in block)
Cedar Creek–Jack Creek synclinal area	0.008	300	30	25,000	0.006	400	40	30,000
West Fork Gallatin River synclinal area	.007	850	100	20,000	.005	1,500	150	20,000
Indian Creek–Taylor Creek synclinal area	.007	450	90	35,000	.006	3,500	1,500	90,000
Beaver Creek–Cabin Creek synclinal area					.005	500	100	8,000
Total tonnages and average grades	0.007	1,600	220	80,000	0.006	5,900	1,790	148,000

TABLE 15.—*Summary of uranium in phosphate resources in the Phosphoria Formation in southwest Montana, by districts*

[Uranium content given in short tons]

District	Uranium in phosphate rock containing >31 percent P_2O_5				Uranium in phosphate rock containing >24 percent P_2O_5				Uranium in phosphate rock containing >18 percent P_2O_5			
	Grade (percent uranium)	Tonnage			Grade (percent uranium)	Tonnage			Grade (percent uranium)	Tonnage		
		Above entry level	In first 100 ft below entry level	Total (in block)		Above entry level	In first 100 ft below entry level	Total (in block)		Above entry level	In first 100 ft below entry level	Total (in block)
Retort Phosphatic Shale Member												
Melrose	0.005	365	270	15,800	0.005	5,500	1,165	54,300	0.005	14,050	2,520	118,00
Dillon					.005	1,300	365	23,000	.005	7,510	2,680	198,000
Lima									.006	2,350	800	38,500
Ruby Valley					.008	250	30	12,000	.007	8,800	2,050	360,000
Centennial Mountains									.005	2,500	250	15,000
Madison Range					.007	1,600	220	80,000	.006	5,900	1,790	148,000
Total tonnages and average grades	0.005	365	270	15,800	0.006	8,650	1,780	169,300	0.006	41,110	10,090	877,500
Meade Peak Phosphatic Shale Member												
Dillon					0.007	70	35	350	0.007	75	40	400
Lima					.009	1,700	600	22,000	.009	4,000	1,450	80,000
Ruby Valley					.008	5,150	1,125	198,000	.005	6,750	1,600	304,000
Centennial Mountains	0.012	4,000	400	20,000	.010	5,500	500	25,000	.009	7,500	700	35,000
Total tonnages and average grades	0.012	4,000	400	20,000	0.007	12,420	2,260	245,350	0.006	18,325	3,790	419,400
Grand total tonnages and average grades, both numbers	0.007	4,365	670	35,800	0.006	21,070	4,040	414,650	0.006	59,435	13,880	1,296,900

OTHER MINERAL RESOURCES

FLUORINE

Marine phosphorites are composed of the mineral carbonate fluorapatite (Altschuler and others, 1952), which was shown to be a distinct mineral species by Gruner and McConnell (1937) and contains about 1 part of fluorine for each 10 parts of P_2O_5. Altschuler, Cisney, and Barlow (1952) noted that "this apatite is generally characterized relative to fluorapatite by a deficit in P_2O_5 content of 3 to 6 percent, an excess of F, OH (or both) of 0.5 to 1.0 percent, and by the presence of 2 to 3 percent carbonate." Therefore the ratio F/P_2O_5 ranges from 0.104 to 0.120, if the excess is all fluorine. The average ratio in fluorapatite is 0.089, and that in francolite, as defined by Gruner and McConnell (1937), is 0.109. The ratio for 44 samples from Montana (weighted for thickness, p. 674) is 0.101, a little lower than that of 4 samples from the Bone Valley Formation of Florida (Altschuler and others, 1958, p. 49), which range from 0.104 to 0.110 and average 0.107.

McKelvey (1946, p. 57) has shown that the F/P_2O_5 ratio decreases westward from Wyoming into Idaho, from the platform to the geosyncline. (See also McKelvey, Swanson, and Sheldon, 1953, p. 54.) This appears to apply to Montana, also, for the 34 samples from the area of the southwest Montana synclinorium have an average ratio of 0.099 (weighted for thickness), whereas the 10 samples from farther east have a ratio of 0.104. This excludes the two samples of lot 1239 that have fluorine of 0.187 and 0.550 that apparently reflect the presence of free fluorite or, possibly, analytical errors; these two samples are from one of the localities close to intrusive rocks (p. 756; fig. 197), and the presence of free fluorite seems the more likely explanation.

Free fluorite has been noted in the Permian rocks from several localities in Montana. Some appears to be directly related to hydrothermal activity, but at other localities no such relation is suspected, and the fluorite may have migrated to its present locality under conditions of weathering. Probably most (if not all) fluorite in these rocks represents fluorine deposited in the Permian seas as part of the phosphate mineral, from which some of the fluorine was subsequently leached by aqueous solutions and was redeposited as fluorite.

Much of the fluorine in the western phosphate rock is lost during treatment. In February 1958, however, it was announced (Chemical Week, 1958) that "United Heckathorn Co. may build a $250,000 artificial cryolite plant at Garfield, Salt Lake County, Utah, if Western Phosphates, Inc., agrees to supply the necessary flourides" (fluorides) from their "triple superphosphate and ammonium phosphate plant." The plant was closed in 1961 (Cook, 1961). Except for some recovery of hydrofluoric acid for plant use, this plant was apparently the first to commercially recover fluorine from western-field phosphate rock.

Fluorine has been recovered as synthetic cryolite in the laboratories of the U.S. Bureau of Mines in defluorination of western phosphate rock (Hall and Banning, 1958; Waggaman and Ruhlman, 1960, p. 23). In the treatment of phosphate rock by the electric-furnace process, much of the fluorine remains in the slag and is lost, but some "is volatilized and collected in the phosphorus condensing water as fluosilicic acid," which is neutralized by addition of soda ash to minimize corrosion of equipment (Waggaman and Ruhlman, 1960, p. 8).

Waggaman and Ruhlman also noted (1960, p. 14) that when phosphate rock is treated with sulfuric acid, "a large part of this [the] fluorine is evolved as silicon tetrafluoride (SiF_4), which reacts with water to form fluosilicic acid and gelatinous silica." Further indication of the potential of recovery of fluorine from western phosphate rock is indicated by a recent contract in Florida whereby International Minerals and Chemical Corp. will supply to Kaiser Aluminum and Chemical Corp. more than 10,000 tons of fluosilicic acid annually (Mining Congress Journal, 1957). This acid is recovered at Bonnie, Fla., from the processing of Florida phosphate rock, most of which is chemically and mineralogically almost identical with western phosphate rock. The acid is converted into sodium silicofluoride which is then converted into synthetic cryolite. In a presumably similar operation, "additional equipment to recover fluorine compounds was installed at the Plant City [Fla.] plant of Smith-Douglass Co., Inc." (Ruhlman and Tucker, 1960, p. 839). According to Chemical & Engineering News (1957, p. 81), engineers at "Tennessee Valley Authority have worked out several ways to recover fluorine in usefull forms—and at the same time get rid of pollution headaches."

The marketable production of phosphate in the United States in 1966 was more than 12 million tons of contained P_2O_5, of which 1,677,000 tons (nearly 14 percent) was from the western field (U.S. Bureau of Mines, 1967, p. 527). In terms of the F/P_2O_5 ratio noted above, this production represents more than 1.2 million tons of contained fluorine nationally, or about 170,000 tons from the western field. Data are not available to determine how much of this total fluorine is driven off during treatment and how much of that loss might be recoverable; however, a high percentage of this fluorine might be recoverable in usable form. Apparently a large part of the fluorine released in the treatment of phosphate rock from Florida and Tennessee is now recovered in insoluble (unusable) form and is discarded.

The domestic consumption of fluorspar in 1966 was more than 1 million short tons, of which nearly 880,000 tons was imported (U.S. Bureau of Mines, 1967a, p. 475). The amount of fluorine in the fluorspar consumed was not noted, but if the fluorspar were all in the form of pure fluorite, it would contain about 520,000 tons of fluorine, or a little less than half the total fluorine contained in phosphate produced in this country in 1966. The actual content must be significantly lower. Therefore, each year in the United States much more fluorine is lost from the treatment of phosphate rock (a small part of the phosphate rock produced is applied directly to soils and must be excluded) than is consumed in the form of fluorspar.

The amount of fluorine consumed in the form of cryolite (natural and synthetic) is not known, but it is believed to be much lower than that of fluorspar. In 1966 less than 32,000 tons was imported (U.S. Bureau of Mines, 1967a, p. 482); data on the production and consumption of synthetic cryolite were not noted.

The F/P_2O_5 ratio of western phosphate is fairly constant, and fluorine is recovered only as a byproduct of phosphate treatment; therefore, the resources of fluorine are a direct function of the resources of phosphate. The grades and tonnages noted in the tables of phosphate resources in this report should suffice for defining the fluorine resources. Since 1 million tons of phosphate containing 25 percent P_2O_5 would contain approximately 25,000 tons of fluorine, the total fluorine resources in southwest Montana in phosphate rock containing 31, 24, and 18 percent P_2O_5 (table 8) at an F/P_2O_5 ratio of 0.101 would be 14½, 160, and 460 million short tons, respectively. The total content of fluorine in the two shale members (for the area computed) is a little more than 1 billion short tons.

SYNTHETIC GYPSUM

In the manufacture of triple-superphosphate fertilizer by the wet process, rock containing about 31 percent P_2O_5 is digested in sulfuric acid to produce phosphoric acid, which is then added to more raw rock to make the fertilizer. In the first step of the process, the lime in the phosphate mineral (carbonate fluorapatite, or apatite) combines with the sulfate and water of the acid to produce hydrated calcium sulfate, or synthetic gypsum, which is filtered off with the nonsoluble impurities. About 75 percent of the P_2O_5 in the final product goes through the digestion process, and the lime represents almost 55 percent of the apatite; thus, roughly 40 percent of all rock used in this process goes into the form of synthetic gypsum. This is equivalent to about 1⅓ tons of gypsum for each ton of fertilizer produced, or 1 ton of gypsum for each ton of rock used, or more than 3 tons of gypsum for each ton of P_2O_5 contained in that rock. In the manufacture of wet process phosphoric acid, about 4.3 tons of gypsum are produced for each ton of contained P_2O_5.

Rock that contained 2.491 and 2.395 million tons of P_2O_5, respectively, was used in manufacture of wet process phosphoric acid and triple superphosphate in this country in 1966 (U.S. Bureau of Mines, 1967c, p. 530). The synthetic gypsum so produced and probably mostly discarded must have exceeded 18 million tons, an amount almost double the 9.6 million tons of crude gypsum mined in this country that year (U.S. Bureau of Mines, 1967b, p. 489).

In August 1960 an article in the Washington Post announced that a plant was to be constructed at Claymont, Del., to manufacture gypsum board from "a byproduct of phosphoric acid" instead of from gypsum rock. However, Kuster and Jensen (1962, p. 632) reported that "Plans of the Barrett Division, Allied Chemical Corp., to build a chemical gypsum plant at Claymont, Del. [presumably the plant referred to in the Washington Post] were postponed indefinitely." G. A. McHugh of the J. R. Simplot Co. (oral and written commun., 1961) reported on tests made in recent years toward the utilization of byproduct gypsum from the Pocatello, Idaho, phosphate-fertilizer plant of that company, perhaps by mixing synthetic with natural gypsum.

Lewis and Tucker (1962, p. 991) stated that a new method for producing phosphoric acid has been developed in Japan and that "A high quality gypsum suitable for wallboard was said to be a product of the process. The quality of the gypsum was stated to be dependent upon close temperature and chemical control during crystallization."

The principal uses of gypsum are for prefabricated building products, for plasters and other building materials, such as portland-cement retarder, and for agricultural purposes (Kuster and Jensen, 1962). Synthetic gypsum from phosphate-fertilizer production would not be suitable for some of these uses because of impurities and color or other properties, such as content of unremoved acid; but for other uses it might be just as suitable as natural gypsum, and for agricultural uses the content of relict phosphoric acid would probably be advantageous.

OIL SHALE

The occurrence of oil shale in the Permian strata of southwest Montana was first recorded by Bowen (1918), who noted that the shale (Retort Member) at Small Horn Canyon "has been opened up by a tunnel about 150 feet long, driven in the hope of finding coal," and that a "sample representing a thickness of about 5 feet taken from the tunnel * * * yielded, on distillation, 24 gallons of oil per ton." Condit (1919) conducted a much more extensive investigation of the oil content of Permian strata in the western phosphate field. In southwest Montana he found significant quantities of oil in the shaly beds of the Retort Member at several localities south of Dillon and west of Dell; the oil content is lower at localities farther east, as at Warm Springs Creek in Ruby Valley and in the east end of the Centennial Mountains. The samples from the Retort Member at Sheep Creek (lot 1234, near Small Horn Canyon south of Dillon) were also analyzed for their oil content. The beds richest in oil occur in the poorly phosphatic mudstones immediately above the principal phosphate zone at both Sheep Creek and Dalys Spur (6 miles farther northwest), but the oil-rich zone extends down into the lower phosphate zone at Sheep Creek and up into the upper one at Dalys Spur.

At Dalys Spur, Condit (1919, p. 23-26) described a generalized section (p. 24) and reported oil analyses of samples from that section. Years later, F. C. Armstrong and G. A. Duell (in A. P. Butler, Jr., and C. W. Chesterman, unpub. data, 1945) measured the same section in detail, and in 1947 Lowell (Cressman and Swanson, 1964, lot 1222) made detailed measurements of a section a short distance farther north; but oil analyses were not made for either of these sections. The three sections correlate well (fig. 198*A*) if it can be assumed that there is a printing error in Condit's table and that the bed he measured above his sample 393 is 9+ inches thick, rather than 9+ feet, as printed. If this assumption is incorrect, then correlation is poor.

Condit (1919) sampled at two places in the Sheep Creek or Retort Mountain area (fig. 198*B*): one at a prospect trench near the "head of Small Horn Canyon," probably near lot 1234, and the other about 1½ miles farther north in an old "coal" prospect tunnel—probably the tunnel mentioned by Bowen (1918). In the subsurface samples from the northern locality, Condit found an 18-foot-thick deposit that contains more than 18 gallons of oil per ton, the top 5½ feet containing 21 gallons per ton. From the surface trench, however, 21½ feet contains an average of 9 gallons per ton, the middle 11 feet of which contains 15 gallons. Of the section sampled at lot 1234, 26 feet contains an average of 9.7 gallons per ton, and of this, 9½ feet in the upper part contains 16 gallons and 10 feet in the lower part contains nearly 9 gallons. The 9½-foot sequence lies on top of the lower phosphate zone. Below this horizon the more phosphatic beds contain less oil; however, one bed containing nearly 19 percent P_2O_5 is an exception, for it also contains 13.4 gallons of oil per ton. Thus, the subsurface samples gave higher yields, and a significant loss of oil content is believed to have occurred during weathering.

At Dalys Spur (fig. 198*A*), Condit (1919) found that 24 feet (including 1 ft of "shale, brownish gray" that was not analyzed) contains nearly 15 gallons of oil per ton. These strata are overlain by 4½ feet of phosphatic shale, which, in turn, is overlain by 4 feet 8 inches of shale containing 14 gallons of oil per ton.

At Big Sheep Creek in the Lima district, Condit found that 27 feet contains 13 gallons of oil per ton. At Little Sheep Creek, 24½ feet — including two beds (totaling 4 ft thick) that were not analyzed and that are here treated as barren—averages more than 12 gallons per ton.

The specific gravity of the oil shale is not known, but it is probably about 2.5, which signifies a tonnage factor of nearly 13 cubic feet per ton (fig. 178). Because the thicknesses of oil shale and of low-grade phosphate rock in the Dalys Spur and the Small Horn Canyon areas are fairly comparable, although the oil shale is a little thicker than the phosphate, the tonnages of oil shale at these localities are probably comparable to those of low-grade phosphate rock (table 3). This rock is assumed to contain a little more than 10 gallons of oil per ton.

In the Lima district the oil shales average more than three times as thick as the low-grade phosphate rock. The tonnage of oil shale is accordingly assumed to be about three times that of low-grade phosphate rock (table 4), and the shale is assumed to contain more than 12 gallons of oil per ton. No other estimate of oil shale resources can be made at this time.

MINOR METALS

The phosphatic shales of the Phosphoria Formation contain, in addition to phosphorite and oil shale, small concentrations of many metals. Other than uranium, those metals that are most notable are chromium, vanadium, and nickel. Although little information is available on the content or distribution of these elements in the phosphatic shales in Montana, spectrographic data from a few localities (lots 1218, 1234, 1239) suggest that the range in chromium and vanadium contents is from 0.01 to 1.0 percent, and in nickel, from 0.001 to 1.0 percent, mostly < 0.1. Vanadium

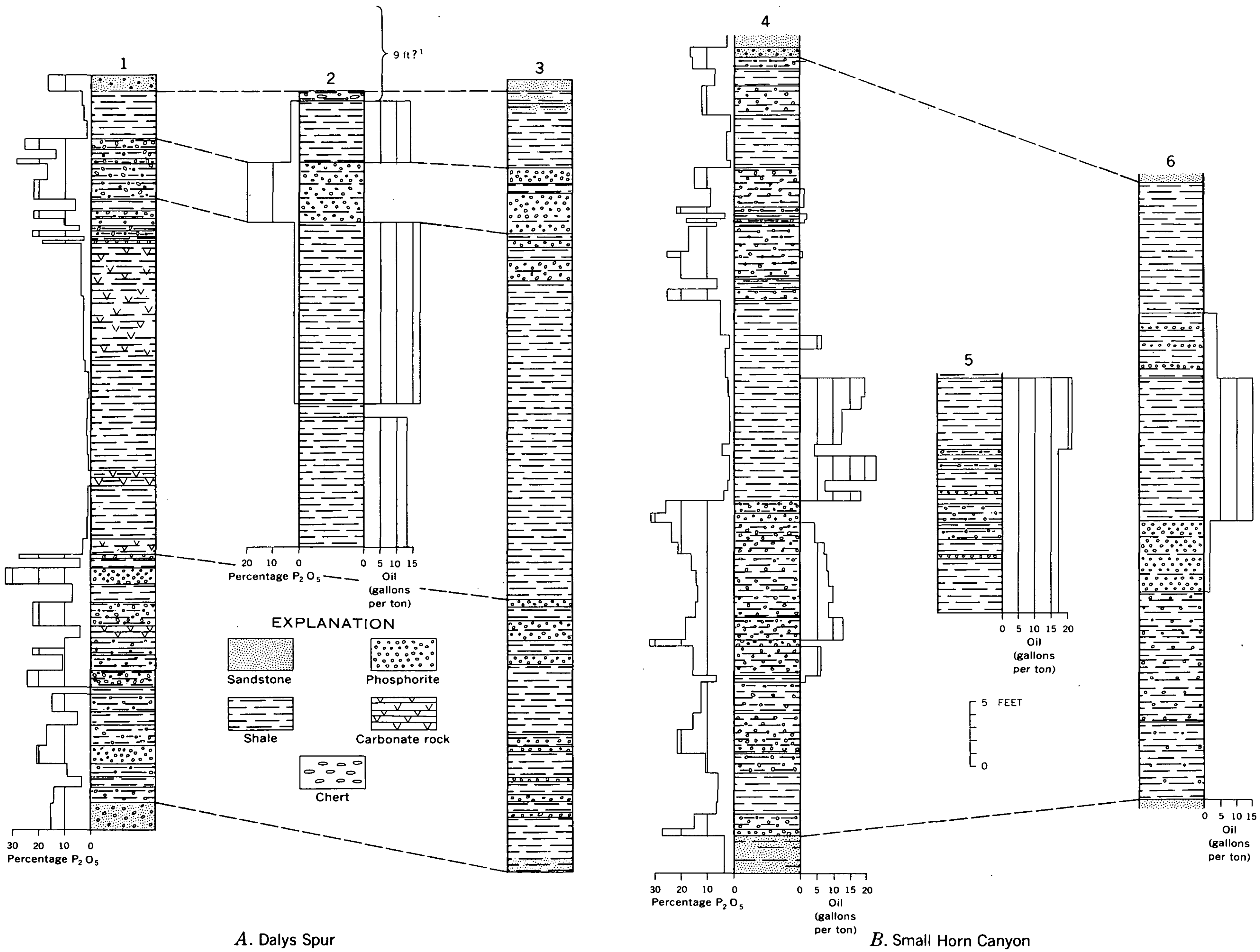


FIGURE 198.—Comparison of measured sections of the Retort Phosphatic Shale Member of Phosphoria Formation at Dalys Spur (lot 1222) and at Small Horn Canyon area (lot 1234) showing contents of P_2O_5 and of oil where known. *A*, Dalys Spur: (1) lot 1222; (2) Condit (1919, p. 24); (3) F. C. Armstrong and G. A. Duell (in A. P. Butler, Jr., and C. W. Chesterman, U.S. Geol. Survey, unpub. data). *B*, Small Horn Canyon: (4) lot 1234; (5) Condit (1919, p. 24); (6) Condit (1919, p. 25).

was recovered at Anaconda (Mining World, Nov. 1942) for more than 15 years from phosphate rock containing 31.7 percent P_2O_5 and 0.28 percent V_2O_5 (Caro, 1949) that was mined in Idaho, but no recovery has been made from Montana rock.

In the furnace treatment of phosphate rock (p. 746, methods of treatment) these metals become concentrated in the ferrophosphorus. Smelting tests by the Tennessee Valley Authority in 1947 on phosphatic shale that contained 0.1 percent vanadium, mined near Fort Hall by the Simplot Co., yielded ferrophosphorus that contained 4.0 percent chromium, 3.85 vanadium, and 0.95 percent nickel; and two samples of ferrophosphorus produced at the Westvaco electric furnace near Pocatello, which treats the furnace shales mined near Fort Hall, contained 5.7 and 5.2 percent chromium, 4.0 and 5.2 percent vanadium, and 0.98 and 1.0 percent nickel (Banning and Rasmussen, 1951). Because the recoverability of all these metals from ferrophosphorus has been demonstrated (Banning and Rasmussen, 1951), the metals represent a potential byproduct resource worthy of consideration. The Minerals Engineering Co. announced plans to build a plant in Salt Lake City that will recover vanadium from ferrophosphorus produced in Pocatello (Engineering and Mining Journal, 1960, p. 356). Kermac Nuclear Fuels Corp. announced plans to build a vanadium recovery plant in Soda Springs, Idaho, to recover 1½ million pounds of high purity vanadium pentoxide (V_2O_5) annually from ferrophosphorus produced in the phosphate furnaces of the Monsanto Chemical Co. (Salt Lake Tribune, 1962).

The mode of occurrence of these elements in the phosphatic shales is not known. These elements are commonly more abundant in the more phosphatic parts of the section, but their abundance does not vary directly with the P_2O_5 content of the strata. Pardee (1936, p. 185) reported that "thin greenish films that contain vanadium" coat cleavage planes in the sheared rock in a small phosphate mine at Maxville but no other identification has been made in Montana.

RARE EARTHS

At least 10 rare-earth elements have been identified by spectrographic means in phosphatic shale samples from Idaho. (See, for example, lot 1304, Davidson and others, 1953). Most of these elements occur in quantities of only a few hundredths to a few tenths of a pound per ton and, combined, probably seldom represent more than 2-3 pounds per ton. Presumably the rare-earth elements occur in Montana phosphatic shales in comparable amounts, but their distribution in relation to that of other elements is not known.

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