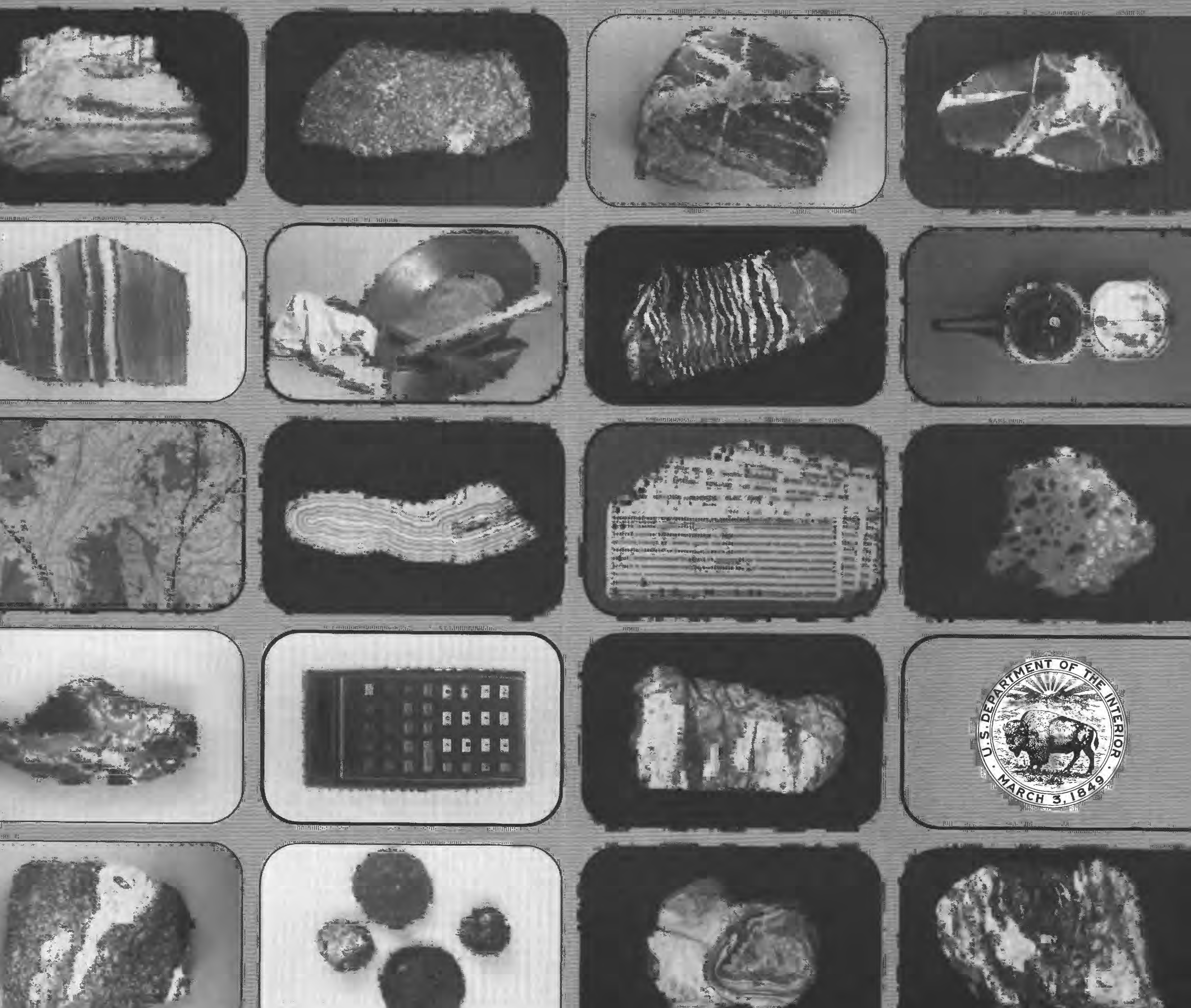
Geology and Description of Thorium and Rare-Earth Deposits in the Southern Bear Lodge Mountains, Northeastern Wyoming

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1049-D



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3. Chromite-chromium ore, Washington
4. Zinc ore, Friedensville, Pa.
5. Banded iron-formation, Palmer, Michigan
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12. Manganese nodules, ocean floor
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Geology and Description of Thorium and Rare-Earth Deposits in the Southern Bear Lodge Mountains, Northeastern Wyoming

By MORTIMER H. STAATZ

GEOLOGY AND RESOURCES OF THORIUM IN THE UNITED STATES

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A description of the size, mineralogy, chemical composition, economic geology, and geologic setting of the thorium and rare-earth veins and newly discovered large disseminated deposits

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By MORTIMER H. STAATZ

ABSTRACT

The Bear Lodge Mountains are a small northerly trending range approximately 16 km northwest of the Black Hills in the northeast corner of Wyoming. Thorium and rare-earth deposits occur over an area of 16 km² in the southern part of these mountains. These deposits occur in the core of the Bear Lodge dome in a large multiple intrusive body made up principally of trachyte and phonolite. Two types of deposits are recognized: disseminated deposits and veins. The disseminated deposits are made up of altered igneous rocks cut by numerous crisscrossing veinlets.

The disseminated deposits contain thorium and rare-earth minerals in a matrix consisting principally of potassium feldspar, quartz, and iron and manganese oxides. Total rare-earth content of these deposits is about 27 times that of the thorium content.

The general size and shape of the disseminated deposits were outlined by making a radiometric map using a scintillation counter of the entire Bear Lodge core, an area of approximately 30 km². The most favorable part of this area, which was outlined by the 40 count/s (count-per-second) isograd on the radiometric map, was sampled in detail. A total of 341 samples were taken over an area of 10.6 km² and analyzed for as many as 60 elements. Rare earths and thorium are the principal commodities of interest in these deposits. Total rare-earth content of these samples ranged from 47 to 27,145 ppm (parts per million), and the thorium content from 9.3 to 990 ppm. The amount of total rare earths of individual samples shows little correlation with that of thorium. Contour maps were constructed using the analytical data for total rare earths, thorium, uranium, and potassium. The total rare-earth and thorium maps can be used to define the size of the deposits based on what cut-off grade may be needed during mining. The size is large as the 2,000 ppm total rare-earth isograd encloses several areas that total 3.22 km² in size, and the 200 ppm thorium isograd encloses several areas that total 1.69 km². These deposits could be mined by open pit. The Bear Lodge disseminated deposits have one of the largest resources of both total rare earths and thorium in the United States, and although the grade of both commodities is lower than some other deposits, their large size and relative cheapness of mining make them an important future resource.

Vein deposits in the Bear Lodge Mountains include all tabular bodies at least 5 cm thick. Twenty-six veins were noted in this area. These veins are thin and short; the longest vein was traced for only 137 m. Minerals vary greatly in the amount present. Gangue minerals are commonly potassium feldspar, quartz, or cristobalite intermixed with varying amounts of limonite, hematite, and various manganese oxides. Rare earths and thorium occur in the minerals monazite, brockite, and bastnaesite. Thorium content of 35 samples ranged from 0.01 to 1.2 percent, and the total rare-earth content of 21 samples from 0.23 to 9.8 percent. Indicated reserves were calculated to a depth of one-third the exposed length of the vein. Inferred reserves lie in a block surrounding indicated reserves. Indicated reserves of all veins are only 50 t of ThO_2 and 1,360 t of total rare-earth oxides; inferred reserves are 250 t of ThO_2 and 6,810 t of total rare-earth oxides.

The Bear Lodge dome, which underlies the greater part of this area, is formed by multiple intrusive bodies of Tertiary age that dome up the surrounding sedimentary rocks. In the southern part of the core, the younger intrusive bodies surround and partly replace a granite of Precambrian age. This granite is approximately 2.6 b.y. old. The sedimentary rocks around the core are (from oldest to youngest): Deadwood Formation of Late Cambrian and Early Ordovician age, Whitewood Limestone of Late Ordovician age, Pahasapa Limestone of Early Mississippian age, Minnelusa Sandstone of Pennsylvanian and Early Permian age, Opeche Formation of Permian age, Minnekahta Limestone of Permian age, Spearfish Formation of Permian and Triassic age, Sundance Formation of Middle and Late Jurassic age, Morrison Formation of Late Jurassic age, and the lower part of the Lakota Formation of Early Cretaceous age. In places, especially around the north half of the dome, the intrusive rock replaces one or more of these formations. Generally only the most resistant quartzite layers of the Deadwood Formation are not replaced. The best exposed section of the Deadwood occurs along the east flank of the area where a separate intrusive plug has pushed up a circular block of sedimentary rocks. Here, although not a complete section, 270 m of Deadwood Formation was measured, one of the thickest known sections of this formation.

The Tertiary intrusive bodies not only form the center of the Bear Lodge dome but also form many smaller plugs, dikes, and sills along its flanks. The intrusives all have a relatively high potassium and a low silica content. These rocks represent a complex sequence of alkalic rocks that were intruded into the older sedimentary rocks at shallow depth over a considerable period of time. In a few places the magma reached the surface, forming flows and pyroclastic deposits. Six age determinations have been made on intrusive bodies from this area, including four that are first reported here. They indicate that the intrusives formed over a minimum time span of 12.2 m.y. (million years) (38.3 to 50.5 m.y. ago). During waning stages of the Tertiary intrusion, many of the intrusive bodies were fractured and altered by

hydrothermal solutions. This alteration is most intense in the central part of the Bear Lodge dome, and here the various rock types are difficult to separate. Many of the outlying intrusives show little alteration, and the various rock types are more easily mapped. The greater part of the intrusive rocks are trachyte and phonolite. In addition, however, there are other intrusives of latite, syenite, and nepheline syenite. Irregular areas of intrusive breccia indicate the force of intrusion in some areas, and patches of tuff are still preserved in a few places. Dikes and (or) sills of lamprophyre, pseudoleucite porphyry, carbonatite, and younger trachyte and syenite are present. Carbonatites form numerous dikes at depth near the headwaters of Whitelaw Creek. These interesting rocks are commonly rich in rare earths and strontium. Rare earths occur in bastnaesite and ancylite; strontium occurs in ancylite and strontianite.

Along the flanks of the Bear Lodge dome, the Tertiary intrusive rocks and older sedimentary rocks are overlain by sedimentary rocks of Tertiary and Quaternary ages. The Tertiary rocks consist of loosely consolidated sandstones and conglomerates of the White River and Ogallala Formations. Those rocks formed on the flanks of a rising upland whose center is now located near Warren Peaks. The Quaternary rocks are landslide deposits and alluvium.

Although the central structure is the large Bear Lodge dome, another dome, folds, and small faults also occur here. The Hershey Creek dome, underlying 3 km², is in the northwestern part of the area. Anticlines, synclines, and 10 short faults are found on the flanks of the Bear Lodge dome. All the domes, folds, and faults have been formed by the force of intrusion of one or more intrusives. The most striking example of the relationship between faulting and intrusion is on Sheep Mountain, where several curved faults outline the approximate shape of the underlying plug, which has pushed the overlying rocks up like a cork in a bottle.

INTRODUCTION

Thorium and rare-earth deposits have been known in the Bear Lodge Mountains since 1949 (Wilmarth and Johnson, 1953, p. 5). Their discovery brought about a flurry of prospecting accompanied by location of more than 100 claims and the digging of several hundred bulldozer trenches. The lack of a readily available thorium and rare-earth market in the 1950's caused active exploration for these ores to cease. The largest and potentially most economic deposits occur in large disseminated deposits consisting of numerous criss-crossing veinlets in altered intrusive rocks. These deposits, which are first described here, are similar in occurrence to copper and molybdenum porphyry-type deposits. Thorium and rare earths occur in disseminated deposits and veins over an area of about 16 km² and represent a sizable future resource of these elements. The deposits occur in and are related to a large multiple alkalic intrusion, made up mainly of trachyte and phonolite. These intrusive bodies, which underlie an area of approximately 31 km², dome up the surrounding rocks to form the Bear Lodge dome and expose sedimentary rocks as old as Cambrian in age. The present study describes the geology and mineralogy of the thorium and rare-earth deposits, the petrology of both the principal and adjacent outlying intrusives, and the geologic setting of the surrounding rocks.

LOCATION AND ACCESSIBILITY

Thorium- and rare-earth-bearing veins and disseminated deposits occur near the middle of an oval-shaped body of intrusive rock in Crook County, Wyo. This area makes up the higher part of the southern Bear Lodge Mountains and includes the Warren Peaks, Smith Ridge, and Bull Hill (pl. 1). The size of the region covered by this report is approximately 112 km² (pl. 1). This area occupies most of the southern Bear Lodge Mountains (fig. 1), and the greater part of it is within the boundaries of the Black Hills National Forest. The area mapped is roughly rectangular in shape, and is approximately bounded by lats 44° 25′ 15″ and 44° 32′ 50″ N., longs 104° 22′ 25″ and 104° 30′ W. The town of Sundance, Wyo., is 1.5 km south of this area's southeast corner and the town of Hulett, Wyo., lies 16 km northwest of its northwest corner.

The principal road through the study area is a north-south-trending all-weather road that divides the area roughly in half. Its southern terminus is on U.S. Highway 14 about 2.8 km west of Sundance. Other improved U.S. Forest Service roads follow Beaver Creek, Whitelaw Creek, Ogden Creek, Lytle Creek, Togus Creek, and Blacktail Creek. The road down Blacktail Creek connects the area with the town of Hulett. In addition numerous secondary roads have been added to aid in lumbering operations. Some of the older roads became abandoned and overgrown, and newer roads have been added in the same region with the start of new lumbering operations. The only habitations are two farm houses in and adjacent to Krusee Canyon in the southwest corner of the region (pl. 1).

GEOGRAPHY

The Bear Lodge Mountains are a low, northerly trending range 43 km long by 13 to 20 km wide. This range lies approximately 16 km northwest of the northwest end of the Black Hills (fig. 1). The two are separated by a broad, undulating depression called the Red Valley (Darton, 1909, p. 27), which is underlain for the most part by the Spearfish Formation and extends continuously around the Black Hills. The Bear Lodge Mountains have a relief of about 869 m and vary in elevation from about 1,160 m at the north end of the range to 2,029 m on the northernmost of the Warren Peaks in the

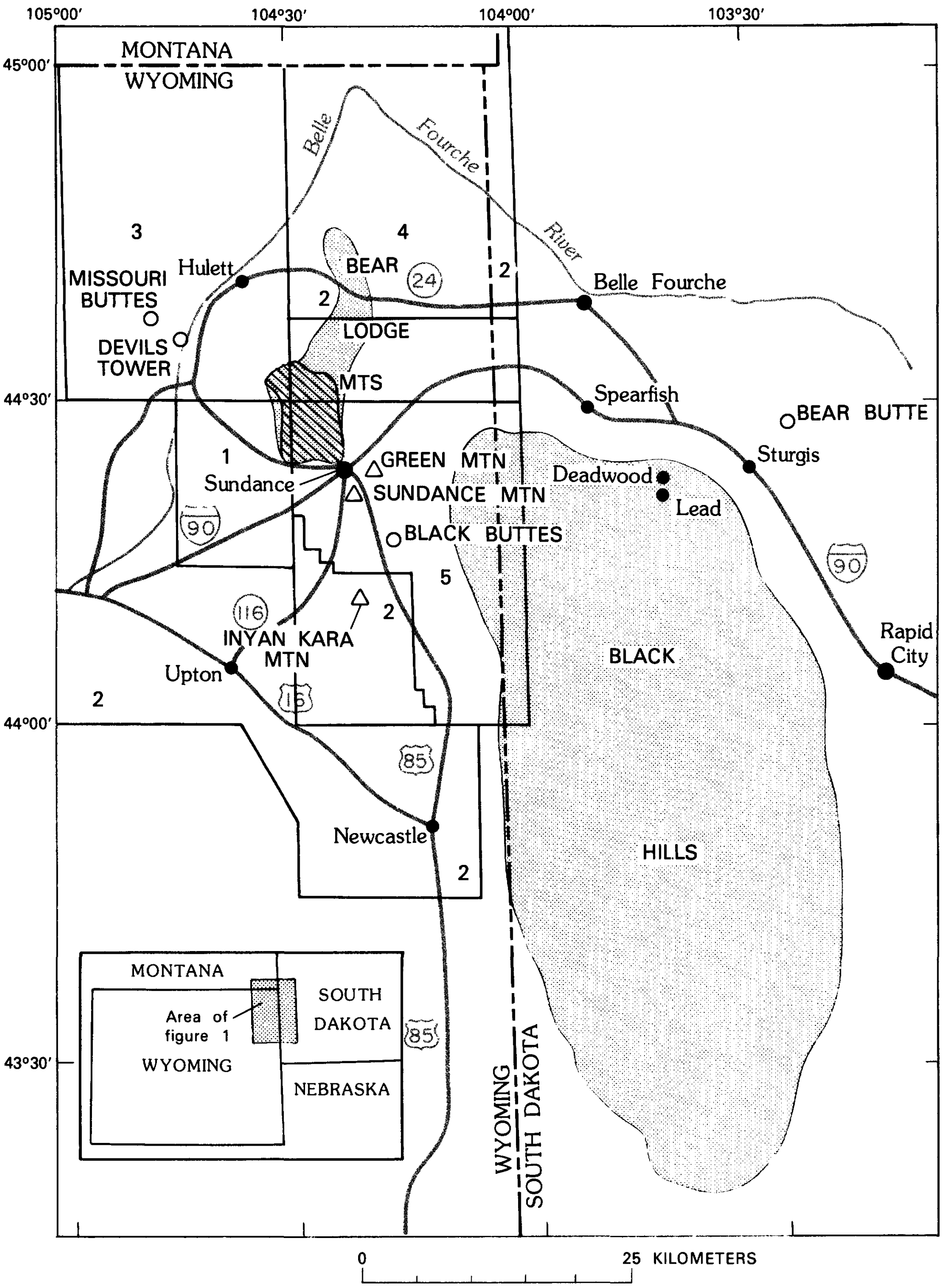

FIGURE 1.—Index map of northeastern Wyoming and northwestern South Dakota showing the location of the area mapped (diagonal-line pattern) in relation to the Bear Lodge Mountains and the Black Hills. Adjacent mapped areas mentioned in text are 1, Nefsy Divide quadrangle (Pillmore and Mapel, 1963, pl. 1); 2, northern and western flanks of the Black Hills uplift (Robinson and others, 1964, pl. 1); 3, Devils Tower quadrangle (Darton and O'Harra, 1907); 4, Aladdin quadrangle (Darton and O'Harra, 1909); 5, Sundance quadrangle (Darton, 1905).

southern part of the range. Difference in elevation in the area mapped is about 555 m. The Warren Peaks occur near the center of an intrusion that domes up the southern part of the Bear Lodge Mountains. Here the mountain tops are rounded, and the drainage pattern radiates off this uplifted highland. Although the streams flow off these highlands in all directions, they all, either directly or via other streams, flow into the Belle Fourche River, which flows along the west and northeast sides of the Bear Lodge Mountains (fig. 1). The longest stream in the Bear Lodge Mountains is Beaver Creek, which heads on the northeast side of Warren Peaks and then follows a meandering northward course along much of the length of the Bear Lodge Mountains for 50 km to the Belle Fourche River. Some streams near the center of the domed-up area form broad, shallow valleys, like Whitelaw Creek and the upper parts of Lytle and Beaver Creeks. Other creeks, generally on the flanks of the dome, form steep, V-shaped valleys, like Reuter, Tent, and Ogden Creeks. These steep-walled valleys, however, rarely have more than 125 m of relief. The shape of the valleys is also, in part, determined by the rock type. The broad, gently sloping valleys of the upper part of Beaver and Winchester Creeks change to steep narrow rock-bound gorges where they flow through the resistant Minnelusa Sandstone (pl. 1).

The Bear Lodge Mountains are covered with western yellow pine, which in parts of these mountains is the only tree found. Other trees include aspen, white birch, hawthorn, and burr oak. These small trees are most common along valley bottoms and on north-facing slopes. In the northern part of the mapped area, the smaller trees form dense thickets in some places; but in the central and southern parts, they are rare. The western yellow pine has supported a small lumbering industry for many years. Logs from this area are hauled to sawmills in Hulett.

PREVIOUS WORK

One of the first to mention the rocks in the vicinity of the Bear Lodge area was Lieutenant G. K. Warren, who led an expedition from Fort Laramie to Inyan Kara Mountain in 1857 (Warren, 1859, p. 60). Warren Peaks, the highest peaks in the Bear Lodge Mountains, were named after this explorer. Early geologists were attracted not only to mineral deposits of this region, but also to the prominent small- to medium-sized intrusives that occur in an east-west-trending belt from Bear Butte on the northeast side of the Black Hills to Missouri Buttes, 25 km to the west of the Bear Lodge Mountains (fig. 1). Newton and Jenney (1880, p. 199–200, 283–289) briefly described the geology and early gold prospecting activity in the vicinity of Warren Peaks; their report contains the first published description of one of the veins that contains thorium and rare earths (p. 199–200). The petrography of some of the trachytic rocks collected by Newton and Jenney is described in detail by Caswell (1880, p. 517–523). Russell (1896, p. 390–410) and Jaggar (1901, p. 251) briefly studied the intrusive rocks near Warren Peaks. In the early 1900's, N. H. Darton and C. C. O'Harra mapped the Sundance, Devils Tower, and Aladdin 30-minute quadrangles at a scale of 1:125,000 (Darton, 1905; Darton and O'Harra, 1907; 1909) (fig. 1). These three quadrangles cover the greater part of the present study area. The geology of these quadrangles and of the adjoining northern part of the Black Hills was summarized by Darton (1909). In the 1950's Brown in a thesis study made a reconnaissance map and described the main intrusive body in the Bear Lodge Mountains (Brown, 1952; Brown and Lugn, 1952). Another result of this study was the dating of some of the sedimentary rocks of Tertiary age (Lugn and Brown, 1952). In another thesis, Chenoweth (1955) described the rocks of the southeastern part of the Bear Lodge Mountains. Also during the 1950's, the U.S. Geological Survey investigated the uranium deposits that occur in the Lakota and Fall River Formations along the western flanks of the Bear Lodge Mountains and the Black Hills. One of the results of this work was the mapping of the Nefsy Divide quadrangle (Pillmore and Mapel, 1963), the northeast corner of which overlaps a small part of the present study area (fig. 1). The stratigraphy and structure of the northern and western flanks of the Black Hills uplift which included the Nefsy Divide and Devils Tower quadrangles were correlated over an area of about 13,000 km^2 (Robinson and others, 1964) (fig. 1). The sedimentary section in this study area is chiefly the Sundance and younger formations, because outcrops of the older units are sparse where present at all.

Brief studies of the mineral resources of the Bear Lodge Mountains have been made previously by the U.S. Bureau of Mines and the U.S. Geological Survey. The Bureau of Mines trenched and sampled some fluorspar deposits on the east side of the main intrusive body to the north and east of Peterson Spring in 1944 (Dunham, 1946), and they drilled and sampled a few of the rare-earth deposits in 1951 (E. D. Everett, written commun., 1951). Later, Wilmarth and Johnson (1953) of the U.S. Geological Survey studied and sampled some of the thorium- and rare-earth-bearing veins.

PRESENT WORK AND ACKNOWLEDGMENTS

Little previous work has been done on the thorium and rare-earth deposits of the Bear Lodge Mountains, and what has been done was either confined to a few small areas or has been reconnaissance in nature. The mineralogy of these deposits is poorly known, owing primarily to the small grain size and to the masking of minerals and their relation to one another by considerable pulverulent black manganese oxides and red and yellow iron oxides. The radioactivity of individual deposits has been noted, but few data are available on the widespread anomalous radioactivity in the central part of the district.

The present work in the Bear Lodge Mountains was originated to study the thorium and rare-earth deposits and their geologic setting. This investigation includes a detailed study of the mineralogy of many of the thorium and rare-earth deposits, which was carried out by separating the individual minerals by means of heavy liquids, a magnetic separator, and hand picking. All visually unrecognized minerals were then identified by their X-ray diffraction patterns. The radioactivity of both the deposits and adjoining intrusive rocks was measured with a scintillation counter, and a total count radiometric map was constructed. The results of this work indicated that the thorium and rare-earth disseminated deposits, which underlie an area of approximately 10.6 km^2, needed further study. Hence, during the summer of 1979, a detailed radiometric study using a portable gamma-ray spectrometer and a sampling program was carried out in and adjacent to the disseminated deposits. In this study some 318 new samples were taken and analyzed for thorium, uranium, and potassium on a quantitative gamma-ray spectrometer by C. M. Bunker and C. A. Bush. In addition, semiquantitative spectrographic analyses were made on 192 samples, primarily to determine their rare-earth content, by N. M. Conklin. These detailed analytical data are available in Staatz and others (1980).

The geology of the area was mapped in detail on a scale of 1:24,000 (pl. 1). Mapping was done directly on a composite topographic base, which was compiled from parts of four 15-minute quadrangles: Sundance (1958), Alva (1958), Nefsy Divide (1957), and Devils Tower (1955). Exposures are poor in many of the thickly wooded parts in the central and northern parts of the area, and the positions of contacts were inferred in many places. Furthermore, the entire central part of the intrusive body has been altered, and the various igneous rock types are not everywhere recognizable. Hence, although the intrusive rocks are separated where they are less altered near the margins of the area, they are lumped as one complex unit in the central part of the region.

The fieldwork was done during the summers of 1975, 1976, and 1979 and the spring of 1977. I was assisted by T. M. Staatz during 1975, by A. J. Staatz during 1975 and 1976, by L. F. Osmonson during the spring of 1977, by D. F. Piske, Jr., for 1 week in June 1979, by T. E. Mower for 2 weeks in July 1979, and by R. F. Dubiel for 1 week in September 1979. Isabelle Brownfield did sample preparation, ran X-ray diffraction patterns, and did mineral identification.

During the first 3 years, Duval Corporation was carrying out an exploration program in the northern part of this area. I am indebted to geologists of this company, particularly John L. McGillis, Fred Reisbick, and Richard K. Larsen, for definite information on geology of the area. I am also indebted to the U.S. Department of Energy, which furnished funds for resource studies in 1978.

ROCK UNITS

Four general groups of rocks occur in the southern Bear Lodge Mountains. They are: (1) intrusive rocks of Precambrian age, (2) sedimentary rocks of Paleozoic and Mesozoic age (fig. 2), (3) intrusive rocks of Tertiary age, and (4) consolidated and unconsolidated rocks of Tertiary and Quaternary age. The only Precambrian rocks exposed in the area are remnants of a granitic body that have been intruded and in part replaced by later intrusive bodies of Tertiary age. Biotite-bearing schists probably occur at depth, inasmuch as inclusions of schist are found in the Tertiary intrusive rock near Warren Peaks. Sedimentary rocks of Paleozoic and Mesozoic ages have a total thickness of approximately 1,070 m in the southern Bear Lodge Mountains (fig. 2). Paleozoic rocks account for about two-thirds of this section. The rocks of Paleozoic age are mainly limestone with some sandstone, quartzite, shale, and siltstone. These are divided into: (1) the Deadwood Formation of Late Cambrian and Early Ordovician age, (2) the Whitewood Limestone of Late Ordovician age, (3) the Pahasapa Limestone of Early Mississippian age, (4) the Minnelusa Sandstone of Pennsylvanian and Early Permian age, (5) the Opeche Formation of Permian age, (6) the Minnekahta Limestone of Permian age, and (7) the lower part of the Spearfish Formation of Permian age. Mesozoic rocks are principally siltstones and shales but include some minor sandstones. These rocks make up: (1) the upper part of the Spearfish Formation, which is

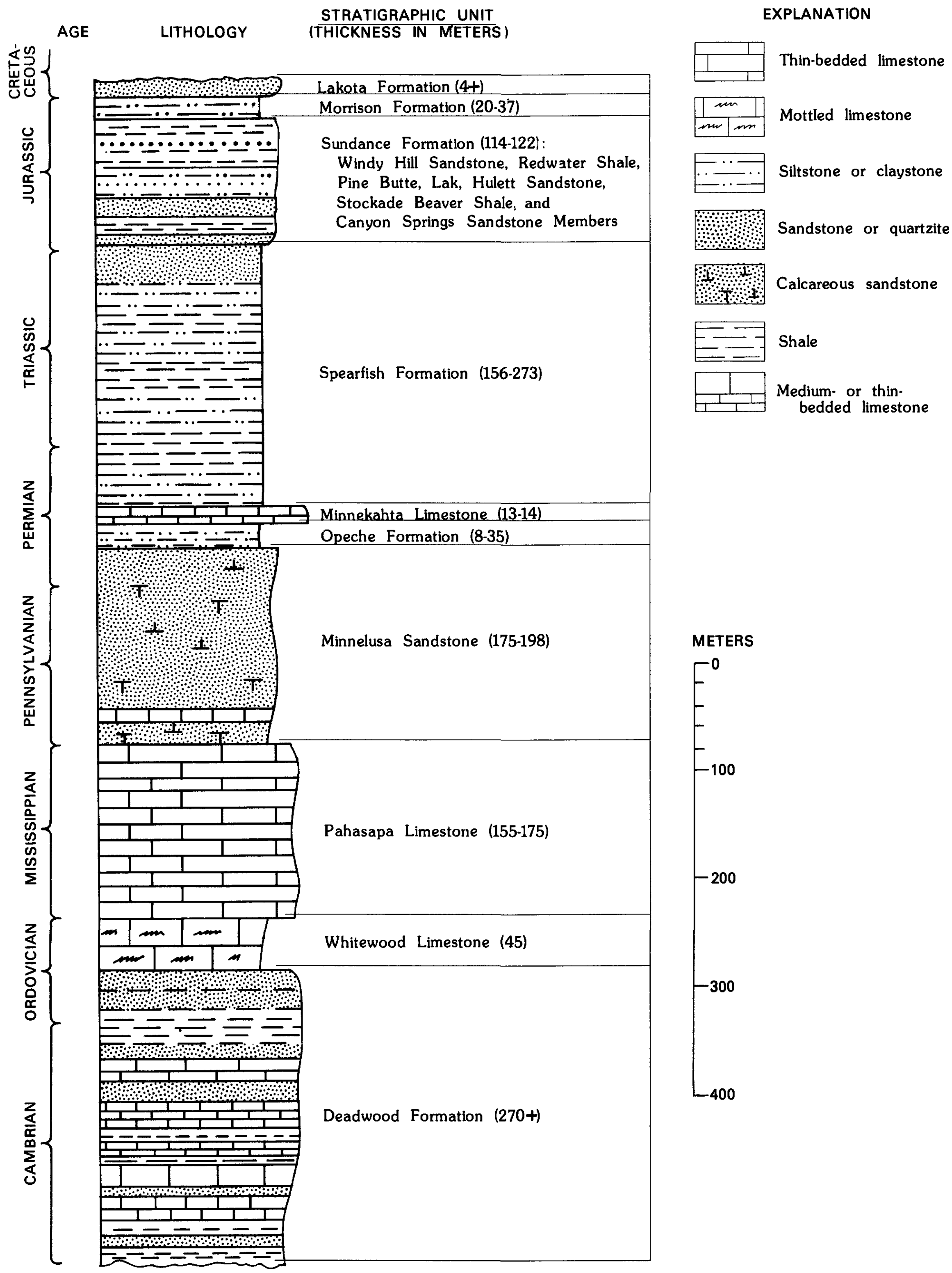

FIGURE 2.—Generalized columnar section of the Paleozoic and Mesozoic rocks in the southern Bear Lodge Mountains, Wyo. (pl. 1).

of Triassic age, (2) the Sundance Formation of Middle and Late Jurassic age, (3) the Morrison Formation of Late Jurassic age, and (4) the lowest part of the Lakota Formation of Early Cretaceous age. A generalized column of these rocks is shown in figure 2.

Multiple intrusive bodies of early Tertiary age domed up and replaced older rocks in the central part of this district. Smaller intrusives cut the Paleozoic and Mesozoic rocks that lie on the flanks of the principal intrusive. All these intrusives are alkalic and deficient in silica. The principal rock types are trachyte and phonolite, but minor amounts of latite, syenite, nepheline syenite, pseudoleucite porphyry, lamprophyre, pyroclastic rocks, intrusive breccia, and carbonatite occur.

The sedimentary rocks of Tertiary and Quaternary ages unconformably overlie the older rocks and are made up of material derived at the most from a few kilometers away. The Tertiary rocks are the White River and Ogallala Formations, consisting of loosely consolidated clastics, mainly siltstones, sandstones, and conglomerates that formed on the flanks of an eroded and beveled upland whose center is now represented by Warren Peaks. Alluvium and landslide deposits make up the Quaternary rocks.

FIGURE 3.—Granite along southeast side of Ogden Creek showing typical massive outcrop.

GRANITE (PRECAMBRIAN)

The granitic rocks in the Bear Lodge Mountains are confined to the south half of the core of the Bear Lodge dome (pl. 1), where they occur as isolated bodies surrounded by intrusive rocks of Tertiary age. Dikes of the intrusive rocks cut the granite at many places. Granite is also found as clasts in a trachytic-flow breccia exposed on Smith Ridge. The largest granite body (fig. 3), which is irregularly lenticular, is approximately 3.4 km long and has a maximum width of 600 m. This granite body lies along the northeast side of the core of the Bear Lodge dome. One of the lower quartzite beds in the Deadwood Formation lies adjacent to the northeast side of this granite body and at one place on Smith Ridge overlies the older granite. The contact between the two rock types is not exposed. The next largest granite body is T-shaped and underlies Warren Peaks. The various granite bodies, as a whole, have a discontinuous ring-shaped form within the south half of the main Tertiary intrusive (pl. 1). The semicircular outcrop pattern of the granite (pl. 1) resembles a ring dike, but the granite is the older rock rather than the reverse. One explanation for this ring-like shape is that the separate granite bodies may be at the periphery of a Precambrian mountain whose center was replaced by the intrusive. North of this outcrop ring, granite may be absent, as it is neither exposed on the surface nor encountered in a 900-m-deep drill hole located 2.3 km north of the edge of the granite on Warren Peaks.

The granite for the most part is a medium-grained holocrystalline leucocratic igneous rock. This rock is generally fairly homogeneous, and its grain size at most places is about 1 to 3 mm. The rock has a porphyritic texture in a few areas, feldspar phenocrysts being two or three times as large as surrounding grains. The rock is uniformly light colored with the actual color ranging from light gray to tan; however, at many places the weathered rock is a light brown because of limonite stain along numerous fractures.

The common minerals are quartz, albite, and microcline. This rock is everywhere silica rich, having a quartz content that ranges from about 20 to 35 percent. Normative quartz in three chemically analyzed samples is approximately 35 percent (table 1). Albite is generally the most common feldspar, and the albite to microcline ratio varies from about 3:1 to 7:10. Albite is, in general, poorly twinned and contains many dust-like inclusions. The lack of good twinning makes measurement of maximum extinction angles of limited use in determining the type of plagioclase. The sodium:calcium ratio of the plagioclase was obtained from the normative minerals (table 1). The anorthite content of the three analyzed specimens ranged from An_2 to An_7, so all three are

TABLE 1.—*Chemical analyses and normative compositions in weight percent of Precambrian granite*

[Analyst, Lowell Artis, U.S. Geological Survey. Leaders (–), none]

Constituent or mineral	Sample No. 1	2	3
Chemical analyses			
SiO_2	75.1	75.5	75.2
Al_2O_3	13.8	13.8	15.1
Fe_2O_3	.61	.48	.66
FeO	.08	.04	.08
MgO	.07	.00	.10
CaO	.17	.12	.80
Na_2O	2.8	2.3	4.9
K_2O	6.2	6.9	2.8
H_2O+	.39	.61	.51
H_2O-	.10	.15	.10
TiO_2	.08	.05	.11
P_2O_5	.04	.03	.05
MnO	.02	.03	.01
CO_2	.08	.05	.03
Total---	99.54	100.06	100.45
Normative compositions			
Quartz	35.2	36.2	34.7
Orthoclase	37.3	40.6	16.7
Albite	23.6	19.4	41.4
Anorthite	.56	.56	2.8
Hypersthene	.20	—	.30
Corundum	2.4	2.5	3.0
Hematite	.64	.70	.64
Ilmenite	.15	.15	.15
Apatite	—	—	.34
Calcite	.20	.10	.10
Total---	100.25	100.21	100.13

SAMPLE LOCALITY DESCRIPTIONS

1. Ridge top south of Tent Canyon, NE1/4 NE1/4 sec. 33, T. 52 N., R. 63 W.
2. Roadcut just south of U.S. Forest Service lookout tower on Warren Peaks, SE1/4 SE1/4 sec. 20, T. 52 N., R. 63 W.
3. End of ridge top just north of the mouth of Richardson Creek, SE1/4 NW1/4 Sec. 27, T 52 N., R. 63 W.

albite. The potassium feldspar is probably chiefly microcline, as well-defined cross-hatch twinning is found in some thin sections. In other thin sections the potassium feldspar is untwinned and might be either untwinned microcline or orthoclase. The discrimination of untwinned potassium feldspar from untwinned plagioclase was made by staining the potassium feldspar yellow with sodium cobaltinitrite. Accessory minerals are biotite, magnetite, apatite, zircon, monazite, hornblende, anatase, rutile, galena, pyrite, and fluorite. Black biotite is the most common accessory mineral, generally making up 1–3 volume percent of the rock. Tiny black octahedra of magnetite constitute less than 1 percent of some granite specimens; in others magnetite has been altered to limonite. White apatite, pale-gray zircon, and yellowish-orange monazite make up trace amounts of the granite in many places. The granite was fractured and underwent minor alteration when it was metamorphosed by the surrounding Tertiary intrusive bodies. During this period a little pyrite was formed in the granite; later weathering converted the striated cubes of pyrite to goethite. Small flakes of sericite, which make up from a trace to 5 percent of the rock, formed on the potassium feldspar. A little hematite is present locally.

Granite samples from three widely separated areas were chemically analyzed in the U.S. Geological Survey's rapid rock-analysis laboratory (table 1). All three are typical of granite in the area from which they came and are similar in appearance. The oxide contents of samples 1 and 2 are also quite similar (table 1), but that of sample 3 differs principally in having almost twice as much Na_2O and less than half as much K_2O. These differences are best shown in the normative feldspar content, where the orthoclase content of samples 1 and 2 is 37 and 41 percent by weight, that of sample 3 is 17 percent; the albite content of samples 1 and 2 is 24 and 19 percent, respectively, and that of sample 3 is 41 percent. The maximum normative anorthite is 2.8 percent, indicating that the plagioclase is unusually rich in albite.

Dating the granite is uncertain, because all of its outcrops are within a relatively short distance of and may be affected by a much larger intrusive body of Tertiary age. The age of the granite was determined by lead-uranium ratios in zircon, because lead-uranium isotopic ratios are not as easily affected by heat as the isotopic ratios of other elements used in some other methods. The zircon crystals have a clear, pale-purple central part that is mantled by a thick, opaque, pale-gray rind. These rinds are the direct result of radiation damage. K. R.

Ludwig of the U.S. Geological Survey (oral commun., 1976) stated that only zircons of Precambrian age exhibit the extreme radiation damage found in zircons from the granite of the southern Bear Lodge Mountains. Zircons from a sample of granite collected on Houston Ridge in the NE¼SE¼ sec. 33, T. 52 N., R. 63 W. were dated by the uranium-lead isotope method by Ludwig. The results are as follows:

Uranium (ppm)	Lead (ppm)	$\frac{^{206}Pb}{^{238}U}$ age	$\frac{^{207}Pb}{^{235}U}$ age	$\frac{^{207}Pb}{^{206}Pb}$ age
1863	129.9	389 m.y.	939 m.y.	2628 m.y.

The extreme discordance between the ages is at least in part due to the heating of the zircons by the Tertiary intrusive. The heating of the granite tends to drive off lead from the zircons and makes the ages obtained appear to be too young. Thus, although a definite age cannot be determined, the above data do give a minimum age of about 2,600 m.y. Samples from two other areas in the Black Hills have similar ages. An age of approximately 2,500 m.y. has been reported both from the Little Elk Granite on Little Elk Creek in the northeastern part of the Black Hills (Zartman and Stern, 1967) and from a gneissic granite in the Bear Mountain dome on the west side of the central Black Hills (Ratté and Zartman, 1970).

DEADWOOD FORMATION (LATE CAMBRIAN AND EARLY ORDOVICIAN)

The Deadwood Formation, a unit made up principally of quartzite and shaly limestone, is the oldest sedimentary unit in the Bear Lodge Mountains. This formation is exposed in three areas: (1) in and around the edge of the igneous core of the Bear Lodge dome, (2) on Sheep Mountain, and (3) along the north edge of the intrusive core of Hershey Creek dome (pl. 1). Around the edge of the Bear Lodge dome, the intrusive bodies have replaced much of the Deadwood and the lower part is not present. Around the northern part of this dome, the entire Deadwood has been replaced and in places the main intrusive body extends out into the Minnelusa Formation. As many as four layers of the Deadwood separated by intrusive rock are present in the southern part of this dome. These layers are principally quartzite; the intrusive preferentially replaced the intervening limestone parts of the Deadwood. At some places the quartzite layers are completely replaced by the intrusive, and in other places the quartzite remains to form prominent ledges that protrude as much as 4 m above the surrounding terrain. Small areas of unreplaced limestone were noted in several places, notably on the ridge at the north end of Ragged Top in the SE¼ sec. 32, T. 52 N., R. 63 W., and on top of a narrow ridge north of Ogden Creek in the NE¼NE¼ sec. 27, T. 52 N., R. 63 W.

The thickest and most complete exposure of the Deadwood Formation is on Sheep Mountain on the east edge of the area shown on plate 1 and on figure 12. Here a thick sequence of shaly limestone interbedded with some quartzite is found in an uplifted block that overlies a partly concealed intrusive plug. The lower part of the Deadwood is cut off by faulting. The northernmost exposure of Deadwood is on the north side of the Hershey Creek dome, where small areas of quartzite and thin-bedded limestone are exposed.

The Deadwood Formation in the Bear Lodge and Hershey Creek domes differs from that in the Black Hills in being metamorphosed and having many of the calcareous layers replaced by the Tertiary intrusive. A section measured on Sheep Mountain indicates that the greater part of the Deadwood in the Bear Lodge Mountains was originally thin bedded shaly limestone; yet the remanent layers of Deadwood around the Bear Lodge dome are mainly quartzite.

The most continuous and in some places the only part of the Deadwood present is an upper quartzite unit. This is a massive layer of hard, white, medium-grained quartzite, 6–9 m thick, that at many places has acted as a dam to the outward penetration of intrusive magma. Around much of the south end of the Bear Lodge dome and around part of the north end of the Hershey Creek dome, this resistant layer of quartzite marks the edge of the intrusive rock. Farther north in the Bear Lodge dome, where intrusive rock extends out into the younger rocks, remnants of this layer commonly form isolated islands in the intrusive rock. Between this quartzite and the overlying Whitewood Limestone is approximately 15 m of shale, which is rarely exposed. Directly below the massive quartzite unit is found approximately 15 m of thin-bedded, medium-grained, brown to red quartzite. Beds are from about 0.5–30 cm thick, and worm burrows are locally present. This unit is not nearly as well exposed as the massive quartzite. In some places a little limestone is present below the thin-bedded quartzite. The limestone is fine grained and pinkish gray, pink, or red, containing greenish-gray silty partings that commonly exhibit worm trails. Below these rocks occur three similar-appearing quartzite layers, which generally consist of hard, white, medium-grained quartzite made up of well-rounded quartz grains. In places these quartzites are cross-bedded, contain some small pebbles up to about 0.3 cm in diameter, and have thin shale or slate layers.

The Deadwood Formation is exposed on Sheep Mountain in a thick unbroken section (Section 1), but faulting has cut out some of the lower quartzite units around the south side of the Bear Lodge dome (pl. 1).

The Deadwood Formation near the town of Deadwood was reported to be 116–122 m thick (Darton, 1909, p. 12). From there it tends to thin to the south and thicken to the northwest. On Elk Creek, 14.3 km southwest of Deadwood, it has thinned to 61 m thick (Darton, 1909, p. 12), and in the southern Black Hills it is as little as 1.2 m thick (Gries, 1952, p. 70). Although the Deadwood is present in the subsurface northwest of the Black Hills, only a few drill holes in the vicinity of the Bear Lodge Mountains extended into it. One hole, C. H. Jackson's R-1-Fredricks in the NE¼NE¼ sec. 28, T. 57 N., R. 61 W., although not drilled completely through the Deadwood, did cut 176.5 m of the formation. On Sheep Mountain 270.3 m of Deadwood is exposed in the partial section given previously. To the northwest of the Bear Lodge Mountains, in the northwestern part of the Powder River Basin, more than 335 m of Cambrian rocks are shown on an isopach map by McCoy (1958a, p. 22).

SECTION 1.—*Deadwood Formation*

[Measured on the south side of Sheep Mountain in the SW¼NW¼ sec. 13, T. 52 N., R. 63 W.]

	Meters
Top of ridge.	
Whitewood Limestone (part):	
20. Limestone, massive; light gray with pink mottling	6.0
Partial thickness of Whitewood Limestone	6.0
Deadwood Formation:	
19. Covered	50.0
18. Covered; white quartzite float	14.9
17. Shale, greenish-gray	1.2
16. Quartzite, red, hard	0.5
15. Quartzite, massive, white, medium-grained	5.5
14. Quartzite, brown, medium-bedded; beds 0.3–0.9 m thick; worm trails along bedding planes	7.4
13. Quartzite, brown, calcareous, medium- to thick-bedded; beds 0.9–2.4 m thick	7.6
12. Limestone, thin-bedded, red-stained gray; shale partings; contains several thin intraformational limestone conglomerates	18.0
11. Covered	10.5
10. Quartzite, medium-bedded, medium-grained, brown, calcareous; beds 0.10–0.45 m thick; contains greenish-gray shale interbeds	6.1
9. Limestone, thin-bedded, gray to brown, locally sandy; beds 0.6–10 cm thick; contains greenish-gray shale interbeds. Sparse worm trails in partings near top	46.7
8. Covered	22.3
7. Limestone, thin-bedded; beds 0.3–5 cm thick, like unit 12, but worm trails are common along shale partings	47.0
6. Covered	6.0
5. Limestone, like unit 7	4.7
4. Quartzite; reddish brown with darker reddish brown mottles, feldspathic	0.4
3. Limestone, like unit 7	6.9
2. Limestone, thin-bedded, gray; interbedded with thin layers of gray shale	0.6
1. Covered	14.0
Partial thickness of Deadwood Formation	270.3
Fault.	

The Deadwood Formation as mapped by Darton (1909, p. 12–18) in the northern Black Hills is a clastic sequence containing sandstone, shale, conglomerate, and silty limestone that lies below the Whitewood Limestone and above metamorphosed Precambrian rocks. Fossils collected by Darton in the lower part of the Deadwood and identified by C. D. Walcott (Darton, 1909, p. 18), were originally thought to represent a Middle Cambrian fauna. Darton and Paige (1925, p. 5–7, 24–25) later changed the age of the Deadwood to Late Cambrian. In 1936, fossils of Ordovician age were described from the upper part of the type section of the Deadwood (Furnish and others, 1936). Fossils are scarce in the southern Bear Lodge Mountains because the intrusive rocks cut out most of the fossiliferous limestone beds. A small collection was made from the first limestone below the upper massive quartzite bed on a saddle on a ridge in the SE¼SE¼ sec. 32, T. 52 N., R. 63 W. This collection contained several kinds of trilobites, one indeterminant conodont fragment, and some fish remains. The trilobites were examined by Michael E. Taylor, who identified the following fossils:

Ellipsocephaloides sp.
Ptychaspis striata Whitfield 1878
? *Ptychaspis tuberosa* Feniak 1952
Linguloid brachiopods

Taylor noted that these fossils are Late Cambrian in age and probably came from more than 30 m below the Cambrian-Ordovician boundary.

The fish remains were identified as *Anatolepis,* cf. *A. heintzi* Bockelie and Fortney by Repetski (1978, p. 529). *Anatolepis* is the earliest vertebrate genus known. Four small phosphatic plates and about two dozen individual tubercles of this fossil were originally found in the collection reported above. A later collection made of the same rock contained several thousand fragments consisting mostly of inclined bony scales of the same genus. *Anatolepis* is assigned by Bockelie and Fortey (1976) to the heterostracan fishes. This collection is important, as the rocks from which it came are among the oldest in which fishes have yet been found. These fish fossils from the Bear Lodge Mountains are approximately 510 m.y. old, or about 40 m.y. older than any previously collected vertebrate fossils.

Although the upper part of the Deadwood is in general similar to the lower part, McCoy (1952) revised the upper boundary because he felt that the name Deadwood should not be applied to the part of the formation of Ordovician age. He divided the Ordovician part of the section into three thin formations. In ascending order these are: Aladdin Sandstone, 3.7–7.6 m thick; Ice Box Shale, 10.6–12.2 m thick; and Roughlock Siltstone, 7.6–9.1 m thick.

Later study showed additional rocks of Ordovician age in rocks below the Roughlock (McCoy, 1958b, p. 28). In the Bear Lodge Mountains the Ordovician clastic rocks are difficult to differentiate separately due to their thinness, their poor exposure, and their partial replacement by the later intrusive bodies. Hence, boundaries of the Deadwood Formation used here are the same as those used by Darton (1909, p. 12–17), and include all the sedimentary rocks below the Whitewood Limestone. Their age is Late Cambrian and Early Ordovician.

WHITEWOOD LIMESTONE (LATE ORDOVICIAN)

The Whitewood Limestone is a thin, inconspicuous, and poorly exposed unit in the Bear Lodge Mountains (pl. 1). It forms a U-shaped outcrop pattern around the south half of the Bear Lodge dome. The outcrop is not continuous, however, as in places, like along Houston Ridge and on Ragged Top, the Whitewood is cut out by Tertiary intrusive rocks. The Whitewood is also exposed on the northeast side of the Hershey Creek dome and on Sheep Mountain. The best exposures of the Whitewood are found on Sheep Mountain, where the formation makes cliffs as much as 19 m high at the top of this prominent mountain.

The Whitewood Limestone at most places in the Bear Lodge Mountains is light-gray, fine-grained limestone with irregular pink mottles as much as 4 cm across. Beds are generally massive but range from thin bedded to massive.

The lower contact of the Whitewood Limestone is generally not well exposed, because the upper part of the underlying Deadwood Formation rarely crops out. The base of the Whitewood is placed below the lowest exposure of light-gray limestone.

The thickness of the Whitewood Limestone in the mapped area is probably close to 45 m. At its type section in Whitewood Canyon just north of Deadwood, S. Dak., McCoy (1958b, p. 25) reported the formation to be 15.2 m thick. The Whitewood in general thickens to the northwest, and in Mobil Producing Company's Helmer No. F-13-21P well, which is approximately 56 km northwest of the type section and 29 km northeast of Sheep Mountain, it is 68.3 m thick (McCoy, 1958b, p. 26). Farther northwest in Sinclair Oil Company's No. 1 McCanns well, 27.4 km north-northwest of Sheep Mountain, the Whitewood is 158 m thick.

No fossils were found in the Whitewood Limestone in the Bear Lodge Mountains, but Darton (1909, p. 19–20) reported numerous large invertebrates in the northern Black Hills. This fauna is Late Ordovician in age.

PAHASAPA LIMESTONE (EARLY MISSISSIPPIAN)

The Pahasapa is the only thick gray limestone found in the Bear Lodge Mountains. This formation extends around the Bear Lodge dome (pl. 1). Exposures are best around the southern part of the dome, and excellent ones are found in Cole, Ogden, and Tent Canyons. Around the northern part of the dome, the Tertiary intrusive rocks locally have replaced part or all of the Pahasapa. The Pahasapa Limestone also crops out around most of the Hershey Creek dome in the northwestern part of the area, and on Sheep Mountain on the area's eastern margin (pl. 1).

The Pahasapa Limestone, for the most part, is a massive, hard, gray, fine-grained limestone that commonly weathers bluish gray. It is resistant and generally forms prominent hills and low cliffs. The contact of the Pahasapa Limestone and the overlying Minnelusa Sandstone is marked in many places by an abrupt topographic steepening of the slopes underlain by the Pahasapa. Although much of the Pahasapa is massively bedded, the lower part of the formation is partly medium bedded and a few layers are thin bedded. A few light-tan beds were noted, some of which contain a small amount of quartz sand. The lower contact of the Pahasapa is generally not well exposed, and it is placed at the base of the first thick-bedded medium-gray limestone that lies above the pink-mottled, light-gray Whitewood Limestone.

The thickness of the Pahasapa Limestone was not measured in this region, but the formation has been measured in several drill holes both to the north and south of the mapped area. The Pahasapa is 154.2 m thick in Jay Huisman's No. 1 Shelldorf well that lies 10.5 km south of the area. It is 184.1 m thick in Sinclair Oil Company's No. 1 Lawrence well that is 18.2 km northwest of the area, and it is 193.6 m thick in Mobil Producing Company's No. F-13-21P Helmer well that is 30.1 km northeast of the present study area. Thus, the Pahasapa is probably between 155 and 175 m thick within the southern Bear Lodge Mountains. The Pahasapa varies considerably in thickness regionally, and Darton (1909, p. 21) noted that it ranged from 30.5 to 213 m thick in the northern Black Hills.

Although fossils in the Pahasapa are scarce in the Bear Lodge Mountains, they are plentiful in other areas. Numerous brachiopods and corals collected by Darton (1909, p. 21–22) in the Black Hills date this formation as Early Mississippian. The fauna and stratigraphy of the Pahasapa Limestone, as a whole, are similar to those of the Lodgepole Member of the Madison Limestone of western Wyoming.

MINNELUSA SANDSTONE (PENNSYLVANIAN AND EARLY PERMIAN)

The Minnelusa is a tan to light-brown, friable sandstone that underlies the lower slopes of the Bear Lodge dome. The Minnelusa Sandstone almost continuously rings the dome, except around the dome's northern part, where the sandstone has been replaced locally by Tertiary intrusive rocks (pl. 1). The Minnelusa also is exposed on the flanks of the Hershey Creek dome. Good exposures are found along the south and east sides of the Bear Lodge dome, but the best ones occur on the east side of the map area (pl. 1) south of Cole Canyon, where the forest has been removed by a fire and considerable topsoil has been stripped by later erosion. Most outcrops consist of gently to moderately dipping sandstone ledges a few meters high, but in the lower part of Winchester Creek and along Beaver Creek east of Ladogar Flats, this formation forms cliffs as much as 20 m high that bound steep gorges.

The greater part of the Minnelusa is fine-grained calcareous sandstone. Color of the sandstone, although predominantly tan, locally varies from white to brown. The sand grains are generally subangular and well sorted, and the sand in some layers is medium grained. Calcareous layers are interspersed with noncalcareous ones. Most of the Minnelusa Sandstone is either thin or medium bedded, and at places the unit has well-developed crossbedding. The base of the Minnelusa is placed below the lowest sandstone and above the massive gray Pahasapa Limestone. Some gray to tan limestone beds occur within the Minnelusa. A conspicuous medium-bedded, gray limestone bed approximately 4 m thick that resembles limestone in the Pahasapa occurs about 10 m above the base of the Minnelusa. Thinner beds of sandy tan limestone are found in the middle part of the formation. A bed of red siltstone less than a meter thick is exposed in a few places in the upper part of this formation. The uppermost member of the Minnelusa is a massive, coarse-grained, cliff-forming sandstone.

The thickness of the Minnelusa Sandstone in northeast Wyoming has been compiled from drill-hole measurements by Foster (1958). His maps show the Minnelusa to be 175–198 m thick in the southern Bear Lodge Mountains. The Minnelusa has the following variation in thickness in the drill holes closest to the map area: (1) 233 m thick in a hole 10.6 km south of the study area, Jay Huisman's No. 1 Shelldorf; (2) 199 m thick in a hole 4.2 km west of the area, Murphy Corporation's Snook No. 1 well; (3) 166 m thick in a hole 9.7 km north of the area, Sinclair Oil Company's No. 1 Mahoney; and (4) 160 m thick in a hole 15.3 km east-northeast of the area, Investor Drilling Company's No. 1 Simons.

No fossils were noted in the mapped area nor were any found by Darton (1909, p. 25) in the northern Black Hills. Fossils, however, have been found along Redwater Creek about 15 km east of the mapped area, where Brady (1958, p. 47) identified 40 species in limestone and dolomite of a local evaporite section. The age of these species ranges from Pennsylvanian to Early Permian.

OPECHE FORMATION (PERMIAN)

The Opeche Formation is a thin, distinctive red clastic unit that separates calcareous tan sandstone of the Minnelusa from the light-gray limestone of the Minnekahta. The Opeche Formation occurs along the lower flanks of the Bear Lodge dome. It is found also along the eastern and northern flanks of the Hershey Creek dome. Although nowhere well exposed, the best exposures are found along the southern and southeastern flanks of the Bear Lodge dome where the Opeche lies directly below gently sloping crests formed by the more resistant overlying Minnekahta Limestone (fig. 4). The Opeche Formation consists of fine-grained, reddish-brown siltstone and some shale. Purplish-red shales crop out at the top of the formation beneath the Minnekahta Limestone. Siltstones commonly are calcareous; calcite makes up the matrix between the quartz grains. The lower boundary is placed at the base of the lowest hematitic, reddish-brown siltstone, and it is an unconformity. The Opeche, being quite friable, is rarely exposed; and this formation is generally marked by scattered patches of reddish-brown soil identical to that of the Spearfish Formation from which it is separated by the intervening Minnekahta Limestone.

The thickness of the Opeche Formation was measured at two places in the study area: (1) northeastern part of the area in a roadcut on the southeast side of Beaver

FIGURE 4.—Opeche Formation (Po) lies between ledges of the more resistant overlying Minnekahta Limestone (Pm) and the underlying Minnelusa Sandstone (PIPm).

Creek in the NE¼SW¼ sec. 3, T. 52 N., R. 63 W., and (2) southeastern part of the area on a small ridge in the NW¼NW¼ sec. 10, T. 51 N., R. 63 W. At the first locality, the Opeche is 20.6 m thick and at the second, 26.1 m thick. The thickness of the Opeche varies considerably in short distances because of its unconformable relation with the underlying Minnelusa Sandstone (Privrasky and others, 1958, p. 50). The Opeche ranges irregularly from 7.6 to 36.3 m in thickness in 60 drill holes that lie within a distance of 36 km of the north, west, and south sides of the study area.

No fossils were noted in the Opeche Formation in the study area, nor have any been reported from the Black Hills. Its age assignment of Permian is based on its stratigraphic position between formations that contain fossils of Permian age.

MINNEKAHTA LIMESTONE (PERMIAN)

The Minnekahta Limestone is a thin gray limestone unit that forms a prominent marker in the Bear Lodge Mountains and the northern Black Hills (Darton, 1909, p. 26). The hardness of this unit combined with the softness of the overlying Spearfish Formation gives rise to broad gentle dip slopes made up entirely of the Minnekahta. The Minnekahta encircles the outermost part of the Bear Lodge dome except in the northeastern part of the area, where it has been replaced by the Tertiary intrusive rocks. Where it laps up on the dome, the limestone commonly forms a low scalloped ridge.

The Minnekahta is for the most part light-gray, thin-bedded, fine-grained limestone. At places the limestone is pinkish gray or is mottled pink and gray. Tan blotches of fine sandy limestone occur in places in the upper and middle parts of this unit. From a distance the Minnekahta appears fairly massive because it commonly forms a low unbroken cliff where it caps ridges. The beds, however, are generally 2.5–8 cm thick, although some are as thick as 75 cm. Some of the beds are finely laminated. The base of the Minnekahta is distinct and is placed at the contact between the uppermost reddish brown, friable siltstone in the Opeche with the lowermost light gray limestone in the Minnekahta.

The thickness of the Minnekahta Limestone was not measured in the study area, but the formation has been measured in four drill holes 4.4–8.9 km west of the area. Its thickness in the Amerada Petroleum Company's Garman No. 1, Nicholson No. 1, and Rathbun No. 1, and the Murphy Corporation's Snook No. 1 holes ranged from 12.8 to 14.0 m. The Minnekahta was also measured 11.0 km south of the mapped area in Jay Huisman's Shelldorf No. 1 hole, where it is 14.3 m thick.

Fossils were not noted in the Bear Lodge Mountains and are rare in other areas. A meager fossil collection made by Darton (1909, p. 26) from the east side of the Black Hills is assigned a Permian age. The Minnekahta Limestone probably correlates with the lower part of the Goose Egg Formation in southeastern Wyoming.

SPEARFISH FORMATION (PERMIAN AND TRIASSIC)

The Spearfish Formation is a thick sequence of reddish-brown shale, siltstone, and fine-grained sandstone that discontinuously encircles the Bear Lodge dome. It is friable and easily eroded, and forms part of the valley bottoms along Togus, Blacktail, Lytle, and Miller Creeks, and Krusee Canyon. The Spearfish forms the center of a syncline between the Bear Lodge and the Hershey Creek domes. It also underlies broad, rolling range land both south and east of the Bear Lodge Mountains.

The lower part of the Spearfish Formation consists of reddish-brown siltstone, shale, and irregular thin interbeds and lenses of white gypsum. The gypsum is more resistant to erosion than the friable clastic rocks and commonly forms the capping on small hills. The upper part of the Spearfish is made up principally of reddish-brown siltstone and fine-grained sandstone. Outcrops are few, and areas underlain by Spearfish are characterized by broad, low areas covered with red soil. The most resistant bed is a thin-bedded, reddish-brown siltstone that is discontinuously exposed about 6 m below the top of the formation. The Spearfish rests with a sharp contact on the underlying Minnekahta Limestone.

The thickness of the Spearfish Formation was not measured within the study area, but in logs of 64 wells drilled within a distance of 35 km of its north, west, and southwest sides, its thickness ranges from 155.7 to 273.1 m. The Spearfish is 248.7 m thick in the well nearest the map area, the Murphy Corporation's Snook No. 1, which lies 4.0 km west of the southwest corner of the area in the NE¼SW¼ sec. 33, T. 52 N., R. 64 W. Only 6.0 km to the northwest of this hole, the Spearfish thins to 193.0 m in Amerada Petroleum Company's Garman No. 1 hole in the NE¼NE¼ sec. 26, T. 52 N., R. 65 W.

Fossils have not been reported from the Spearfish Formation. The age of this formation is based in part on its position above the Minnekahta Limestone of Permian age and below the Sundance Formation of Jurassic age and in part on the ages of other formations with which it can be correlated. Burk and Thomas (1956) and Privrasky and others (1958, p. 49–50) included the lower gypsum-bearing part of the Spearfish along with the Minnekahta Limestone and Opeche Formation in the Goose Egg Formation of "Permo-Triassic" age in southwestern Wyoming. The upper part of the Spearfish has the same lithology and position as the Red Peak Member of the Chugwater Formation of Triassic age (Robinson and others, 1964, p. 9).

SUNDANCE FORMATION (MIDDLE AND LATE JURASSIC)

The Sundance Formation consists mainly of sandstone and shale. It crops out along the western and northern borders of the mapped area (pl. 1), and it underlies much of the region from the Bear Lodge Mountains westward and northwestward to the Belle Fourche River (Robinson and others, 1964, pl. 1). The Sundance was divided by Imlay (1947, p. 246) into five members, which from oldest to youngest are: Canyon Springs Sandstone, Stockade Beaver Shale, Hulett Sandstone, Lak Shale, and Redwater Shale Members. Subsequently, the Redwater Shale Member of Imlay (1947) was subdivided by Pipiringos (1968, p. D12) into the Pine Butte Member of the Sundance overlain by the Redwater Shale (redefined) and Windy Hill Sandstone Members, giving a total of seven members.

The Canyon Springs Sandstone Member ranges from about 1 to 7.5 m thick and is generally found near the base of a ridge, where the more resistant sandstone units of the Sundance overlie the friable, valley-forming Spearfish Formation. The Canyon Springs is a medium-bedded, light-yellowish-brown, fine-grained, calcareous sandstone that closely resembles the Hulett Sandstone Member in appearance. The base of the Sundance is placed at the base of the first yellowish-brown sandstone above the red soils formed on the Spearfish Formation. Farther west the Sundance overlies the Gypsum Springs Formation (Robinson and others, 1964, p. 10–11), but in the southern Bear Lodge Mountains, the Sundance directly overlies the Spearfish.

The Stockade Beaver Shale Member in two sections measured in the Nefsy Divide quadrangle was 15.2 and 27.4 m thick (Pillmore and Mapel, 1963, p. E12). The Stockade Beaver is for the most part a soft, green, calcareous shale, but it has some thin siltstone and sandstone units in its upper part. This member is generally poorly exposed; its best exposures in this area are found above the road down Lytle Creek in the NE¼NE¼ sec. 3, T. 52 N., R. 64 W. The Stockade Beaver Shale and the Canyon Springs Sandstone Members are mapped as a single unit on plate 1.

The Hulett Sandstone Member is the most topographically prominent unit in the Sundance Formation and generally crops out as a cliff (fig. 8*A*) that can be followed continuously for several kilometers. The member is generally from 20 to 25 m thick. It is well exposed in the map area on the east side of lower Beaver Creek, the north side of Blacktail Creek, on lower Lytle Creek, and along Miller Creek. The Hulett is a yellowish-brown to tan, thin-bedded, well-sorted, calcareous, fine-grained sandstone and siltstone. Ripple marks were noted locally. The lower 1–3 m have some green shale partings.

The Lak Member is 38–57 m thick (Pillmore and Mapel, 1963, p. E12). This unit is made up of yellowish-brown to tan poorly sorted siltstone and fine-grained sandstone. The Lak has few outcrops in the map area. It differs from the underlying Hulett Sandstone Member in being more massively bedded and in being less firmly cemented.

The Pine Butte, Redwater Shale, and Windy Hill Members taken together are approximately 52 m thick, and for the most part they underlie rolling, heavily forested ridges. The Pine Butte Member at the base is made up principally of interbedded calcareous, greenish-white sandstone and interbedded siltstone and greenish-gray shale. The overlying Redwater Shale Member is greenish-gray shale with interbeds of gray to tan calcareous siltstone and subordinate fine-grained sandstone. Glauconite is present in most of the sandstone layers in both the Pine Butte and Redwater Shale Members. Just west of the map area in the Redwater Shale Member on lower Hershey Creek is a bed of brownish-gray, fragmented limestone, 0.2 m thick, that contains numerous shell fragments. The Windy Hill

Member, at the top of the Sundance, is yellowish-gray, fine-grained, calcareous sandstone.

The entire Sundance Formation is about 114 m thick along Miller and Houston Creeks in the northwestern part of the Nefsy quadrangle (Pillmore and Mapel, 1963, p. E8). The formation does not vary much in thickness along the western flanks of the Bear Lodge Mountains and the Black Hills, where Robinson, Mapel, and Bergendahl (1964, p. 14) noted that in most places it is between 114 and 122 m thick.

Fossils have been found in all but the Lak Member of the Sundance Formation; they include ammonites, pelecypods, brachiopods, foraminifera, and ostracodes (Pillmore and Mapel, 1963, p. E8). The age of the Lak and lower members was considered by Imlay (1947, p. 230–231) to be Callovian (Late Jurassic) and the Redwater Shale Member as defined by him to be Oxfordian (Middle Jurassic). The lower four members of the Sundance are correlated by Peterson (1954, p. 484) to the Rierdon Formation of Montana and the upper part of the Twin Creek Formation of western Wyoming and southeastern Idaho; the upper three members (the Pine Butte, Redwater Shale, and Windy Hill Sandstone) are correlated by Peterson (1954, p. 491, 494) to the Swift Formation of Montana and the Stump Sandstone of western Wyoming and southeastern Idaho.

MORRISON FORMATION (LATE JURASSIC)

The Morrison Formation, consisting chiefly of crumbly claystone, is not exposed in the mapped area. It is exposed along the lower slopes of low ridges to the west and north of the mapped area (Robinson and others, 1964, pl. 1), but in the mapped area (pl. 1) it occurs in only two small wooded areas along the west edge, where it underlies the Lakota Formation. As it is exposed in neither area, the description of the Morrison comes from outcrops to the west of the map area (Pillmore and Mapel, 1963, p. E14–E16; Robinson and others, 1964, p. 19–22).

The Morrison Formation is made up mainly of greenish-gray claystone, although in the uppermost beds it is dark gray to dark brownish gray in color. The Morrison can be divided into two parts: the upper 0 to about 15 m being noncalcareous claystone, and the lower part being mostly calcareous claystone. The lower 7 m of the formation is commonly sandy and contains one or more 0.3- to 1.2-m-thick beds of cross-laminated, fine-grained, calcareous sandstone and light-gray limestone. The Morrison grades downward into the Sundance Formation, and the base of the Morrison is placed on the top of a persistent bed of yellow-weathering sandstone in the Windy Hill Member of the Sundance. In some areas, such as the thickly wooded hills along the western margin of the map area, the position of this contact is not easily located.

In 17 measured sections in the Nefsy Divide quadrangle (fig. 1) Pillmore and Mapel (1963, p. E14, pl. 2) found that the Morrison Formation ranged in thickness from about 19.8 to 36.6 m. Locally, however, it may be much thinner, and 3 km north of the northwest corner of the map area in sec. 22, T. 53 N., R. 64 W., it is only 6.1 m thick (Robinson and others, 1964, p. 19).

Fossils are locally abundant in the lower calcareous part of the Morrison Formation and include ostracodes, charophytes, dinosaur bones, a few pelecypods, and silicified wood (Pillmore and Mapel, 1963, p. E16). Their age is considered to be Late Jurassic (Reeside, 1952; Sohn, 1958, p. 124; and Peck, 1957, p. 8).

LAKOTA FORMATION (EARLY CRETACEOUS)

The Lakota Formation is the uppermost unit of Mesozoic age exposed in this region. This formation is widespread just west of the Bear Lodge Mountains and is well exposed on Sherrard Hill adjacent to the northwest corner of the map area (pl. 1). In the mapped area, however, it underlies only two small areas along the west edge (pl. 1).

Only the lowermost part of the Lakota Formation is present in the study area. It is mainly a medium-grained, light-gray to white, medium-bedded to massive sandstone. Sand grains are well rounded and fairly well sorted, and almost all are quartz. Rounded chert and quartzite pebbles are scattered through the rock in some places. Some beds are conspicuously crossbedded. The lower contact is placed at the base of the first sandstone along a covered slope formed on the much less resistant Morrison Formation.

Only the lower 3–4 m of the Lakota Formation are present in this area. Pillmore and Mapel (1963, p. E17) reported the Lakota Formation to range in thickness from 30.5 to 36.6 m in the neighboring Nefsy Divide quadrangle (fig. 1), and it thickens northward to about 90 m in the northern part of the Bear Lodge Mountains (Robinson and others, 1964, p. 23).

The Lakota Formation is considered to be Early Cretaceous in age on the basis of fossil ferns, cycads, conifers, ostracodes, and charophytes (Robinson and others, 1964, p. 26). The Lakota has been correlated with the lower part of the Cloverly Formation of central and western Wyoming (Cobban and Reeside, 1952, chart 10b).

TERTIARY INTRUSIVE AND VOLCANIC ROCKS

INTRODUCTION

The Tertiary intrusive rocks in the southern Bear Lodge Mountains are a group of interrelated alkalic rocks that have a relatively high potassium content and a low silica content. These rocks form a central mass 8.4 km long by about 3.4 km wide that underlies the central part of the area. Other smaller intrusive bodies are intruded into both the sedimentary rocks surrounding the main mass and into older intrusive rocks (fig. 5*A*). They are especially numerous northwest of the main mass along Lytle and Hershey Creeks, where more than 30 separate intrusive bodies have been recognized (pl. 1). The intrusive rocks form dikes, sills, irregular bodies, and possibly laccoliths. These bodies cut older rocks ranging from Precambrian to Jurassic in age. A similar intrusive cuts rocks of Early Cretaceous age 1.6 km west of the area (Pillmore and Mapel, 1963, pl. 1). The intrusive rocks are overlain within the area by both the White River and Ogallala Formations. Both of these formations contain subangular clasts of Tertiary intrusive rocks.

The Tertiary igneous rocks that are now exposed represent, for the most part, a composite sequence of alkalic rocks that were intruded into the older rocks at a fairly shallow depth. These rocks tend to be porphyries, as they were emplaced close to the surface and cooling rate was rapid. Flow banding is common in many of the intrusives (fig. 5*B*), although in the more altered rocks it may be difficult to discern. Flows and pyroclastic deposits were formed in a few places where the magma reached the surface. A vesicular flow top was noted on the ridge at the head of Whitelaw Creek in the SE¼SE¼ sec. 7, T. 52 N., R. 63 W. Tops of flows are commonly difficult to determine, as not all vesicular rocks are extruded on the surface. Pyroclastic deposits, on the other hand, are easier to identify and give proof of surface breaching. They are not common and occur as a few, small, widely scattered erosional remnants in the northwestern part of the area. Small bodies of fine-grained syenite or nepheline syenite are found in a few places, where cooling was slower. Syenite and nepheline syenite were also encountered in several deep holes drilled near the headwaters of Whitelaw Creek, where they make up the bulk of the rock.

The greater volume of intrusive rocks is either trachyte or phonolite. Distinction between these two rock types is commonly based on the recognition or lack of recognition of some feldspathoid. In addition to

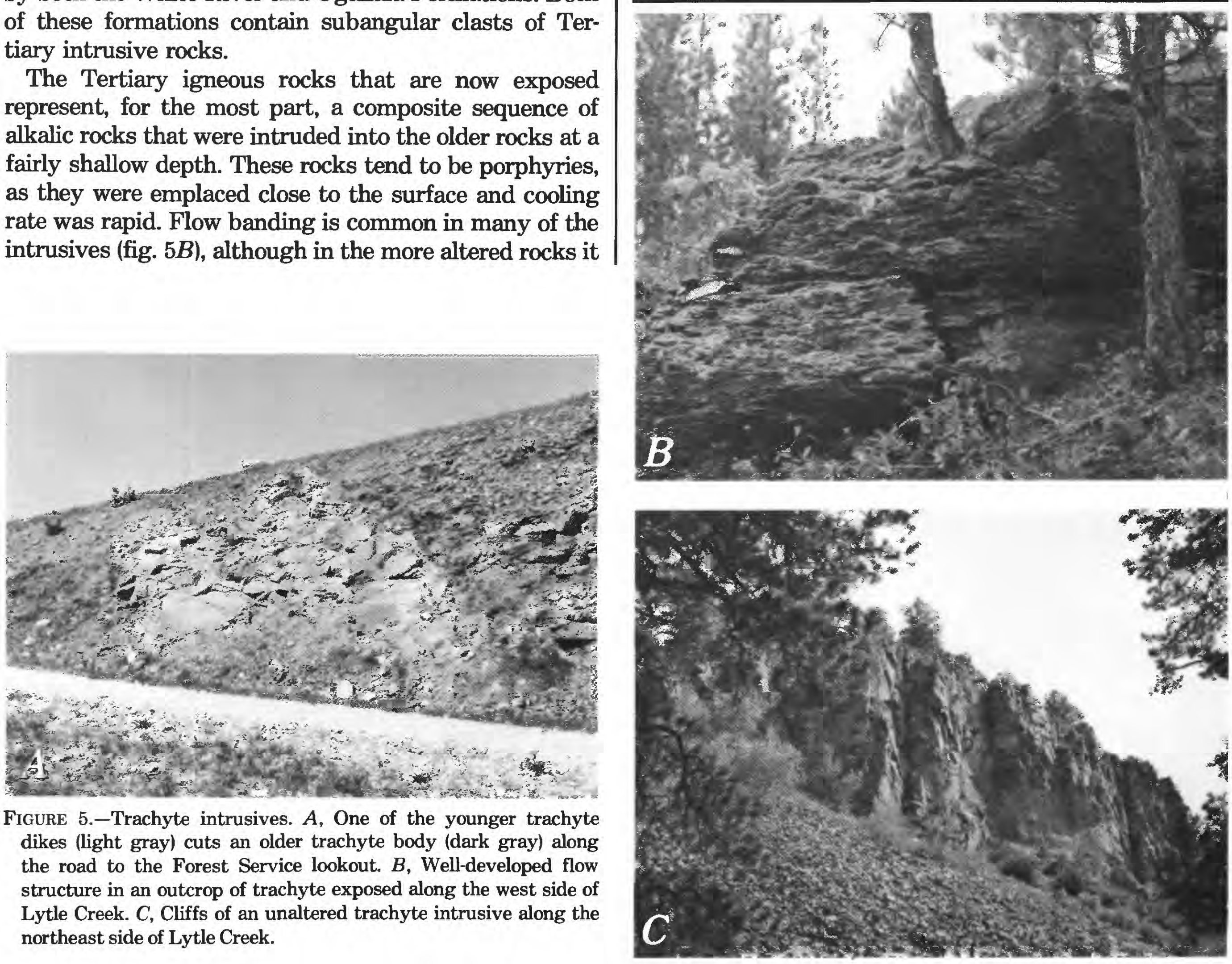

FIGURE 5.—Trachyte intrusives. *A*, One of the younger trachyte dikes (light gray) cuts an older trachyte body (dark gray) along the road to the Forest Service lookout. *B*, Well-developed flow structure in an outcrop of trachyte exposed along the west side of Lytle Creek. *C*, Cliffs of an unaltered trachyte intrusive along the northeast side of Lytle Creek.

trachyte and phonolite, lesser amounts of latite and minor amounts of syenite, nepheline syenite, lamprophyre, pseudoleucite porphyry, carbonatite, and intrusive breccia were noted within the main mass or in outlying intrusives.

The distinguishing of various rock types from one another or of bodies of the same rock type formed at different times is difficult for two reasons: (1) a single intrusive unit is commonly not homogeneous, and (2) most of the intrusive rock has been hydrothermally altered after formation. The phenocrysts in the different porphyritic rocks are commonly used to distinguish between the various rock types. Phenocrysts are an unreliable guide to rock type in the Tertiary intrusive rocks of the Bear Lodge Mountains; in part this is because not all rocks of the same composition have phenocrysts. For example, one intrusive rock may have well-developed rectangular phenocrysts of sanidine as long as 2 cm, whereas another may have few or no visible phenocrysts. Yet in places rocks with 15 percent of large sanidine phenocrysts can be traced a few meters laterally into a nonporphyritic rock. Phenocrysts are an unreliable guide in this study area, because minor changes in composition in the same dike may result in different suites of minerals. For example, in the southern part of a dike that crosses Lytle Creek in the S½ sec. 12, T. 52 N., R. 64 W., phenocrysts consisted of 24 percent hornblende, 6 percent magnetite, and 5 percent biotite. Phenocrysts from near the north end of this same dike, however, consisted of 20 percent sanidine, 8 percent hornblende, 4 percent magnetite, and less than 1 percent biotite.

During the waning stages of Tertiary intrusion, many of the intrusive rocks were fractured and altered by hydrothermal solutions. This alteration is most intense in the intrusives in the central part of the Bear Lodge dome, although most of the rocks show some sign of alteration. In many places most of the mafic minerals have been partly or entirely destroyed. In some places only crystal molds filled or partly filled with iron oxides indicate the former presence of mafic minerals. Nepheline is also easily altered to a mixture of compound feldspar and clay, which occur in hexagonal holes. Less altered rocks are most commonly found in some of the smaller intrusives peripheral to the major igneous mass. Thus, many of the outlying rock types are more easily identified than those in the main body, and here I have separated syenite, lamprophyre, pseudoleucite porphyry, and latite from trachyte and phonolite. In the central mass of Tertiary intrusion, these rocks were not mapped separately, but an intrusive breccia body, a carbonatite, and several younger dikes were readily distinguishable. The younger dikes were intruded into the central body of the intrusion during the waning stages of Tertiary magmatism after most of the hydrothermal alteration was completed. These unaltered dikes with their greenish-gray matrices stand out from the surrounding bleached, light-gray to white older rocks. These latter dikes, although not all of the same composition, have also been mapped separately (pl. 1). A large, poorly exposed, intrusive breccia body in the northern part of the central mass was crudely outlined. Many carbonatite dikes were intercepted during drilling in secs. 17 and 18, T. 52 N., R. 63 W., but only one such dike in the SE corner sec. 7, T. 52 N., R. 63 W. is exposed and mapped on the surface (pl. 1).

PHONOLITE AND TRACHYTE

These two rock types make up the bulk of the Tertiary intrusive rocks exposed in the southern Bear Lodge Mountains. They not only make up the greater part of the core of the Bear Lodge dome, but they also make up most of the smaller separate intrusions that occur on the flanks of this dome (pl. 1; fig. 5*C*).

Phonolite and trachyte are discussed together in this report because of the difficulty in separating these two rock types in the field or laboratory. Separation of these two rock types is based on silica content. A rock is considered a trachyte when sufficient silica is present to form feldspar from all the alkalies; the rock is a phonolite when it contains insufficient silica to form feldspars from all the alkalies. Thus, the presence of a feldspathoid, such as nepheline, denotes a silica deficiency. Feldspathoids generally form small inconspicuous crystals that in many places are not readily identifiable in hand specimens. Nepheline may occur only in the matrix and its presence may be determinable only by chemical analysis. For example, nepheline was not identified in thin sections of samples collected from an intrusive body just east of Jim Wayne Canyon. The composition of this sample (table 2, No. 10), however, indicated a deficiency of silica (3.4 percent nepheline) (table 2, No. 10). Thus, these two rock types are in many places not readily separable in the field. Phonolite and trachyte may be light gray, dark gray, or greenish gray, although where stained by iron oxides they are commonly shades of brown. They are commonly porphyritic with most having 20–35 percent phenocrysts, although some have as little as 2 percent and others as much as 95 percent. The most common phenocrysts are distinctive white tabular crystals of sanidine, which range in size from about 1 to 35 mm. Dull-white hexagonal phenocrysts of nepheline (1–6 mm in diameter) in amounts up to 25 percent are visible in some of the phonolite. Small trapezohedrons of pseudoleucite were noted in a few places. Plagioclase phenocrysts were also noted in a few

TABLE 2.—*Chemical analyses and normative compositions in weight percent of Tertiary intrusive rocks*

[Sample Nos. 1-10, analysts, Hezekiah Smith and Lowell Artis; sample No. 11 collected by N. H. Darton; analyst, George Steiger (Darton, 1965, p. 6); sample No. 12, analysts, K. F. Coates and Hezekiah Smith. Leaders (--), none]

Constituent or mineral	Sample No. 1	2	3	4	5	6	7	8	9	10	11	12
						Chemical analyses						
SiO_2	52.3	54.3	58.7	58.9	56.7	55.4	56.4	57.0	58.1	59.2	55.14	60.1
Al_2O_3	15.0	16.4	17.1	16.8	17.4	19.2	20.5	17.7	21.8	17.2	18.98	16.9
Fe_2O_3	6.1	5.0	5.5	5.7	3.4	2.3	1.8	2.4	1.5	2.6	2.60	3.5
FeO	2.5	1.7	.76	.80	1.8	1.5	.40	1.5	.48	1.3	1.62	1.4
MgO	3.2	1.3	1.7	1.5	1.4	.77	.23	1.2	.54	1.1	.32	1.4
CaO	5.9	3.5	3.8	3.4	4.1	3.3	.90	3.5	1.1	2.8	3.96	3.5
Na_2O	2.8	4.8	5.0	4.9	4.9	5.5	8.3	5.2	6.4	5.5	5.38	5.1
K_2O	6.5	6.4	3.7	3.9	5.2	7.0	6.4	6.2	6.7	6.5	6.64	5.8
H_2O+	1.9	2.7	.83	.84	1.1	2.8	2.9	2.3	2.9	1.9	3.70	.91
H_2O-	1.1	1.4	.76	.53	.54	.52	.34	.56	.47	.42	.63	.52
TiO_2	1.4	1.1	.84	.80	.68	.52	.18	.54	.16	.59	.50	.82
P_2O_5	.57	.19	.46	.43	.31	.13	.04	.14	.04	.13	.17	.22
MnO	.14	.15	.14	.10	.10	.12	.14	.12	.10	.12	Trace	.11
CO_2	.12	.01	.03	.08	1.0	.07	.07	.36	.05	.01	.00	.24
	99.53	98.95	99.32	98.68	98.63	99.13	98.60	98.72	100.34	99.37	99.64	100.52
						Normative compositions						
Quartz	--	--	7.08	7.74	1.38	--	--	5.04	--	--	--	3.24
Orthoclase	39.48	40.03	22.24	23.91	31.69	43.37	39.48	26.69	40.59	39.48	41.14	35.03
Albite	23.06	31.44	42.97	42.44	42.97	26.72	34.06	40.87	39.82	41.39	29.87	39.82
Anorthite	10.29	4.45	13.90	12.79	10.01	7.51	.56	15.29	5.56	3.34	8.62	8.06
Nepheline	--	6.25	--	--	--	11.36	20.73	--	8.52	3.41	9.37	--
Hypersthene	1.80	--	3.70	3.40	2.70	--	--	2.10	--	--	--	.40
Diopside	12.74	7.34	1.51	1.36	2.45	4.81	1.30	2.16	--	6.05	1.94	6.70
Wollastonite	--	1.86	--	--	--	1.51	1.04	--	--	1.39	3.60	--
Olivine	.84	--	--	--	--	--	--	--	1.96	--	--	--
Corundum	--	--	--	--	--	--	--	--	2.24	--	--	--
Magnetite	4.41	2.78	.46	.46	4.18	3.48	1.16	3.71	1.39	2.55	3.71	2.32
Hematite	3.20	3.19	5.28	5.60	.64	--	1.12	--	.64	.96	.16	1.92
Ilmenite	2.89	2.28	1.67	1.52	1.37	1.06	.46	1.06	.30	1.22	.91	1.52
Apatite	1.34	--	1.34	1.01	.67	--	--	--	--	--	.34	.34
Calcite	--	--	--	.20	2.40	--	--	--	--	--	--	--
Na_2O_3	.32	--	--	--	--	.21	.21	.95	--	--	--	.64
TOTAL--	100.37	99.62	100.15	100.23	100.46	100.03	100.12	97.87	101.02	99.79	99.66	99.99

SAMPLE DESCRIPTIONS

1. Lamprophyre collected on ridge top on west side of the North Fork of Miller Creek, NE1/4 NE1/4 sec. 23, T. 52 N., R. 64 W.
2. Pseudoleucite porphyry from east side of road that follows a tributary of Lytle Creek, SE1/4 SE1/4 sec. 11, T. 52 N., R. 64 W.
3. Latite from ridge top about 400 m east of paved road, SE1/4 SW1/4 sec. 28, T. 52 N., R. 63 W.
4. Latite from roadcut SW1/4 SW1/4 sec. 28, T. 52 N., R. 63 W.
5. Latite from roadcut near headwaters of Ogden Creek, SW1/4 NW1/4 sec. 28, T. 52 N., R. 63 W.
6. Phonolite from dike on lookout tower road, SE1/4 SE1/4 sec. 20, T. 52 N., R. 63 W.
7. Phonolite from small intrusive body on ridge, SW1/4 NW1/4 sec. 3, T. 51 N., R. 63 W.
8. Trachyte from Bock Mine to west of lookout tower, SW1/4 SE1/4 sec. 20, T. 52 N., R. 63 W.
9. Phonolite from intrusive body in southeast corner of area, NE1/4 SE1/4 sec. 3, T. 51 N., R. 63 W.
10. Trachyte from intrusive body on ridge to east of Jim Wayne Canyon, NW1/4 SW1/4 sec. 30, T. 52 N., R. 63 W.
11. Phonolite from Warren Peaks (Darton, 1905, p. 6).
12. Trachyte from intrusive body that crosses Lytle Creek, SE1/4 sec. 2, T. 52 N., R. 64 W.

samples. The principal mafic mineral is aegirine-augite, which may make up as much as 20 percent of the rock but is generally less than half this amount. This mineral occurs in small, greenish-black, prismatic crystals. Tiny black magnetite grains commonly make up a few percent of the rock. Sphene, apatite, and biotite are other common accessories that generally make up less than 1 percent of the rock. Other phenocrysts noted in a few samples are hornblende and the black garnet, melanite. The phenocrysts are set in a brown matrix, which contains numerous feldspar and, in some places, mafic microlites. Staining tests with sodium cobaltinitrite indicate that much of the feldspar in the matrix is potassium rich.

Chemical analyses on six samples of phonolite and trachyte are reported in table 2 (Nos. 7-12). These samples are noted for their low silica content, and four of the six contain nepheline in the norm. They also have relatively high potassia and soda content. The high alkali content and low silica content of these rocks are also apparent in the norms, which have high orthoclase and albite contents, as well as containing nepheline. The relations between CaO, Na_2O, and K_2O are shown in figure 6 along with that of various average rock types compiled by LeMaitre (1976). The Bear Lodge rocks with the exception of the lamprophyre contain about equal amounts of Na_2O and K_2O. The CaO contents of the trachyte and phonolite show considerable spread; most samples are somewhat richer in CaO than LeMaitre's average trachyte or phonolite. The magnesia and total iron contents are similar in the trachyte and phonolite (table 2). The MgO content does not exceed 1.5 percent, and the total iron oxide content ranges from about 2 to 4 percent. Plotting the MgO content against the total iron content for all the analyses of Tertiary intrusive rocks of the southern Bear Lodge Mountains shows that in general the MgO content increases proportionally as the total iron oxide content increases (fig. 7).

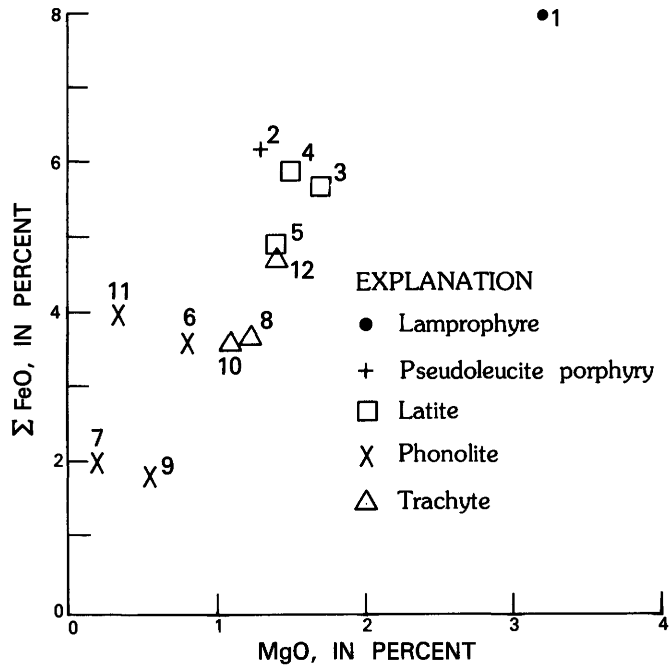

FIGURE 7.—Relation of MgO to total iron oxide in the Tertiary intrusive rocks of the southern Bear Lodge Mountains. Numbers used correspond to those used in table 2.

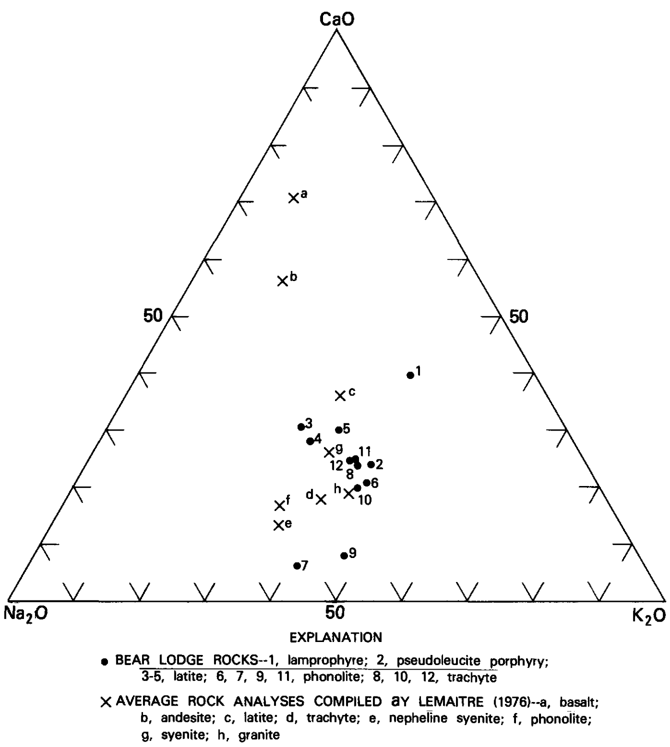

FIGURE 6.—Relations of K_2O, Na_2O, and CaO in the Tertiary intrusive rocks of the southern Bear Lodge Mountains compared to average rock analyses by LeMaitre (1976). Numbers on Bear Lodge rocks correspond to those used in table 2.

LATITE

Fine-grained latite is found principally in the core of the Hershey Creek dome and in places in the southeastern part of the main intrusive complex. Latite makes up all the Tertiary rocks in the Hershey Creek dome except for two trachyte dikes and a small patch of pyroclastic rocks. In the southeastern part of the main complex, scattered latite intrusives occur south of Richardson Creek. The latite in Hershey Creek dome is unaltered and the phenocrysts are readily recognizable. Here it is mapped separately. The latite in the southeastern part of the main Tertiary igneous mass is partly altered, fine grained, and difficult to distinguish from the other Tertiary igneous rock types without the aid of a microscope. These rocks were included in my mapping with the other Tertiary intrusive rocks of the central complex. Most of the latite forms irregular masses presenting indistinct contacts with other Tertiary intrusive rocks. A 3- to 5-m-thick north-trending latite dike that cuts trachyte is well exposed in a roadcut in the headwaters of Ogden Creek. Not all the latite is younger than all the trachyte, as several dikes of trachyte cut latite in the Hershey Creek dome. In some places, the latite has flow banding. This can be seen on the ridge east of the main road and southwest of the headwaters of Ogden Creek where weathering along flow banding has developed into irregular platy layers, 1–5 cm thick. These layers dip 25°–40° N. (pl. 1).

Latite is a light-gray porphyritic rock, generally with 30–35 percent small phenocrysts, although as much as 65 percent phenocrysts have been noted. Most phenocrysts are 0.5–1.2 mm long; a few as long as 3 mm occur in some places. White, elongate plagioclase (8–50 percent), which is either oligoclase or andesine, is commonly the most abundant phenocryst. Black, prismatic hornblende (<1–15 percent) is generally the most abundant mafic mineral, although aegirine-augite (trace to 6 percent) may be locally more common. Other minerals identified are biotite (0–2 percent), augite (0–2 percent), magnetite (1–4 percent), apatite (trace to <1 percent), sphene (0–<1 percent), and zircon (0 to trace). The matrix is aphanitic and consists principally of tiny plagioclase microlites with some black mafic minerals and some indeterminate leucocratic minerals. Staining of all thin sections with sodium cobaltinitrite indicates potassium in the matrix.

Three samples of latite from sec. 28, T. 52 N., R. 63 W. in the southeastern part of the area were chemically analyzed (table 2, Nos. 3, 4, and 5). These rocks contain the least amount of K_2O of any rocks analyzed. They also differ from the trachytes and phonolites with which they are generally associated by having more total iron oxides, MgO, TiO_2, and P_2O_5, and less Na_2O and total water. The normative mineral compositions of the three latites all have quartz, more than 40 percent albite, and a substantial amount of orthoclase. Each sample has similar proportions of alkalies (fig. 6). The CaO content, however, is somewhat lower that that of the average latite given by LeMaitre (1976) and shown on figure 6. All three of these samples would also be classified as latites according to the system of Rittmann (1952).

SYENITE AND NEPHELINE SYENITE

These two rock types are the holocrystalline phase of trachyte and phonolite. They are sparse at the surface in the study area. Syenite and nepheline syenite were mapped in three areas: (1) a dike approximately 190 m in length cuts the Minnelusa Sandstone near the east edge of the area 300 m north of Ogden Creek; (2) several outcrops occur along one of the tributaries to Winchester Creek in the central part of sec. 6, T. 52 N., R. 63 W.; and (3) several small bodies intrude trachyte and phonolite 1,800 m east of Fort Ranch in the northwestern part of the study area. In addition, syenite and nepheline syenite are common at depth in several drill holes located near the headwaters of Whitelaw Creek. Most of the larger bodies of trachyte and phonolite probably grade downward into syenite and nepheline syenite where the cooling of this alkali magma was slower.

Average grain size of various samples of syenite or nepheline syenite ranges from about 0.1 to 3 mm or from fine to medium grained. Most of the small bodies of this rock exposed at the surface are syenite, although an intrusive on the nose of the mountain 1,800 m east of Fort Ranch is nepheline syenite. The syenite consists of 60–80 percent potassium feldspar, a little plagioclase, and 20–35 percent aegirine-augite or augite. Small black crystals of magnetite make up 1–8 percent of the rock, and apatite, sphene, and hornblende range from a trace to 1 percent of the rock. The nepheline syenite east of Fort Ranch is in general similar but contains less potassium feldspar and 22 percent nepheline. Samples from drill holes from near the headwaters of Whitelaw Creek have as much as 20 percent biotite, but only a little pyroxene. The black garnet, melanite, also makes up several percent of some of these rocks.

LAMPROPHYRE

Lamprophyre is the term applied to those porphyritic igneous rocks whose phenocrysts consist almost entirely of mafic minerals and whose groundmass consists of the same mafic minerals and leucocratic minerals. Five lamprophyre dikes and sills have been noted in the southern Bear Lodge Mountains. The largest is a sill (fig. 8*A*) along the western margin of the area that crosses the North Fork of Miller Creek. The sinuous outcrop pattern of this sill has been traced for 4.5 km and it is approximately 4–12 m thick. Two other lamprophyre sills are exposed within 150 m of each other 700 m southeast of Fort Ranch in the northwest corner of the area. These two sills are approximately 45 m vertically

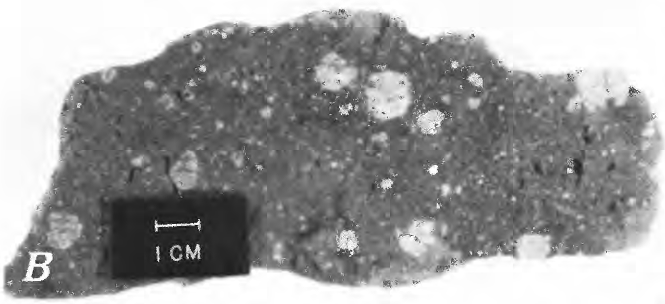

FIGURE 8.—Tertiary intrusive rocks. Photographs *B*, *C*, and *D* by L. S. Hedricks, U.S. Geological Survey. *A*, Lamprophyre sill (between lines) intruded into the Sundance Formation along the north side of Miller Creek. The flaggy sandstone above the lamprophyre belongs to the Hulett Sandstone Member. *B*, Pseudoleucite porphyry. Large white pseudoleucite and small white sanidine phenocrysts set in a dark-gray aphanitic matrix. *C*, Close-up of pseudoleucite phenocryst showing pattern formed by white, potassium feldspar rims around gray central part consisting of nepheline and clay. *D*, Trachyte consisting of large white sanidine and small black aegerine-augite phenocrysts set in a gray aphanitic matrix.

apart with one being intruded into the upper part of the Spearfish Formation and the other into the lower part of the Sundance Formation. Two lamprophyre dikes too small to show on plate 1 were noted in the central part of the intrusive complex. One is a small dike exposed on the southeast side of Bear Den Creek, 1,000 m southwest of the U.S. Forest Service Lookout tower; the other crosses a pit on Smith Ridge 1,330 m south of Davis Spring.

The lamprophyres vary somewhat in mineralogy, with augite being the most abundant phenocryst in the large sill that crosses Miller Creek, biotite in the two sills south of Fort Ranch, and hornblende on the exposure on Smith Ridge. The sill on Miller Creek is made up of small phenocrysts up to about 1 mm in length that consist of 18–25 percent augite, 2–5 percent magnetite, and less than 1 percent apatite and biotite set in a matrix containing many small mafic and plagioclase microlites. The sill is freshest on the ridge south of Miller Creek; it is commonly altered along Miller Creek, and in specimens collected here just above the road, most of the pyroxene has been altered to limonite. This sill contains oval amygdules 3–20 mm long, filled with calcite and feldspar. The only visible phenocryst in the sills south of Fort Ranch is biotite, which makes up 10–20 percent of the rock. These sills also have small, white, oval amygdules. The small lamprophyre dike on Bear Den Creek consists of 60 percent mafic phenocrysts (30 percent augite, 15 percent biotite, 10 percent magnetite, 4 percent hornblende, and 1 percent apatite) and 5 percent plagioclase phenocrysts set in a gray aphanitic matrix. The fine-grained lamprophyre exposed on Smith Ridge consists of 85 percent mafic minerals (40 percent hornblende, 15 percent chlorite, 10 percent epidote, 10 percent biotite, and 10 percent sphene) set in a light-gray matrix made up mainly of plagioclase.

A chemical analysis of the lamprophyre that crosses the North Fork of Miller Creek is given in table 2 (No. 1). This analysis compared to those of phonolite and trachyte is low in SiO_2, Al_2O_3, and Na_2O, but high in Fe_2O_3, FeO, MgO, CaO, TiO_2, and P_2O_5. The high mafic-mineral content in the mode is reflected in the 27 percent mafic minerals in the normative compositions, which includes 12.7 percent diopside and 4.4 percent magnetite (table 2). The rocks of the southern Bear Lodge Mountains are noted for their high K_2O content, and this lamprophyre in spite of its high content of mafic minerals is no exception, having 6.4 percent K_2O.

PSEUDOLEUCITE PORPHYRY

The pseudoleucite porphyry is a type of phonolite, but the presence of large pseudoleucite crystals makes it distinctive from all the other intrusives in the area (figs. 8*B*, 8*C*). The pseudoleucite porphyry occurs principally in the northwestern part of the area, where it forms one long intrusive and several smaller ones. The large intrusive is principally a sill in the middle of the Sundance Formation, but in places it has crosscutting relations. The sill-like body is the westernmost intrusive in the study area and occurs about 3 km south of Fort Ranch. It has an irregular, sinuous form and a length of approximately 2,600 m. Thickness is difficult to measure because at many places it caps a ridge, but it is approximately 6 m thick. Five other small pseudoleucite sills and dikes were mapped in the same area. Two small lens-like bodies occur in the middle of the Sundance Formation north of the big body, two dikes cut the Morrison Formation south of it, and an intrusive body occurs along the road to its southeast. The longest dimension on any of these bodies is 140 m.

The pseudoleucite porphyry is a medium-gray porphyritic rock containing 5–20 percent white pseudoleucite and 3–10 percent sanidine set in an aphanitic matrix that has microlites of both feldspar and mafic minerals. The sanidine phenocrysts are inconspicuous, as they are generally less than 1 mm in length. The pseudoleucite crystals, on the other hand, range from 1 to 38 mm in diameter, with most of them between 5 and 10 mm. The pseudoleucite crystals are round to octagonal, and some crystals show the outline of several intergrown minerals (fig. 8*C*). The pseudoleucite crystals are made up of intergrowths of potassium feldspar, nepheline, and clay. Generally the potassium feldspar forms a narrow white rind around the exterior of the crystal (fig. 8*C*), although in some places this rind is pink. Potassium feldspar also forms narrow septa cutting across the interior of the crystal. The feldspar can be distinguished from the other minerals on a weathered surface, because it stands out in relief.

Pseudoleucite porphyry, like most of the other rocks in this area, has a high potassium content. The presence of abundant potassium was noted both from staining this rock with sodium cobaltinitrite solution and by chemical analysis of one sample (table 2, No. 2). This sample contained 6.4 percent K_2O, which is similar to the amount found in trachyte and phonolite in the southern Bear Lodge Mountains. This sample was also deficient in silica, containing less SiO_2 than all the other rocks analyzed except the lamprophyre. Classified on the basis of its chemical composition according to the system used by Rittmann (1952), this rock would be a dark leucite phonolite.

PYROCLASTIC DEPOSITS

Pyroclastic deposits are rare in the southern Bear Lodge Mountains, but they are geologically important because they indicate that the Tertiary igneous rocks breached the surface in a few places. These deposits occur in two areas: (1) two separate patches of pyroclastics are found on the northeast side of Lytle Creek near the eastern border of sec. 13, T. 52 N., R. 64 W., and (2) a small area of pyroclastics is found on a small ridge in the center of the Hershey Creek dome (pl. 1). The position of most of the pyroclastics along the valley walls on the steep northeast side of Lytle Creek and part way up the south side of Hershey Creek suggest that they were preserved principally along Tertiary valleys. The pyroclastic deposits, which were at one time more widespread, have been largely removed by erosion. Those patches preserved are where the pyroclastics were thicker and somewhat protected in the valleys.

The pyroclastic deposits range from volcanic breccia to tuff. The volcanic breccia is medium gray to light brown and made up of subangular to subrounded fragments, a few to 40 mm across, set in a glassy matrix. Fragments are chiefly porphyritic volcanic rock containing small sanidine phenocrysts. A few of the lithic fragments in the Hershey Creek dome locality are of syenite and fine-grained quartzite. The tuff is light brown to white in color. Fragments are principally lithic, although this rock can contain as much as 10 percent crystal fragments. The lithic fragments are chiefly volcanic glass, aphanitic volcanic rock full of microlites, and porphyritic volcanic rock. Minor syenite and quartzite fragments also occur in the tuff. Crystal fragments include sanidine, magnetite, plagioclase, and apatite. The matrix, which in thin section is a devitrified glass, was an ash. Both volcanic breccia and tuff commonly contain small (as much as 1 mm long) vesicles filled with opal and (or) chalcedony. Staining tests using sodium cobaltinitrite indicated abundant potassium minerals in both the volcanic fragments and the ash.

CARBONATITE

Carbonatite exposures are rare in the Bear Lodge Mountains, and only one known carbonatite dike was found at the surface. This dike occurs in two bulldozer trenches on a ridge in the southeast corner of sec. 7, T. 52 N., R. 63 W. It strikes N. 36° W., and dips 62° SW. It has been traced for 26 m and is approximately 4.6 m thick. Carbonatite dikes have also been cut in seven drill holes in the NE¼ sec. 18 and NW¼ sec. 17, T. 52 N., R. 63 W. More than 20 carbonatite dikes were cut in one 435-m-deep hole. These dikes range from thin stringers to 3.5 m in thickness. All dip steeply.

The weathered carbonatite dike exposed at the surface is a brown to yellowish-brown mottled rock in contrast to unweathered carbonatites from the drill holes, which are principally white or light-gray rocks banded or streaked with pink, green, white, or purple accessory minerals. All the carbonatites consist principally of calcite. Other minerals vary in kind and amount from place to place. Rare-earth minerals are plentiful in many samples. The commonest rare-earth minerals are pink ancylite [(Ce,La)(Sr,Ca)$(CO_3)_2(OH)\cdot H_2O$] and brown bastnaesite [(Ce,La)FCO_3]. Although those two minerals occur together in a few samples, only one or the other is found in most samples. Ancylite was not found in the dike exposed on the surface. Strontianite fluorite, and the sulfides, pyrite, pyrrhotite, sphalerite, and galena, occur in most samples, although the quantity of each may be highly variable with one or more being common in some places and absent in others. Acmite and actinolite are locally abundant. Other minerals found in minor amounts in some samples are magnetite, marcasite, muscovite, barite, biotite, quartz, siderite, potassium feldspar, and rutile.

The mineralogy of carbonatite samples obtained from the dike on the surface varies somewhat from that found in the drill cores. At the surface bastnaesite intergrown with minor synchysite [(Ce, La) Ca $(CO_3)_2F$] is the principal rare-earth mineral. A small amount of xenotime (YPO_4) was noted in one sample. Ancylite and strontianite are absent, as are the sulfides. Hematite and goethite are fairly abundant. Bastnaesite obtained at the surface is a friable, yellowish-brown, powdery material unlike that of primary bastnaesite seen in other areas such as Mountain Pass, Calif., and Gallinas Mountains, N. Mex. The general shape of the bastnaesite patches in surface samples is similar to that of ancylite from the drill core. Bastnaesite in the carbonatites of the southern Bear Lodge Mountains, because of its apparent relationship to the land surface and its association with limonite, is probably formed by weatherings of ancylite. Adams and Young (1961, p. C293) also have noted secondary bastnaesite in the Pikes Peak Granite in southern Jefferson County, Colo., which they believed to have formed from allanite by reaction with late-stage magmatic solutions.

The thorium and uranium contents of 12 samples of carbonatite were determined by gamma-ray spectrometer (table 3); the thorium content ranges from 54 to 1,510 ppm and uranium ranges from 10 to 340 ppm.

TABLE 3.—*Gamma-ray spectrometric analyses of carbonatites in the southern Bear Lodge Mountains in parts per million*

[Analysts, C. M. Bunker and C. A. Bush]

Sample No.	MHS-1-77	MHS-2-77	MHS-3-77	MHS-4-77	MHS-7-77	MHS-10-77	MHS-11-77	MHS-13-77	MHS-15-77	MHS-20-77	MHS-22-77	MHS-25-77
Thorium	68.	115.	149.	54.	155.	225.	860.	445.	110.	182.	1,510.	204.
Uranium	11.	27.	17.	16.	10.	29.	82.	19.	45.	16.	340.	26.
Thorium:uranium	6.2	4.3	8.8	3.4	15.5	7.8	10.5	23.4	2.4	11.4	4.4	7.8

These carbonatites have greater thorium concentrations than any other type of Tertiary intrusive rock, although the concentration is lower than in veins. The thorium-to-uranium ratio varies from 2.4 to 23 (table 3). In addition semiquantitative spectrographic analyses of 17 samples (table 4) show that these carbonatites compared to most other rocks contain abnormal amounts of rare earths, strontium, and barium. The Bear Lodge carbonatites contain abundant rare earths, as do carbonatites occurring at Mountain Pass, Calif., and in the Bear Paw Mountains, Mont. Total rare-earth content of the samples analyzed from the Bear Lodge Mountains ranges from 0.58 to 64 percent (table 4). Although other samples are undoubtedly lower grade, the grade of the analyzed samples is similar to that of many of the carbonatite dikes in the Mountain Pass area (Olson and others, 1954, p. 68). The rare earths in the Bear Lodge samples are also similar to those in the Mountain Pass area in being predominantly of the light rare earths. In the 17 analyzed samples the lighter elements make up more than 95 percent of the rare-earth group.

The strontium content of the Bear Lodge carbonatites is unusually high compared with most other carbonatites, and several samples contain in excess of 10 percent. Regions containing strontium-rich carbonatites are not common, but strontium-rich carbonatites include the dolomite-barite-monazite carbonatites at Gem Park in the Wet Mountains of Colorado (Parker and Sharp, 1970, p. 19–20), niobium-bearing carbonatites of Ravalli County, Mont. (Heinrich and Levinson, 1961, p. 1442), and the massive carbonatites of Kangakunde Hill, Malawi (Holt, 1965, p. 14–15).

The barium content of the Bear Lodge carbonatites ranges from 0.10 to 3.0 percent (table 4). Barium in this range is a common constituent of many carbonatites in the United States and other countries.

Considerable niobium and phosphorus are found in many carbonatites, such as in the massive carbonatite at Iron Hill in the Powderhorn district of central Colorado and at Oka in Quebec, Canada. The niobium content of the Bear Lodge carbonatites is relatively low, ranging from less than 10 to 50 ppm. The phosphorus of these samples is also low, and although not shown in table 4, was less than the limit of detection (3,000 ppm) in all samples.

INTRUSIVE BRECCIA

Intrusive breccia bodies of several ages are found in the central part of the Bear Lodge dome. Most of these breccia bodies form small dikes that cut Precambrian granite and older Tertiary intrusives. An irregular breccia body having a length of 1,470 m and a maximum width of 700 m is found just north of the headwaters of Whitelaw Creek in the northern part of the central core (pl. 1). The breccia is poorly exposed and its presence is generally noted either from exposures in trenches or

TABLE 4.—*Semiquantitative spectrographic analyses of samples of carbonatites in the southern Bear Lodge Mountains in parts per million*

[Analyst, N. M. Conklin, U.S. Geological Survey; <, less than value indicated; >, greater than value indicated]

Sample No.	BL-1-76	BL-2-76	BL-3-76	BL-7-76	BL-14-76	BL-16-76	BL-17-76	BL-18-76	MHS-25-77	MHS-1-77	MHS-2-77	MHS-3-77	MHS-4-77	MHS-7-77	MHS-10-77	MHS-13-77	HS-20-77
Lanthanum	10,000	15,000	7,000	15,000	10,000	15,000	10,000	15,000	10,000	15,000	30,000	3,000	10,000	1,500	15,000	15,000	1,500
Cerium	15,000	15,000	10,000	20,000	10,000	15,000	15,000	15,000	15,000	30,000	30,000	7,000	15,000	3,000	15,000	30,000	7,000
Praesodymium	1,500	2,000	1,500	3,000	1,500	1,000	3,000	2,000	2,000	1,500	3,000	700	1,000	200	1,500	3,000	300
Neodymium	3,000	5,000	3,000	7,000	3,000	15,000	5,000	5,000	7,000	3,000	3,000	1,500	2,000	1,000	3,000	7,000	1,000
Samarium	<100	<100	<100	1,000	<100	3,000	<100	500	300	300	300	150	300	<200	300	700	<200
Europium	<100	<100	<100	<100	<100	500	<100	<100	<100	<100	<100	<100	<100	<100	100	150	<100
Gadolinium	<50	<50	<50	<50	<50	1,000	<50	<50	300	<200	<200	<200	<200	<200	<200	<200	<200
Terbium	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
Dysprosium	<50	<50	<50	<50	<50	<50	<50	<50	<500	<200	<200	<200	<200	<200	<200	<200	<200
Holmium	<20	<20	<20	<20	<20	50	<20	<20	30	<50	<50	<50	<50	<50	<50	<50	<50
Erbium	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Thulium	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ytterbium	7	7	10	20	5	100	3	7	30	<10	<10	<10	<10	3	7	7	7
Lutetium	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Yttrium	200	200	200	200	150	1,000	100	150	500	70	50	70	100	70	150	100	150
Total rare earths	29,707	37,207	21,710	46,220	24,155	51,650	33,103	37,657	35,160	49,870	66,380	12,420	28,400	5,773	35,057	55,957	9,957
Barium	2.000	2,000	5,000	15,000	1,500	30,000	1,000	2,000	1,000	2,000	3,000	700	1,500	700	3,000	20,000	300
Beryllium	1.5	<1.5	7	7	<1.5	20	<1.5	<1.5	3	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5	7	<1.5
Bismuth	30	30	100	100	<30	<50	<30	<50	30	30	<15	70	<15	30	15	100	30
Copper	15	10	<1	1,000	100	20	30	150	30	30	15	200	50	50	10	200	100
Lead	300	700	1,500	2,000	1,500	1,500	1,500	1,000	1,000	700	200	2,000	200	500	200	2,000	500
Manganese	3,000	2,000	5,000	10,000	5,000	10,000	5,000	5,000	10,000	1,500	1,500	1,500	5,000	3,000	3,000	10,000	2,000
Molybdenum	20	15	10	300	70	1,500	15	70	200	30	70	70	30	15	70	150	100
Niobium	30	20	30	50	15	15	<10	10	10	<10	<100	<10	<100	<10	<100	<100	<10
Strontium	>100,000	>100,000	>100,000	>100,000	>100,000	70,000	30,000	30,000	7,000	>100,000	>100,000	70,000	20,000	>100,000	>100,000	>100,000	30,000
Tin	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Vanadium	150	50	300	1,500	500	700	30	150	150	70	200	70	100	30	150	700	70
Zinc	500	1,500	2,000	2,000	2,000	<300	500	2,000	700	1,500	<300	2,000	<300	300	<300	1,500	300
Zirconium	<10	<10	30	150	<10	30	<10	<10	70	150	150	<10	<10	30	150	300	200

from widely scattered pieces of float. Crosscutting relations indicate breccias of several ages in a few places in this large body. Intrusive breccia dikes are common in and adjacent to the large Precambrian granite body east of Richardson Creek. In addition, intrusive breccia has been noted both east and west of Warren Peaks. Most of these areas of outcrop are small, and only the large body north of Whitelaw Creek is shown on plate 1.

The intrusive breccia consists of angular to rounded fragments of rock, a few millimeters to 10 cm across, set in a fine-grained igneous matrix. Most of the fragments are of bleached, light-gray volcanic rock with small sanidine phenocrysts. A few fragments are of coarser grained syenite. The breccia that is adjacent to and cuts the granite commonly contains granitic fragments, which were also noted by W. S. Tangier Smith (Darton and O'Harra, 1905, p. 5). Sparse quartzite fragments from the Deadwood Formation are found in these same breccias. The matrix is aphanitic to fine grained and in places has sanidine phenocrysts a few millimeters across. It is commonly weathered and has minute cavities due to the leaching of minerals, especially the mafic ones. Near the surface, the matrix is commonly colored by red or yellow iron oxides. In drill cores the intrusive breccia is gray.

YOUNGER TRACHYTE AND PHONOLITE DIKES

The younger dikes are those intrusives that intruded trachytes and phonolites that have been hydrothermally altered. Thus, the younger dikes have unaltered white sanidine phenocrysts that stand out sharply against the gray matrix (fig. 8*D*). Any crosscutting intrusives that formed prior to the hydrothermal alteration commonly are bleached and resemble the rocks that they intrude. The dikes discussed here are only those unaltered ones that intrude older igneous rocks. Similar-appearing dikes that intrude the sedimentary rocks are not included because away from the core of the Bear Lodge dome where the rocks show little alteration, these younger dikes cannot be distinguished from older ones.

The younger dikes discussed here represent the waning stages of intrusion. Seven of the 10 dikes are in the central intrusive complex; one is in a subsidiary intrusive just north of the main intrusive body; and two are in the core of the Hershey Creek dome. Others undoubtedly occur in this study area because the dikes are generally small and exposures are poor. The dikes range from about a meter to 12 m in thickness, and have been traced 30-300 m. The dikes are intruded into randomly oriented, steeply dipping fractures and do not have a preferred direction of strike. A 6-m-thick dike is well exposed in the cut of the road that leads to the lookout tower on Warren Peaks (fig. 5*A*).

The younger dikes are all porphyritic, having white, rectangular phenocrysts of sanidine that range from 1 to 25 mm long set in a dark-gray to greenish-gray matrix (fig. 8*D*). In some samples, small mafic phenocrysts are noted. The phenocryst content is highly variable, ranging from about 2 to 75 percent. Sanidine (2-50 percent) is the principal mineral. Aegirine-augite is the chief mafic mineral in most dikes, although in a dike near Corral Springs, augite was the chief mafic mineral and aegirine-augite was absent. Accessory are apatite, magnetite, sphene, and black garnet (melanite). About half the dikes contain 10-15 percent nepheline. Thus, some of the dikes are trachyte and some are phonolite.

A chemical analysis was made of the dike exposed on the road to the lookout tower in the Warren Peaks (table 2, No. 6). A comparison of this analysis with that of the older trachyte and phonolites (table 2, Nos. 7-11) does not indicate any major differences. Thus, the magma that formed this younger dike probably is derived from the same source as that which formed the older trachyte and phonolite intrusives.

AGE

The ages of four samples were determined on sanidine from four localities. Three of these localities are from intrusives in the core of the Bear Lodge dome; one is from a separate intrusive. Field relations indicate that the igneous rocks that form the core of the Bear Lodge dome consist of at least several sets of intrusive bodies, although north of Warren Peaks later alteration has made it difficult to distinguish among them. A few dikes that postdate this alteration cut the older altered intrusives. One such dike about 6.6 m thick is exposed on the road to the U.S. Forest Service lookout tower on the centralmost of the Warren Peaks (fig. 5*A*). Sanidine, which occurs as large phenocrysts, was separated from this rock for age dating (sample No. MHS-64-76). Another sample (MHS-294-79) was taken from a similar-appearing dike, 3.3 km northwest of the first dike. This dike is exposed in a small hand-dug pit on a ridge in the northeast corner of sec. 18, T. 52 N., R. 63 W. A third sample (MHS-256-79) came from a fairly fresh exposure of trachyte near the north end of the core. This sample was collected from a quarry used as a source of local road metal that lies near the northern boundary of the central part of sec. 8, T. 52 N., R. 63 W. A fourth sample of sanidine (MHS-71-76) was obtained from a fresh-appearing phonolite porphyry that is part of a satellitic intrusion on the western flank of the central intrusive core. This sample was taken along the north side of Bear Den Creek in the SE¼SW¼ sec. 30, T. 52 N., R. 63 W. The sanidine from two samples (MHS-64-76 and MHS-71-76) was analyzed for potassium and argon by R. F. Marvin, H. H. Mehnert, and Violet Merritt, U.S. Geological Survey. The other two samples were analyzed by the same three people and J. J. Kenney. The results are as follows:

Field No. MHS-	K_2O (percent; average)	^{40}Ar 10^{-10} moles/g	^{40}Ar (percent)	$^{40}Ar/^{40}K$	Age (m.y. ±2σ)
64-76	11.23	8.275	96	0.00298	50.5±0.8
71-76	12.28	6.833	84	.00225	38.3±0.6
294-79	13.87	10.21	60	.00297	50.5±1.2
256-79	6.12	4.360	87	.00288	48.8±1.7

Two other ages have also been determined by the potassium-argon method on samples from the Bear Lodge Mountains (McDowell, 1971, p. 14). Both samples were collected from rocks in the central intrusive core. One sample came from a little south of the Forest Service lookout tower and the other about 2 km south of this tower. The age of the northernmost sample, which was measured on hornblende and aegirine, is 38.8±2.1 m.y.; that of the southernmost sample, which was measured on augite and hornblende, is 48.9±1.6 m.y. The age spread among these six samples is 12.2 m.y., which represents a minimum age spread, as these samples may represent neither the youngest nor the oldest rocks in this intrusive complex.

The Bear Lodge intrusive bodies, as previously noted, are but a few of many alkalic intrusives occurring in an east-west belt from the east edge of the northern Black Hills through the Bear Lodge Mountains to the Missouri Buttes. Ages of these similar rocks have been determined on 11 minerals from nine other plutons (McDowell, 1971, p. 13-15; Hill and others, 1975). They range in age from 49.4 to 58.9 m.y. Thus, the Bear Lodge intrusives are some of the latest to be intruded in this belt.

WHITE RIVER FORMATION (OLIGOCENE)

The White River Formation consists principally of a poorly bedded, friable, tan siltstone. This formation at one time probably overlay the greater part of this region, but most of it has been stripped off the older rocks by erosion during late Tertiary time. The White River Formation is found in the northwestern part of the mapped area along the sides of flat-topped ridges, where it overlies the Spearfish Formation, Minnelusa Sandstone, Sundance Formation, and Tertiary intrusives. The White River Formation is everywhere unconformably overlain by the Ogallala Formation. In most places the White River is covered by float from the overlying Ogallala. The best exposure of the White River is in landslide scarps of two small adjoining hills on the northeast side of Lytle Creek in the SW¼SW¼ sec. 1, T. 52 N., R. 64 W. This exposure is also one of the best exposures in northeastern Wyoming, and three sections measured at this locality have been described by Brown (1952, p. 16-19) and Robinson, Mapel, and Bergendahl (1964, p. 105).

The White River Formation is mainly tan, but in places it is gray. Although most of the grains are silt sized, the grain size of much of this rock varies from that of a fine sand to a clay. The siltstone is generally noncalcareous, but within it are thin layers and irregular lenses of tan, calcareous siltstone. This calcareous siltstone is somewhat more resistant to weathering, and small ledges of this rock project out from the noncalcareous siltstone. Several layers of gravel 0.15 to 1.0 m thick are interbedded with the siltstone. The gravel was derived principally from the Tertiary intrusives.

The thickest section of the White River Formation, measured by Robinson, Mapel, and Bergendahl (1964, p. 105) on the northeast side of Lytle Creek, is 42.1 m thick; the section measured by Brown (1952, p. 19) at the same locality is 35 m thick. In other parts of the area, the White River is much thinner, and it is missing in Cole Canyon in the eastern part of the area (pl. 1).

Several different fossils were collected by Brown (1952, p. 18-19, 51) from the measured section on the northeast side of Lytle Creek. These are: (1) fossil hackberry seeds from approximately 5.5 m below the top of the White River, (2) the gastropod *Helix* sp. from 14.6 m below the top, and (3) the left maxilla from the oreodont genus *Merycoidodon* from 16.8 m below the top. The oreodont jaw, which was identified by C. B. Schultz, University of Nebraska, dates these beds as middle or late Oligocene in age. The gastropod *Helix* is similar to gastropods found in upper Oligocene beds. Brown (1952, p. 51-52) assigned the upper part of these rocks to the Brule Formation. Lower gravel-bearing units in this same section, because of lithologic similarities, were assigned to the Chadron Formation (Lugn and Brown, 1952). These two formations make up the White River Group. I have used the name White River Formation in preference to the Brule and Chadron Formations as these rocks generally are called White River in northeastern Wyoming, and they are so identified by Robinson, Mapel, and Bergendahl (1964, pl. 1) in their map of the northern and western flanks of the Black Hills uplift.

OGALLALA FORMATION (LATE MIOCENE AND PLIOCENE)

The Ogallala Formation in the southern Bear Lodge Mountains consists mainly of gravels and coarse conglomerate that lap up on the periphery of the Bear Lodge dome. This formation underlies broad, flat-topped ridges on the west, north, and northeast sides of this dome (pl. 1). The tops of these ridges, where not steepened by later erosion, dip gently away from the center of the dome at angles of from 1° to 4°. The upper surface weathers to form about a half-meter of soil that generally supports a thick growth of pine, although some of the ridges in the northern part of the area are covered by grass. The Ogallala is generally poorly exposed due to ease of weathering and the lack of topographic relief. The best exposures occur in recent landslide scarps like those found just north of Cole Canyon and along the northeast side of Lytle Creek.

The Ogallala Formation consists of poorly sorted conglomerate interbedded with thin irregular layers of sandstone or siltstone (fig. 9). The conglomerate clasts (pebbles to boulders) may range from 0.4 to 45 cm across, although in some layers the clasts are more evenly sized. The clasts are subangular to subrounded in shape and consist principally of trachyte and phonolite. In addition, minor amounts of granite, quartzite from the Deadwood Formation, Minnelusa Sandstone, and Pahasapa Limestone are present in some places. These clasts are set in a white, calcareous sandstone matrix. The interbedded sandstone thickens and thins along strike (fig. 9) and in some places pinches out. This rock is friable, and generally calcareous, and ranges from white to tan in color. In places it contains scattered rounded pebbles of trachyte or phonolite. In one place along a narrow ridge top on the north side of Cole Canyon, a 0.3 to 0.6-m-thick gray limestone bed containing fragments of intrusive rock was noted. The Ogallala Formation is much coarser in the southern Bear Lodge Mountains than in many other areas where it is mostly sandstone, algal limestone, siltstone, and claystone (Denson, 1969, p. C27). The rocks here represent the part of the Ogallala closest to the mountains, with the source material being at most only a few kilometers away.

The Ogallala Formation in the northwestern part of the area overlies an irregular erosion surface cut on the White River Formation. Farther east, where the White River is missing, the Ogallala is separated by an angular unconformity from sedimentary rocks ranging from Cambrian to Jurassic in age. Two partial sections measured along the edge of canyons north of Cole Canyon are as follows:

SECTION 2.—*Ogallala Formation (part) measured on steep south-facing slope in the NW¼NW¼ sec. 14, T. 52 N., R. 63 W. (fig. 9)*

	Thickness (meters)
Top of ridge.	
Ogallala Formation:	
6. Conglomerate, poorly sorted; consists of subangular to subrounded clasts, 0.3–5 cm in diameter, made up principally of trachyte or phonolite clasts, but some clasts are of quartz monzonite and quartzite of the Deadwood Formation; matrix a white calcareous sandstone	4.0
5. Sandstone, fine-grained, tan, calcareous	1.4
4. Conglomerate, like unit 6	3.4
3. Sandstone, like unit 5	1.1
2. Conglomerate, like unit 6	5.5
1. Sandstone, like unit 5	1.1
Partial thickness of Ogallala Formation	16.5
Top of landslide deposit.	

SECTION 3.—*Ogallala Formation (part) measured on steep south-facing slope in the NE¼SW¼ sec. 11, T. 52 N., R. 63 W.*

	Thickness (meters)
Top of ridge.	
Ogallala Formation:	
5. Conglomerate, poorly sorted; consists of subangular to subrounded clasts, 0.3–30 cm in diameter, made up principally of trachyte and phonolite clasts, but some clasts are of quartz monzonite, quartzite of the Deadwood Formation, and limestone; matrix a white calcareous sandstone	0.6
4. Siltstone, white, calcareous	0.9
3. Conglomerate, like unit 5	3.6
2. Sandstone, white, calcareous, with about 5 percent subangular 0.3–30 cm clasts of trachyte and phonolite	1.5
1. Conglomerate, like unit 5	5.1
Partial thickness of Ogallala Formation	11.7
Top of landslide deposit.	

The Ogallala Formation varies in thickness, tending to be quite thin toward the center of the area and thickening towards its outer edge. Original total thickness of this formation is difficult to ascertain as its upper boundary is an erosion surface and the lower contact is commonly hidden under talus and slope wash. In the two measured sections described above, 16.5 and 11.7 m of the Ogallala were measured. In a section on the northeast side of Lytle Creek in the SW¼SW¼ sec. 1, T. 52 N., R. 64 W., Brown (1952, p. 18) measured 4.9 m. In several bulldozer trenches on the flats north of Peterson Spring it is less than a meter thick.

Fossil seeds were collected by Lugn and Brown (1952) from the Ogallala Formation along the northeast side of Lytle Creek in the SW¼SW¼ sec. 1, T. 52 N., R. 64 W.

FIGURE 9.—Ogallala Formation exposed in back of landslide scarp along west side of Cole Canyon. Dark-gray resistant layers are of conglomerate. Light-gray layers are of sandstone and siltstone.

They were identified as *Stipidium commune* and *Biorbia fossila*. The former is an index fossil in the lower part of the Ogallala occurring from late Miocene to early Pliocene time (Elias, 1942, p. 115, pl. 17). The latter is an index fossil in the middle and upper parts of the Ogallala; this plant lived in middle and late Pliocene time (Elias, 1942, pl. 17).

LANDSLIDE DEPOSITS

Eighteen landslides were mapped in the southern Bear Lodge Mountains (pl. 1). The greatest concentration of landslides occurs in the northwest corner of the region where 10 landslides underlie approximately a quarter of this study area. The landslides range in size from a small slide northwest of Lytle Creek that is only 120 × 200 m in extent to a slide south of Togus Creek that is 850 × 1,680 m. The upper end of most of the landslides is marked by one or more steep arcuate scarps (fig. 10). Other scarps may be found within the landslide deposit itself, and mark where multiple slippage took place. The most distinct feature of these landslides is their hummocky surface. Some of the landslides like the one south of the mouth of Togus Creek and the one southwest of Fort Ranch in the northwest corner of the area contain jumbled blocks of sandstone. Landslides in this area are found where a resistant rock layer caps a soft friable unit. The erosion of the underlying softer rock along a canyon side causes slope steepening and eventually forms an unstable slope that leads to slippage. Most landslides in this area form either where the soft Spearfish Formation is overlain by a hard layer of Ogallala conglomerate or where the soft Stockade Beaver Shale Member of the Sundance Formation is overlain by the resistant Hulett Sandstone Member. Landslides of the former type are found west of Sheep Mountain, east of Beaver Creek, and along Lytle Creek in secs. 1, 2, 11, and 12, T. 52 N., R. 65 W. Those of the latter type occur south of the mouth of Togus Creek and along the lower part of Lytle Creek.

ALLUVIUM

Alluvium is made up of the modern sediments found along stream valleys. In the southern Bear Lodge Mountains, it consists of soil intermixed with sand and some gravel. All the gravels are locally derived from rocks in the uplifted Bear Lodge dome or reworked from the Ogallala Formation. They consist mainly of intrusive rocks and, depending on the source area, some quartzite, sandstone, and limestone. The alluvium occurs mainly along valleys on the outer edges of the area, as along Cow Creek and the lower parts of Togus, Lytle, and Reuter Canyons. The largest area of alluvium is in the southwest corner of the area near the junction of Krusee Canyon with Lost Houston Creek. Here the alluvium, which underlies broad valleys as wide as 460 m, supports a yearly hay crop.

FIGURE 10.—Moat formed along upper edge of landslide as it slid downhill; just southeast of Fort Ranch in the northwest corner of the mapped area. Landslide is to left.

STRUCTURE AND ITS RELATION TO IGNEOUS BODIES

The Bear Lodge dome is the dominant structure of the southern Bear Lodge Mountains. This dome, which underlies the greater part of the mapped area (pl. 1), is formed by the pushing up of the Paleozoic and Mesozoic sedimentary rocks by intrusives that form the core of the dome. Some of the subsidiary intrusives on the flanks of the main dome have formed smaller folds. Small faults found on the flanks of the Bear Lodge dome are apparently related to it as rocks farther from it are unfaulted.

The central intrusive mass in the Bear Lodge dome has pushed up and exposed formations that generally lie much deeper. These beds dip away from the center of the dome and dip most steeply near its center: some of the innermost beds dip at angles of 40°–50°. Farther away from the center the beds flatten out, and dips along the western, northern, and southern margins of the mapped area are only 10°–20° (pl. 1).

A smaller dome, the Hershey Creek dome, underlies an area of a little more than 3.1 km² in the northwest part of the area (pl. 1). This dome has a latite core and exposes sedimentary rocks as deep as the Deadwood Formation along the north side of that core. Other sedimentary units exposed in this dome are the Whitewood Limestone, Pahasapa Limestone, Minnelusa Sandstone, Opeche Formation, and Minnekahta Limestone. These rocks are not exposed along the dome's west side, where they are hidden under landslides or cut out by other intrusives. A shallow syncline lies between this dome and the larger Bear Lodge dome to the southeast.

Smaller folds occur at several other places along the flanks of the Bear Lodge dome. A parallel northwest-trending anticline and syncline are found in the southeast corner of the area east of Reuter Creek. These two structures, which are each approximately 1,850 m long, are formed in the Pahasapa Limestone and Minnelusa Sandstone (pl. 1). Two intrusives are exposed on the surface at the southeast end and the southwest flank of this anticline. These intrusives are probably only the surface exposure of a larger intrusive body that lies beneath the center of the anticline.

Another fold with a north-northeast trend occurs in the southwest corner of the mapped area along the east side of Krusee Canyon (pl. 1). This fold is approximately 2,750 m long, and at the surface involves the Minnelusa Sandstone, Opeche Formation, Minnekahta Limestone, and Spearfish Formation. The greater part of the surface exposure of this fold is underlain by a dip slope of the Minnekahta Limestone. Although this fold is not pierced by any intrusive bodies, it was probably bowed up by a hidden Tertiary intrusive.

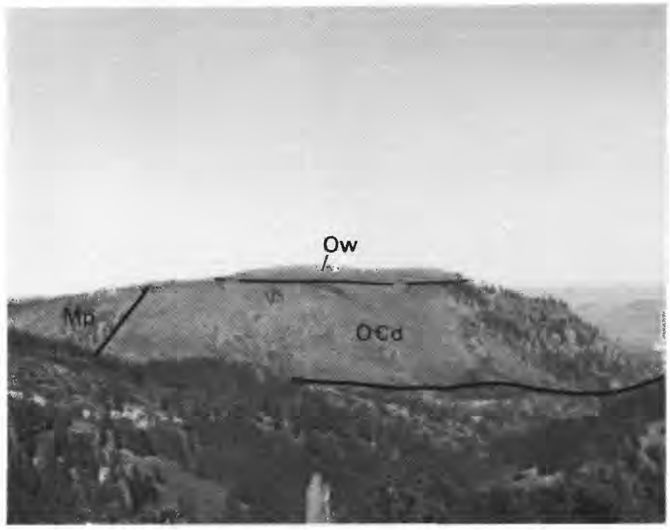

FIGURE 11.—Sheep Mountain on the eastern flank of the Bear Lodge Mountains exposes Deadwood Formation (O€d) overlain by Whitewood Limestone (Ow). A straight fault near the left side of the photograph separates the Deadwood Formation from the Pahasapa Limestone (Mp). A curved fault near the base of the mountain separates these formations from younger Paleozoic rocks in the foreground.

Paleozoic sedimentary rocks are domed up on Sheep Mountain along the east side of the area (fig. 11). In addition to being bowed up over the intrusive, these rocks have been faulted near the intrusive's margins (fig. 12). Several curving faults outline the approximate oval shape of the underlying plug which has pushed the overlying sedimentary rocks up like a cork coming out of a bottle. Rocks exposed in the central part of this uplifted plug are as old as Cambrian (the lower part of the Deadwood Formation). Rocks exposed around the margins of this plug are from Pennsylvanian to Triassic in age (Minnelusa to Spearfish Formations). The fault that bounds the west and south sides offsets the sedimentary rocks approximately 710 m. The fault along the east and north sides offsets the sedimentary rocks 410 m. Differences in offset between the two boundary faults are taken up on several steeply dipping faults that are within the circular plug (fig. 12). The intrusive plug itself is only exposed in a small area on the steep south side of Sheep Mountain.

In addition to the faults associated with the Sheep Mountain uplift, six others were mapped on the western and southern flanks of the Bear Creek dome. These faults do not have a common trend, although all have a general northwest or northeast strike. All have steep dips. Horizontal offset, where measurable, is between

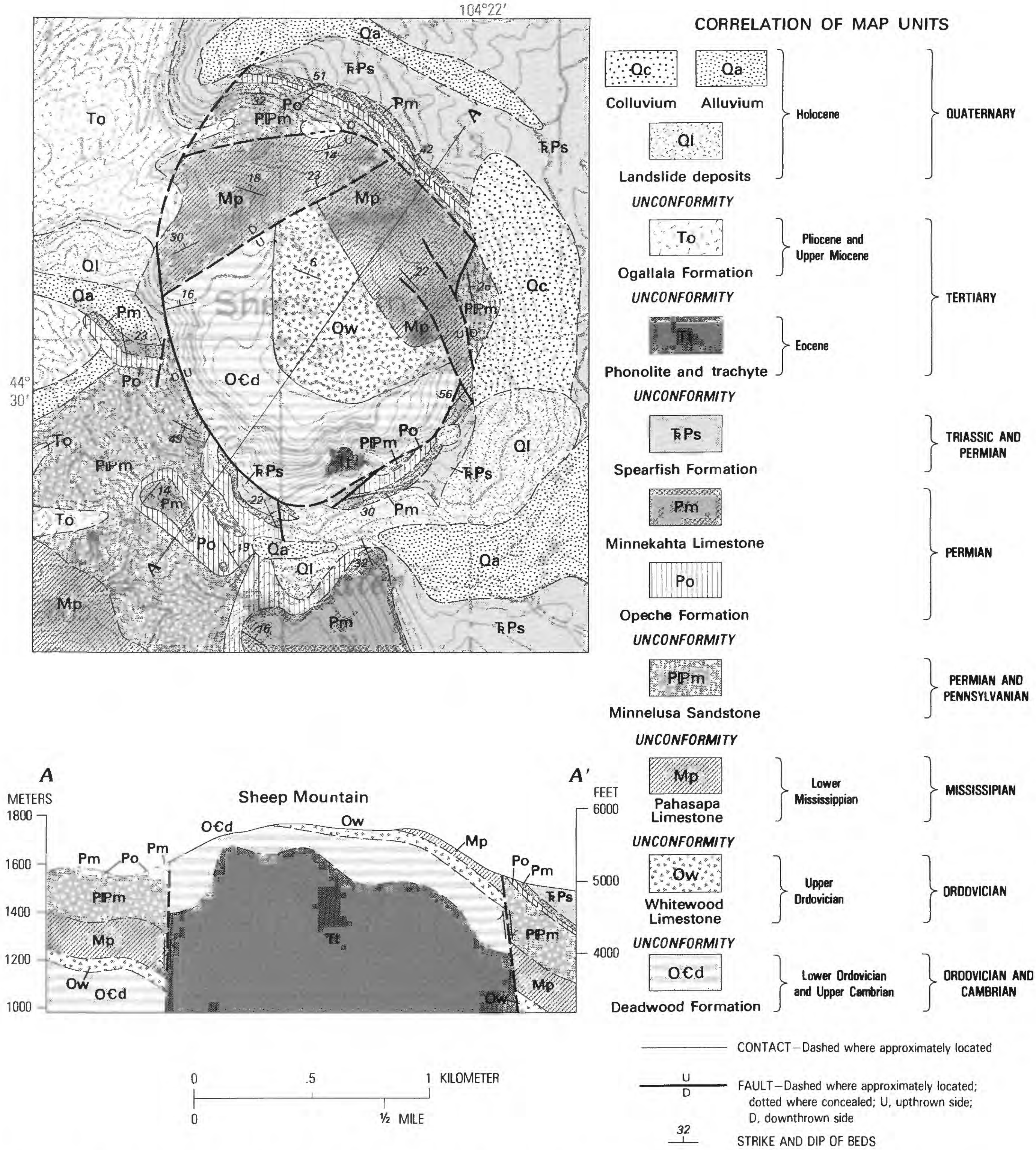

FIGURE 12.—Geologic map and section of Sheep Mountain. Geology by M. H. Staatz, assisted by L. M. Osmonson, June 1977. Base from U.S. Geological Survey 1:62,500 Sundance and Alva (1958). Contour interval 40 ft (1 ft=0.3048 m); datum is mean sea level.

300 and 700 m. Only one fault, which crosses the upper part of Reuter Canyon, cuts the main Tertiary intrusive body. This fault formed after this part of the intrusive had solidified. Two other faults in the southwestern part of the area, however, have Tertiary rocks intruded along them and are therefore older than these intrusives (pl. 1). The Tertiary alkalic rocks were formed over a time span of at least 12 m.y. Thus, some of these rocks may be older and some younger than any particular fault.

The greater part of the doming, folding, and faulting in the southern Bear Lodge Mountains was caused by the force of multiple intrusion during Tertiary time. The size and type of structure depend on the amount of igneous material and how it was injected. Small amounts of magma may be injected along fractures to form dikes. Narrow dikes cut the Pahasapa Limestone and the Minnelusa and Spearfish Formations in the west and northwestern parts of the area (pl. 1). The attitudes of the adjacent sedimentary rocks show little change. In some places access is easier between the beds, and here sills were formed. Two of the larger ones are the lamprophyre that intrudes the Sundance Formation where this rock crosses the North Fork of Miller Creek along the west edge of the area (fig. 8*A*) and the large pseudoleucite porphyry body that also intrudes the Sundance 2.3 km to the northwest. Several sills intruding the Minnelusa Formation are well exposed in roadcuts along Beaver Creek in the eastern part of the area. In some places the sedimentary rocks capping the sill were stripped off, leaving a broad area of sill top exposed. One such sill with an area of about 975 × 610 m occupies most of the SW¼ sec. 2, T. 52 N., R. 64 W. on the southwest side of Lytle Creek. These sills make room for themselves by lifting the overlying strata, but as the thickness of the sills here is generally not more than 15 m and as the movement is mostly at right angles to the bedding, little change is noted in the attitude of the overlying beds.

Much of the magma, however, forms larger intrusive bodies. It may be forced up through sedimentary rocks along a narrow conduit, spread out between the upper layers of rock, and dome up the top to form a laccolith. It may also be intruded or shoulder its way upward over a broad area. This type of igneous body, whose base is essentially the original magma chamber, is called a plug, stock, or batholith, depending on the area it underlies. Sedimentary rocks that overlie a plug, stock, or batholith are also domed up by the force of intrusion. Thus, the rocks overlying both floored and unfloored intrusives may be domed up. The distinction between laccoliths and other massive intrusives depends mainly on one's being able to show that the former are floored. The principal Bear Lodge intrusives, which are generally described as the intrusive underlying Warren Peaks, have been interpreted as a laccolith in several papers (Russell, 1896, p. 39; Jaggar, 1901, p. 251–252; Darton, 1905, p. 8; Darton and O'Harra, 1907, p. 6; Darton, 1909, p. 67–68; and Brown, 1952, p. 48–49).

Laccoliths were first described by G. K. Gilbert in the Henry Mountains of Utah. In subsequent years geologists in various parts of the United States considered many igneous bodies to be laccoliths. In the Black Hills region, Russell (1896, p. 23–24) examined a number of the intrusive bodies. He noted that "they differ from the laccolites of G. K. Gilbert, in the fact that the molten rock did not spread out horizontally among the stratified beds so as to form 'stone cisterns'." Russell (1896, p. 39) did not visit the Bear Lodge Mountains, but in discussing Newton's description of the rocks underlying the Warren Peaks (Newton and Jenny, 1880, p. 199–200) he stated, "Its broad extent and the manner in which the surrounding stratified rocks dip away from it in all directions, seem to indicate that it is a true laccolite, very similar to those of the Henry Mountains." Jaggar (1901) considered the Bear Lodge Mountains to be an elongate laccolithic uplift extending some 32 km in a northwest direction with a porphyry core exposed for 12.8 km. Most of Jaggar's evidence that a particular igneous body is a laccolith was based on the doming of the overlying sedimentary rocks. In some places, he interpreted as laccoliths with even less evidence such obvious plug-like igneous bodies as Devils Tower. In a few places, as on Deadman Mountain, 4.8 km southwest of Sturgis in the northern Black Hills, Jaggar (1901, p. 218–220) could clearly demonstrate both a roof and a floor to a laccolith. Later writers following Jaggar's lead have described the principal intrusive or intrusives of the Bear Lodge Mountains as one or more laccoliths. None have demonstrated that those major intrusions are floored. Doming of the overlying sedimentary rocks could be formed by either a laccolith or a stock. This central intrusive core, however, is not a single intrusive but consists of a number of igneous bodies intruded over a period of at least 12 m.y. Furthermore, a floor, if present, is not a single planar surface. Granite of Precambrian age forms isolated knobs in the central part of the intrusive of Tertiary age south of Warren Peaks (pl. 1). Precambrian rocks are not exposed in the intrusion north of Warren Peaks, nor were any encountered in drilling in this area, although the deepest hole reached a depth of 850 m below the elevation of most of the granite outcrops in the southern part of the area. I believe that the main intrusive is probably a complex stock formed by multiple intrusions.

THORIUM AND RARE-EARTH DEPOSITS

Thorium and rare earths are found in the southern Bear Lodge Mountains in veins and disseminated deposits. The latter type of deposit is somewhat analogous to copper porphyries. Thorium and rare-earth-bearing disseminated deposits have not previously been described in the literature. They represent a large low-grade source of these elements.

Thorium and rare-earth deposits occur principally in the central part of the main intrusive mass. Most are found between Whitelaw Creek on the north and the U.S. Forest Service lookout on Warren Peaks to the south. The favorable area is marked by high radioactivity and is shown on plate 2*A*. Exploration for thorium and rare earths in the Bear Lodge Mountains began in the early 1950's, and high-grade veins were the target. A number of small- to moderate-sized veins were found in this area, but the greater part of the thorium and rare earths occurs in disseminated deposits, which consist of intrusive rock cut by numerous thin, crisscrossing, steeply dipping veinlets. Both types of deposit commonly occur together, although veins are scattered over a much larger area. The veins and the disseminated deposits will be discussed separately because they vary in size, shape, grade, and method of mining.

VEINS

LOCATION AND DESCRIPTION

The veins are distinct, tabular bodies with an average thickness of at least 5 cm. Their separation from smaller veins and veinlets is somewhat arbitrary and assumes that veins thinner than 5 cm would probably be included with the disseminated deposits in any mining operation.

Twenty-six veins were noted at 24 localities (pl. 1). Exposures are generally poor, and most of the veins are seen only in one or more old trenches or pits. Present or past names of the claim or claims on which these veins lie are difficult to ascertain for several reasons. Most of the thorium and rare-earth exploration occurred in the early 1950's, and none of the claim locations made at this time remain. The land in the vicinity of the old radar site on the northernmost of the Warren Peaks has been removed from mineral entry. Many of the claims in sections 17 and 18, T. 52 N., R. 63 W. have been relocated by Duval Corporation. As their discovery locations are based on drill holes, it is commonly difficult to determine which claim or claims a particular vein may now be on. Hence, in order to clarify the discussion of various veins, I have given each locality a number starting with 1 in the north and numbering consecutively to the south. Number 1 is on the ridge northwest of the headwater of Whitelaw Creek and number 24 is on the northeast side of Richardson Creek.

The exposed length of the 26 veins is relatively short with the longest one being traced for only 137 m. Nine of the veins, listed in table 5 as 0.5 m long, are only exposed in one place in a trench or pit. The two longest veins are parallel and lie about 50 m apart on the north slope of the hill to the south of Bull Hill. The lack of traceable length is in places due to the lack of outcrops or workings along the strike. In other areas, as at locality 18, other workings indicate the maximum extent of a particular vein.

The thickness of the veins ranges from 5 to 250 cm (figs. 13*A*, *B*). The maximum thickness is reached in the northwest-trending vein at locality 22 on the east edge of the main intrusive mass. Sixteen of the 26 veins are at least in part more than 30 cm thick. Thickening and thinning are common; the larger vein at locality 22 ranges from 60 to 250 cm in thickness. A tenfold change in thickness occurs at locality 12, south of Bull Hill, where a long vein varies from 15 to 152 cm.

The veins of the southern Bear Lodge Mountains have no common direction of strike (table 5). The strikes of the two longest veins, which are on the hill south of Bull Hill (locs. 11, 12), are parallel, but strikes of other

TABLE 5.—*Dimensions and attitude of the veins in the southern Bear Lodge Mountains*

[N. D., no data]

Location No.	Vein if more than one	Exposed length (m)	Thickness (cm)	Strike	Dip
1	------------	0.5	10.2	N.D.	N.D.
2	------------	.5	25	N.D.	N.D.
3	------------	6.5	92	N. 45° E.	N.D.
4	North vein	4.6	6-10	N. 67° W.	45° NE.
	South vein	16.8	33	N. 56° W.	N.D.
5	------------	90	2.5-45	N. 20° W.	85° NE.
6	------------	.5	5	N.D.	N.D.
7	------------	40	25-40	N. 84° E.	Steep
8	------------	.5	7.5	N. 1° E.	90°
9	------------	12	155	N. 50° W.	Steep
10	------------	23	9-100	N. 44° E.	58° SE.
11	------------	137	15-40	N. 3° W.	Steep
12	------------	135	15-152	N. 2° W.	65° SW.
13	------------	50	150-185	N. 80° E.	59° NW.
14	------------	.5	20+	N.D.	N.D.
15	------------	13.7	108	N. 5° E.	25° SE.
16	------------	.5	30+	N.D.	N.D.
17	------------	7.5	46	N. 23° W.	55° NE.
18	------------	.5	20	N.D.	N.D.
19	------------	6	2.5-10	N. 78° W.	30° NE.
20	------------	.5	5	N.D.	N.D.
21	------------	45	50	N. 15° E.	N.D.
22	NE.-trending	8	20-76	N. 20° E.	80° NW.
	NW.-trending	38	60-250	N. 32° W.	40° SW. 80° NE.
23	------------	.5	35	N. 40° W.	N.D.
24	------------	21	10.2	N. 32° E.	82° SE.

FIGURE 13.—Veins. *A*, Steeply dipping vein (locality No. 24) exposed in cut on northeast side of Richardson Creek. Man's hand is on hanging wall side of vein. Vein is light-colored material lying to viewer's left of this plane. It is about 10 cm thick. *B*, Black manganese-oxide-bearing vein (locality 13) is exposed in a partly overgrown cut. Vein is about 180 cm thick.

adjacent veins may be at considerable angles to one another. For example, the two veins that lie in the same broad bulldozer trench at locality 22 have strikes of N. 20° E. and N. 32° W. The strikes of the veins given in table 5 are the average strike of each vein, and the strike of the veins at any one place may vary somewhat from this average. For example, the vein at locality 18 is fairly sinuous.

Dips are more difficult to determine than strikes because of poor third-dimension exposure of many of the veins. Dips of only 12 of the 26 veins were determined (table 5). These data, however, indicate that the dip also is highly variable. Measurements range from 25° to 90°. Dip in a single vein might also vary, and measurements made on the northwest-trending vein at locality 22 varied from 40° southwest to 80° northeast. In general, however, most of the veins dip at angles greater than 50° (fig. 13*A*).

All the veins except the one at locality 21 lie along irregular fractures in the central Tertiary intrusive complex. This body of rock, as previously noted, has had a complex history of intrusion, and veins that formed along these fractures are divergent in strike and dip, are commonly sinuous, and thicken and thin along strike.

MINERALOGY

A total of 27 minerals have been identified in the samples from the Bear Lodge veins. Some of these minerals are sparse and were found in only one or two places. About a third of the minerals occur in half of the samples. Amounts of various minerals present also vary greatly, and this is particularly noticeable in principal gangue, manganese oxide, and iron oxide minerals. The gangue minerals are commonly intermixed with various amounts of finely granular manganese oxides, iron oxides, or both. The color of the veins chiefly reflects the kind and amount of iron or manganese oxides present. Manganese oxides give the vein a black color (fig. 13*B*); limonite, a tan to dark-brown color; hematite, a black to dark-cherry-red color. At a few localities where the content of iron and manganese oxides is low, the colors of some other minerals may be apparent. For example, at locality 10, which has only 0.1 percent manganese and 5 percent iron, the vein is colored pistachio green by the presence of abundant monazite. Color banding occurs in some veins. The minerals in the various veins are all fine grained, and in a few veins the grain size is submicroscopic. The result of abundant iron and manganese oxides, as well as fine grain size, makes identification of most minerals difficult. Hence, in only a few veins are any minerals other than quartz, manganese oxides, and iron oxides identifiable in hand specimens.

A study of the vein mineralogy was carried out using routine heavy-liquid and magnetic separation procedures. Any mineral not readily identifiable under the binocular microscope was identified by its X-ray diffraction pattern. The minerals identified in samples from all 26 veins are given in table 6. Other minerals undoubtedly occur but are not identified for two reasons. First, the minerals are commonly erratically distributed along a vein, and a particular mineral that occurs in a vein may not be present where the sample was taken. Second, when abundant manganese oxides, or to a lesser extent, iron oxides are present, they commonly coat or surround another mineral so much that it is unrecognizable. This is particularly obvious among the rare-earth minerals. A sample from locality 7 had 5.3 percent total rare earths, yet the presence of any rare-earth minerals was masked by about 5 percent manganese oxide minerals. Conversely, rare-earth minerals were found in samples from localities 21 and 22, that contained only 0.23 and 0.45 percent total rare earths, respectively. These samples, however, have a maximum of 0.02 percent manganese.

The principal gangue minerals are generally potassium feldspar, quartz, cristobalite, or at locality 21, where the country rock is limestone, calcite. Potassium feldspar is the most common gangue mineral in 18 of the 26 samples. Because this mineral is easily stained with iron and manganese oxides, it is rarely conspicuous. Quartz and cristobalite are important in some of the veins; the latter mineral occurs only in the veins in the north half of section 20 just south of Bull Hill. Another gangue mineral that occurs in lesser amounts in some samples is barite. This mineral occurs in over two-thirds of the samples but is generally fairly erratic in distribution. Barite is also a common mineral in the thorium veins of the Lemhi Pass, Wet Mountains, Powderhorn, and Mountain Pass districts (Staatz, 1974, p. 498).

Iron oxide minerals are common in many of these veins, with limonite and hematite making up substantial parts of many veins. Limonite varies in color, from ocherous yellow to dark brown, and may have a dense, granular, or vuggy texture. The term limonite is applied to all the brown, hydrous iron oxides in the sample, but the name of the particular limonite mineral is only used in table 6 if it has been identified by its X-ray diffraction pattern. The variety of limonite present was identified in about half of the samples; it is generally goethite. One sample, however, had some lepidocrocite in addition to goethite. Black to reddish-gray, granular hematite is an important mineral in the veins at localities 1, 11, 13, 15, and 16. This mineral is rarely associated with manganese oxide minerals, although in other veins the manganese minerals are commonly associated with limonite. Magnetite is the most common but least abundant of all the iron oxides. It was noted in all but one of the veins, but rarely does it make up more than a few tenths of one percent. Magnetite occurs in tiny, black crystals, which are commonly intermixed with other iron oxide minerals.

Manganese oxide minerals are black to dark gray in color and, in places, they have a botryoidal structure. The specific manganese oxide mineral was not identified in most samples, but cryptomelane was identified in a sample from locality 5; pyrolusite, in a sample from locality 22; and both these minerals in a sample from locality 24 (table 6). Other manganese oxide minerals may also be present.

Although analytical data indicate abnormal amounts of rare earths compared to unmineralized intrusive rock in all the samples analyzed (table 7), rare-earth minerals were found in only 11 of the 26 samples (table 7). The three rare-earth minerals found are brockite, bastnaesite, and monazite. None were found in the same samples. Brockite [$(Ca,Th,Ce)PO_4 \cdot H_2O$] was noted in five samples. It commonly occurs in hematite-rich samples. Brockite varies in color and appearance in the five samples, although some of the difference in color may be due to hematite or limonite stain. The following colors of brockite occur in various samples: white, light yellow, tan, yellowish brown, brown, and reddish brown. Its surface may be dull, opaque, greasy, or resinous. Brockite-bearing samples were generally those with a higher thorium content. Although brockite is a little-known mineral, it is fairly common in thorium-bearing veins. It has also been identified in some veins from the following districts: Wet Mountains, Colo. (Fisher and Meyrowitz, 1962); Lemhi Pass, Mont. and Idaho (Staatz, 1972, p. 62–64); Laughlin Peak, N. Mex.; Monroe Canyon, Utah (Staatz, 1974, p. 500); and Rawhide Mountains, Ariz. Bastnaesite, ranging from white to yellow in color, was found in three samples. It is the source of most of the rare earths being mined at Mountain Pass, Calif. (Olson and others, 1954, p. 34–35). Monazite was found at three localities, and at two of these (10 and 19) it is clearly visible in hand specimens.

TABLE 6.—*Mineralogy of the thorium and rare-earth-bearing veins in the southern Bear Lodge Mountains*

[Minerals listed in italics were identified by their X-ray diffraction pattern]

Location No.	Vein if more than one	Minerals—relative amounts			
		Large	Moderate	Small	Rare
1	---------	Hematite	Limonite, *sanidine*, *fluorite*.	Barite	Magnetite, calcite, *brookite*.
2	---------	*Sanidine*	*Goethite*	Magnetite, quartz, *chlorite*.	*Anatase* (?).
3	---------	Sanidine	*Montmorillonite*, *goethite*, manganese oxide mineral.	*Hematite*, calcite, *barite*, *brockite*.	Magnetite, *rutile*.
4	North vein.	Sanidine	Manganese oxide mineral.	Limonite, hematite, *chlorite*, barite.	Magnetite.
4	South vein.	Limonite	Sanidine, manganese oxide mineral.	Magnetite, hematite, quartz.	Calcite, fluorite.
5	---------	Sanidine, limonite.	*Cryptomelane*.	*Bastnaesite*, hematite, barite.	Magnetite, *rutile*, *brookite*.
6	---------	Manganese oxide mineral, sanidine.	*Goethite*	Quartz, fluorite.	Magnetite, zircon.
7	---------	Sanidine	*Goethite*, manganese oxide mineral.	*Barite*	Magnetite, calcite.
8	-------	Sanidine	Fluorite, limonite, manganese oxide mineral.	Hematite, barite, *rutile*.	Calcite, magnetite, zircon, *sphalerite*.
9	---------	Sanidine, quartz, limonite.	*Barite*	Manganese oxide mineral.	Magnetite, calcite, *rutile*.
10	---------	*Quartz*, *monazite*.	*Rutile*	*Hematite*, barite.	Magnetite, calcite, *brookite*.
11	---------	*Sanidine*, *beta-cristobalite*, hematite.	*Kaolinite*, quartz, *goethite*, *barite*.	*Lepidocrocite*, *rutile*, *anatase*, *brookite*.	Magnetite, calcite.
12	---------	*Goethite*, *sanidine*.	Manganese oxide mineral, *kaolinite*, *montmorillonite*.	Quartz, cristobalite, barite, *brookite*.	Magnetite, calcite, *biotite*, *rutile*.
13	---------	Sanidine, limonite.	Quartz, hematite, *barite*.	*Rutile*	Magnetite, *brookite*.

TABLE 6.—*Mineralogy of the thorium and rare-earth-bearing veins in the southern Bear Lodge Mountains*—Continued

Location No.	Vein if more than one	Minerals--relative amounts			
		Large	Moderate	Small	Rare
14	---------	Sanidine-------	Quartz, limonite.	Magnetite, rutile, plagioclase.	Zircon, fluorite.
15	---------	Sanidine, hematite, cristobalite.	Limonite, barite, bastnaesite.	Brookite------	Magnetite, rutile, calcite.
16	---------	Hematite, goethite.	Sanidine, cristobalite, barite.	Rutile--------	Calcite, magnetite.
17	---------	Sanidine, goethite.	Monazite---------	Rutile, brookite, barite.	Magnetite.
18	---------	Sanidine-------	Goethite, quartz.	Rutile, barite, brookite.	Do.
19	---------	Cristobalite, goethite.	Quartz, monazite.	Brookite, barite, hematite.	Calcite, magnetite.
20	---------	Cristobalite	Sanidine, manganese oxide mineral, goethite.	Quartz, rutile, brookite, bastnaesite.	Magnetite, calcite.
21	---------	Calcite, sanidine.	Goethite, plagioclase.	Quartz, hematite, dolomite, brockite.	Ilmenite.
22	Northeast-trending vein.	Sanidine-------	Pyrolusite-------	Quartz, limonite, fluorite, brockite, anatase.	Magnetite, biotite.
22	Northwest-trending vein.	Sanidine-------	Goethite, brockite.	Manganese oxide mineral, plagioclase.	Magnetite, hematite, fluorite, anatase, aegirine(?).
23	----------	Sanidine-------	Manganese oxide mineral.	Quartz, plagioclase, limonite, barite.	Calcite, magnetite.
24	----------	Quartz---------	Pyrolusite, cryptomelane.	Limonite, barite.	Magnetite, hematite, anatase, zircon, brookite.

TABLE 7.—*Chemical analyses of samples from veins in the southern Bear Lodge Mountains*

[N.D., not determined; <, less than value indicated; >, greater than value indicated]

Locality No.	1	2	3	4	4	5	5	6	7	8
Vein if more than one---	---	---	---	North vein	South vein	---	---	---	---	---
Sample No.---	MHS-87-75	MHS-99-75	MHS-82-75	MHS-79-75	MHS-80-75	MHS-98-75	MHS-55-77	MHS-56-75	MHS-83-75	MHS-54-75
					In parts per million					
Thorium[1]-----	390	1,320	6,750	3,550	2,300	745	391	2,575	3,725	12,000
Uranium[1]-----	250	45	220	235	80	96	106	40	60	N.D.
Lanthanum[2]---	30,000	N.D.	20,000	15,000	5,000	15,000	N.D.	2,000	10,000	3,000
Cerium[2]------	30,000	N.D.	20,000	15,000	10,000	15,000	N.D.	5,000	15,000	5,000
Praesodymium[2]	3,000	N.D.	7,000	3,000	1,500	3,000	N.D.	1,000	3,000	1,000
Neodymium[2]---	7,000	N.D.	30,000	15,000	7,000	10,000	N.D.	5,000	10,000	5,000
Samarium[2]----	700	N.D.	7,000	3,000	1,000	1,000	N.D.	700	3,000	2,000
Europium[2]----	<100	N.D.	1,500	700	<100	<100	N.D.	300	1,000	700
Gadolinium[2]--	300	N.D.	5,000	3,000	1,000	200	N.D.	700	3,000	5,000
Terbium[2]-----	<300	N.D.	<300	<300	<300	<300	N.D.	<300	<300	<300
Dysprosium[2]--	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Holmium[2]-----	<20	N.D.	300	70	<20	<20	N.D.	70	500	200
Erbium[2]------	<50	N.D.	100	<50	<50	<50	N.D.	<50	300	150
Thulium[2]-----	<20	N.D.	<20	<20	<20	<20	N.D.	<20	<20	<20
Ytterbium[2]---	30	N.D.	200	50	70	15	N.D.	70	500	300
Lutetium[2]----	<30	N.D.	<30	<30	<30	<30	N.D.	<30	<30	<30
Yttrium[2]-----	500	N.D.	7,000	2,000	700	150	N.D.	3,000	7,000	7,000
Total rare earths---	71,530	N.D.	98,100	56,820	26,270	44,365	N.D.	17,840	53,300	29,350
Barium[2]------	20,000	N.D.	30,000	15,000	7,000	1,500	N.D.	20,000	30,000	15,000
Beryllium[2]---	10	N.D.	30	7	3	15	N.D.	15	20	10
Bismuth[2]-----	50	N.D.	300	<50	700	300	N.D.	<50	<50	<50
Copper[2]------	200	N.D.	300	300	20	1,500	N.D.	150	70	1,000
Lead[2]--------	1,000	N.D.	3,000	500	2,000	5,000	N.D.	700	1,500	1,000
Manganese----	[2]>100,000	N.D.	[3]70,500	[2]>100,000	[3]93,400	[3]37,800	N.D.	[3]224,000	[3]45,900	[3]23,600
Molybdenum[2]--	700	N.D.	300	200	300	700	N.D.	1,000	150	300
Niobium[2]-----	50	N.D.	500	150	200	150	N.D.	100	500	1,000
Strontium[2]---	1,000	N.D.	1,500	2,000	150	1,000	N.D.	1,500	3,000	2,000
Tin[2]---------	<10	N.D.	70	<10	<10	<10	N.D.	<10	<10	50
Vanadium[2]----	500	N.D.	700	150	150	30	N.D.	300	300	1,500
Zinc[2]--------	3,000	N.D.	7,000	10,000	7,000	500	N.D.	1,500	1,500	<300
Zirconium[2]---	<50	N.D.	<50	<10	<10	200	N.D.	<10	<50	<50
					In percent					
Calcium[2]-----	2	N.D.	1.	0.3	0.1	2	N.D.	>10	>10	0.7
Iron---------	[2]>10	N.D.	[3]17.20	[2]>10	[3]41.40	[3]34.80	N.D.	[3]7.2	[3]9.5	[3]11.04
Magnesium[2]---	.03	N.D.	1.5	.15	.07	.3	N.D.	.15	.15	.3
Phosphorus[2]--	<.2	N.D.	<.2	<.2	<.2	<.2	N.D.	<.2	10	1
Potassium[1]---	N.D.	9	N.D.	N.D.	N.D.	2	2	N.D.	N.D.	N.D.
Sodium[2]------	.15	N.D.	<.3	1.5	.7	.15	N.D.	.3	.7	.7
Titanium[2]----	.3	N.D.	.7	.3	.7	.7	N.D.	.07	.7	.7

TABLE 7.—*Chemical analyses of samples from veins in the southern Bear Lodge Mountains*—Continued

Locality No.	9	10	11	12	12	13	14	15	16	17
Vein if more than one---	---	---	---	---	---	---	---	---	---	---
Sample No.---	MHS-49-75	BL-5-74	MHS-44-75	BL-8-74	BL-9-74	MHS-45-75	M 43-75	MHS-48-75	MHS-47-75	BL-14-74
					In parts per million					
Thorium[1]-----	1,950	700	1,120	1,020	395	1,850	890	5,100	560	720
Uranium[1]-----	75	255	110	107	150	90	33	60	175	76
Lanthanum[2]---	N.D.	30,000	N.D.	15,000	1,500	5,000	500	30,000	15,000	N.D.
Cerium[2]------	N.D.	30,000	N.D.	15,000	3,000	7,000	1,000	20,000	15,000	N.D.
Praesodymium[2]	N.D.	7,000	N.D.	7,000	700	1,000	200	5,000	5,000	N.D.
Neodymium[2]---	N.D.	20,000	N.D.	15,000	1,500	7,000	1,500	15,000	15,000	N.D.
Samarium[2]----	N.D.	2,000	N.D.	3,000	700	1,500	300	3,000	2,000	N.D.
Europium[2]----	N.D.	500	N.D.	700	<100	300	<100	300	300	N.D.
Gadolinium[2]--	N.D.	1,000	N.D.	3,000	300	1,500	300	1,000	700	N.D.
Terbium[2]-----	N.D.	<300	N.D.	<300	<300	<300	<300	<300	<300	N.D.
Dysprosium[2]--	N.D.	200	N.D.	300	<200	N.D.	N.D.	N.D.	N.D.	N.D.
Holmium[2]-----	N.D.	30	N.D.	70	<20	50	50	30	30	N.D.
Erbium[2]------	N.D.	<50	N.D.	<50	<50	<50	<50	<50	<50	N.D.
Thulium[2]-----	N.D.	<20	N.D.	<20	<20	<20	<20	<20	<20	N.D.
Ytterbium[2]---	N.D.	70	N.D.	70	15	100	50	30	70	N.D.
Lutetium[2]----	N.D.	<30	N.D.	<100	<100	<30	<30	<30	<30	N.D.
Yttrium[2]-----	N.D.	1,500	N.D.	3,000	300	1,500	1,500	700	700	N.D.
Total rare earths---	N.D.	92,300	N.D.	62,140	8,015	24,950	5,400	75,060	53,800	N.D.
Barium[2]------	N.D.	20,000	N.D.	20,000	10,000	30,000	5,000	70,000	50,000	N.D.
Beryllium[2]---	N.D.	20	N.D.	15	3	10	3	7	15	N.D.
Bismuth[2]-----	N.D.	300	N.D.	70	30	200	<30	200	500	N.D.
Copper[2]------	N.D.	50	N.D.	300	200	300	200	200	300	N.D.
Lead[2]--------	N.D.	3,000	N.D.	3,000	1,500	1,500	150	5,000	5,000	N.D.
Manganese----	N.D.	[2]1,000	N.D.	[2]>100,000	[2]100,000	[2]1,500	[2]70,000	[2]300	[2]150	N.D.
Molybdenum[2]--	N.D.	70	N.D.	300	300	500	700	500	300	N.D.
Niobium[2]-----	N.D.	2,000	N.D.	150	100	150	150	700	1,000	N.D.
Strontium[2]---	N.D.	1,500	N.D.	1,500	1,000	200	1,000	500	500	N.D.
Tin[2]---------	N.D.	<10	N.D.	<10	<10	<10	<10	15	50	N.D.
Vanadium[2]----	N.D.	300	N.D.	200	300	500	30	300	700	N.D.
Zinc[2]--------	N.D.	<300	N.D.	7,000	7,000	3,000	500	500	<300	N.D.
Zirconium[2]---	N.D.	50	N.D.	<100	<100	<10	200	30	30	N.D.
					In percent					
Calcium[2]-----	N.D.	0.5	N.D.	3	0.15	0.3	2	0.3	0.5	N.D.
Iron---------	N.D.	[2]5	N.D.	>10	>10	[2]>10	[2]10	[2]>10	[2]>10	N.D.
Magnesium[2]---	N.D.	.1	N.D.	1	.07	.15	.3	.03	.007	N.D.
Phosphorus[2]--	N.D.	1.5	N.D.	1.5	<.2	<.2	<.2	<.2	1	N.D.
Potassium[1]---	2.4	1.6	5	2.2	.74	N.D.	10	N.D.	2	8.8
Sodium[2]------	N.D.	.1	N.D.	.15	.07	<.05	.7	.3	.3	N.D.
Titanium[2]----	N.D.	2	N.D.	.5	.15	.15	.7	.7	1.5	N.D.

TABLE 7.—*Chemical analyses of samples from veins in the southern Bear Lodge Mountains*—Continued

Locality No.	18	19	20	21	21	22	22	23	24
Vein if more than one---	---	---	---	---	---	Northeast trending	Northwest trending	---	---
Sample No.---	MHS-40-75	BL-2-74	MHS-42-75	MHS-96-75	MHS-97-75	BL-12-74	MHS-73-75	MHS-76-75	MHS-60-75
				In parts per million					
Thorium[1]-----	112	1,220	1,020	4,100	917	4,125	2,250	1,600	850
Uranium[1]-----	21	150	77	N.D.	5	270	25	30	30
Lanthanum[2]---	N.D.	15,000	10,000	70	N.D.	150	300	N.D.	300
Cerium[2]------	N.D.	20,000	15,000	<200	N.D.	300	300	N.D.	700
Praesodymium[2]	N.D.	5,000	3,000	<100	N.D.	<100	<100	N.D.	100
Neodymium[2]---	N.D.	15,000	7,000	<70	N.D.	<70	300	N.D.	700
Samarium[2]----	N.D.	2,000	3,000	<100	N.D.	<100	<100	N.D.	200
Europium[2]----	N.D.	500	300	<100	N.D.	<100	<100	N.D.	<100
Gadolinium[2]--	N.D.	1,000	700	N.D.	N.D.	2,000	200	N.D.	150
Terbium[2]-----	N.D.	<300	<300	<300	N.D.	<300	<300	N.D.	<300
Dysprosium[2]--	N.D.	500	N.D.	150	N.D.	1,000	<50	N.D.	<50
Holmium[2]-----	N.D.	30	30	70	N.D.	200	70	N.D.	<20
Erbium[2]------	N.D.	500	<50	300	N.D.	500	150	N.D.	<50
Thulium[2]-----	N.D.	<20	<20	<20	N.D.	70	<20	N.D.	<20
Ytterbium[2]---	N.D.	20	30	200	N.D.	1,000	200	N.D.	7
Lutetium[2]----	N.D.	<30	<30	<30	N.D.	<30	<30	N.D.	<30
Yttrium[2]-----	N.D.	1,000	500	1,500	N.D.	1,000	3,000	N.D.	200
Total rare earths---	N.D.	60,550	39,560	2,290	N.D.	15,220	4,520	N.D.	2,357
Barium[2]------	N.D.	20,000	7,000	3,000	N.D.	3,000	1,000	N.D.	3,000
Beryllium[2]---	N.D.	7	20	20	N.D.	<1.5	20	N.D.	70
Bismuth[2]-----	N.D.	200	50	<30	N.D.	<10	<50	N.D.	70
Copper[2]------	N.D.	300	1,500	70	N.D.	30	50	N.D.	1,000
Lead[2]--------	N.D.	3,000	2,000	70	N.D.	70	70	N.D.	700
Manganese----	N.D.	[2]300	[3]32,300	[3]1,880	N.D.	[2]3,000	[2]700	N.D.	[2]3,000
Molybdenum[2]--	N.D.	700	70	<3	N.D.	<3	<3	N.D.	70
Niobium[2]-----	N.D.	150	200	50	N.D.	3,000	150	N.D.	30
Strontium[2]---	N.D.	1,000	700	700	N.D.	3,000	1,500	N.D.	150
Tin[2]---------	N.D.	<10	50	<10	N.D.	50	15	N.D.	<10
Vanadium[2]----	N.D.	700	700	500	N.D.	7,000	7,000	N.D.	30
Zinc[2]--------	N.D.	<300	1,500	<300	N.D.	<300	<300	N.D.	<300
Zirconium[2]---	N.D.	70	70	1,500	N.D.	500	700	N.D.	150
				In percent					
Calcium[2]-----	N.D.	0.2	1.5	>10	N.D.	1	0.3	N.D.	2
Iron---------	N.D.	[2]>10	[3]11.40	[3]2.91	N.D.	[2]1	[2]7	N.D.	[2]3
Magnesium[2]---	N.D.	.05	1.5	7	N.D.	.3	.15	N.D.	.07
Phosphorus[2]--	N.D.	.7	1.5	<.2	N.D.	.5	<.2	N.D.	<.2
Potassium[1]---	9.8	4.6	2.4	N.D.	0.4	7.9	7	7	3
Sodium[2]------	N.D.	.2	.7	1	N.D.	.5	1.5	N.D.	.5
Titanium[2]----	N.D.	.07	.7	.3	N.D.	3	.7	N.D.	.07

[1]Analyzed by gamma-ray spectrometer by C. M. Bunker and C. A. Bush
[2]Analyzed by semiquantitative six-step spectrographic method by N. M. Conklin
[3]Analyzed by atomic absorption method by C. A. Gent

Here it is a fine-grained, pale-green to light-tan, opaque mineral. Monazite is visible in hand specimens at these localities because the monazite content is high and the manganese oxide content is low. This mineral is also visible in several smaller veinlets in the same area.

Ten other accessory minerals occur in some of these samples. Rutile is the most common, occurring in a little over half the samples. This mineral, found in tiny, black, shiny, granular crystals, reflects the presence of small amounts of titanium (table 7). Titanium also occurs in the minerals brookite, anatase, and ilmenite. Some samples contain more than one titanium mineral, and rutile and brookite occur together in eight samples. Fluorite is another fairly common accessory in the Bear Lodge veins. It varies in color from clear to pale purple to dark purple. The other five accessories are zircon, biotite, chlorite, sphalerite, and dolomite.

CHEMICAL COMPOSITION

The thorium content of 35 vein samples ranges from 112 to 13,000 ppm, and 20 of these samples contain at least 1,000 ppm. Twenty-nine of these samples are reported in table 7, and the other six were reported by Wilmarth and Johnson (1953, p. 21 and table 4). Most of the 29 samples reported in table 7 are chip samples, although a few are grab samples. All were collected to represent the entire thickness of the vein. Thorium analyses on these samples (table 7) were made by C. M. Bunker and C. A. Bush, U.S. Geological Survey, on a gamma-ray spectrometer. This method has an accuracy of ±3 percent. The highest thorium content was obtained from a vein at locality 8, which is only 7.5 cm thick and is exposed in only one pit. The thorium content of a sample from the longest vein (loc. 11) contained 1,120 ppm; that of two samples from the next longest vein (loc. 12) had 1,020 and 395 ppm.

The analyses used for rare earths in this report were done by the semiquantitative spectrographic method. Results are identified within brackets whose boundaries are 1.2, 0.83, 0.56, 0.38, 0.26, 0.18, 0.12, and so forth, but are reported as midpoints between these brackets. Thus, the numbers reported would be 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, and so forth. The precision of a reported value is approximately plus or minus one bracket. The total rare-earth content of the 21 samples analyzed for these elements varies from 3,290 to 98,100 ppm (table 7), and the average is 40,200 ppm.

The rare earths are generally much more abundant than thorium in the Bear Lodge veins. Only one of our samples (table 7) contained more thorium than total rare earths. This sample, which came from the only vein cutting a limestone (loc. 21), contained 4,100 ppm thorium to 2,290 ppm total rare earths. The total rare-earth-to-thorium ratios in the other 20 samples for which I have chemical data range from 2.0 to 184, but 14 of the samples contain 10 times more rare earths than thorium. Although rare earths and thorium commonly occur in the same minerals, little correlation exists between the amounts of rare earths and thorium that occur in these veins. The lack of correlation between the amounts of total rare earths and thorium has also been noted in other areas, such as the Lemhi Pass district, Idaho and Montana (Staatz and others, 1972, p. 75–77), the Hall Mountain district, Idaho (Staatz and others, 1974, p. 680), and in the Wet Mountains, Colo. (Christman and others, 1959, p. 522, 524, and 530). This lack of correlation may be due in part to the separation of rare earths and thorium at depth, and in part to slight differences in chemical and physical conditions at the vein site. Differing conditions would tend to favor the formation of different proportions of rare-earth and thorium minerals at different places.

The rare earths consist of 16 elements with similar chemical properties. Fifteen of the elements—lanthanum (La), cerium (Ce), praesodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu)—occur sequentially in the periodic table, elements 59 through 71. This group is called the lanthanides. One of these, promethium, is almost unknown in nature. Yttrium (Y), not one of the lanthanides but chemically similar to them, is also classed as a rare earth. All rare earths have a +3 valence and similar atomic radii; hence, they can easily substitute for one another, and they are always found together.

In the normal distribution of the lanthanides in the Earth's crust, and in most minerals, the ones with the even atomic numbers are more abundant than the adjacent odd-numbered ones. The average crustal abundance of either even- or odd-atomic numbered lanthanides decreases with an increase in atomic number. Generally, therefore, cerium is the most abundant lanthanide and lutetium the least. This distribution pattern of the lanthanides occurs in many minerals, but may be markedly different in a few, owing to the partial separating out (fractionation) of various rare earths. Thus, in rocks that are not fractionated, cerium is the most abundant lanthanide with an even atomic number, and lanthanum is the most abundant lanthanide with an odd atomic number.

Three principal types of lanthanide distribution are seen in the Bear Lodge veins. In one common type, cerium and lanthanum are the most common even-atomic-numbered and odd-atomic-numbered lanthanides, respectively. This type, which is exemplified by samples from locality numbers 1, 12, 19, and 20, is similar to that of the Earth's crust. A second common distribution type is similar to the first except that the cerium content is much lower, so that the neodymium content of the sample either equals or exceeds that of the cerium. Samples from locality numbers 3, 14, and 16 in the Bear Lodge Mountains are of this type. This type of fractionation is fairly common in thorium veins and was the most common type found in those at Lemhi Pass (Staatz and others, 1972, p. 78). A probable explanation of this type of fractionation is as follows: All lanthanides have a +3 valence, but cerium is the only one that also has a +4 valence. Thus, if cerium is oxidized from Ce^{+3} to Ce^{+4}, the resulting decrease in ionic radius and increase in charge would exclude this element from structural sites in the rare-earth mineral molecule that was normally available to it in the trivalent form. The third principal type of lanthanide distribution involves an abrupt increase in the heavier lanthanides. In two samples, BL-12-74 at locality 22 and MHS-96-75 at locality 21, gadolinium and erbium, respectively, are the principal lanthanides. The possible cause of this type of distribution is not known, but fractionation probably took place prior to vein emplacement.

Mineral content of thorium veins is generally difficult to correlate with lanthanide distribution. Some minerals, such as bastnaesite and monazite, are made up principally of the lighter lanthanides (those with an atomic number less than 63); others, such as xenotime and brockite, are made up principally of the heavier lanthanides (those with an atomic number greater than 63). The structure of a few minerals, such as thorite, is not markedly selective in its acceptance of various lanthanide elements, and proportions of the various rare earths in these minerals closely reflect the lanthanide content of the vein-forming fluids (Staatz and others, 1974, p. 682). In thorium veins in other districts the abundance of thorite, a nonselective mineral, masks any correlation between lanthanide distribution and mineral content. In the thorite-rich Lemhi Pass district, the only correlation between mineral content and lanthanide abundance is found in three brockite-bearing samples, in which gadolinium and other heavy lanthanides are relatively common (Staatz, 1972, p. 77). Brockite is also a marker of high gadolinium and other heavy lanthanides in the Bear Lodge Mountains, where samples containing brockite at localities 21 and 22 have a relatively high proportion of heavy lanthanides (tables 6 and 7). Similarly, in mineral samples where monazite is common (locs. 10, 17, and 19) or bastnaesite is found (locs. 5, 15, and 20), the light lanthanides, cerium and lanthanum, make up the greater part of the total lanthanides. As thorite has not been found in the veins of the Bear Lodge Mountains, the rare-earth minerals might be useful in identifying the major type of lanthanide distribution. Unfortunately, the masking effect of the abundant manganese and iron oxides conceals the presence of most of the rare-earth minerals in many samples, limiting the use of these minerals in determining the lanthanide distribution.

The uranium content of these deposits is less than that of thorium. The uranium content of 27 vein samples ranges from 5 to 270 ppm (table 7). The Th:U ratios of these samples range from 1.6 to 183, but most fall between 3 and 65. The Th:U ratios of these samples are for the most part lower than those of the Lemhi Pass district, which generally range from 20 to 180 (Staatz, 1979, p. A48).

Iron, manganese, calcium, and potassium contents of the 26 veins vary considerably. They are found in amounts exceeding 7 percent in some samples but are scarce in others. Iron makes up 7 or more percent of 17 of the 21 samples analyzed for this element, yet it makes up only 1 percent of the samples from the northeast-trending vein at locality 22 (table 7). Similarly, manganese makes up 7 or more percent of 8 of the 21 samples analyzed for this element but makes up 0.3 percent or less in 9 samples and in 1, only 0.015 percent. The calcium content in these veins is generally between 0.1 and 2 percent, yet, in three samples it exceeds 10 percent. In addition, the potassium content varies from 0.4 to 10 percent in 19 samples, which is approximately a 25-fold change. Eleven of the samples were analyzed by the semiquantitative spectrographic method, which has an upper detection limit of 10 percent Fe. The other eight samples were analyzed by the more accurate atomic absorption method (table 7). Two of these latter samples yielded 34.8 and 41.4 percent iron, which is equivalent to 49.8 and 59.2 percent Fe_2O_3. Thus, ferric oxide is the principal oxide in some of these veins. Black manganese minerals appear to be fairly common in many of these veins. A sample from one of them (table 7, loc. 6) contains 22.4 percent manganese, but in most samples manganese is much less abundant. Manganese appears in hand specimen to make up considerably more of the vein than it does when analyzed. In part this is due to black manganese oxide staining other minerals so that they appear to be mainly manganese oxide, and in part it is due in some veins to the presence of abundant fine-grained black hematite, which is easily confused with the manganese oxide minerals. The potassium content of the greater part of the samples falls into one of two groups: (1) those that contain 1.5–2.5 percent potassium, and (2) those that contain 7-10 percent. Potassium occurs almost entirely in potassium feldspar, which in many places may be the principal gangue mineral. The potassium content of these veins is roughly equivalent to 3-70 percent potassium feldspar. Although the iron, manganese, calcium, and potassium contents of these veins vary radically, this variation seems to have little effect on the amount of thorium or rare earths present. Small amounts of lead, zinc, molybdenum, copper, and bismuth occur in some of these veins. Lead and zinc are the commonest metals in this group and make up from 70 to 5,000 ppm and from <300 to 10,000 ppm, respectively, of various samples (table 7). Copper and molybdenum are anomalous but much less so than the lead and zinc. Only 4 of 21 samples contained as much as 1,000 ppm copper, and only one contained 1,000 ppm molybdenum. Bismuth, although below the limit of detection in eight samples, made up 30-700 ppm of the remaining analyzed samples. Bismuth commonly occurs in lead minerals (Hasler and others, 1973, p. 95), and in the Bear Lodge samples all of the higher bismuth values came from samples that are high in lead.

Barium, strontium, and niobium are commonly found in thorium-bearing veins. Barium content of 21 samples from the Bear Lodge veins varies from 1,000 to 70,000 ppm; 13 of the samples contain at least 10,000 ppm. Barium generally occurs in barite, which was identified in 13 samples. Strontium content of these samples ranges from 150 to 3,000 ppm. No strontium minerals were identified in these veins, but some strontium commonly substitutes for barium in barite. In most samples, where the barium content is 10 or more times larger than the strontium content, all the strontium is probably proxying for barium in barite. In two samples from locality 22, however, the strontium content either equals or exceeds the barium content (table 7). Strontium here is probably in another mineral.

The niobium content of the vein samples ranges from 30 to 3,000 ppm. This is approximately the same range of niobium values found in vein samples from the Lemhi Pass district (Staatz, 1979, p. A49).

ECONOMIC GEOLOGY

The veins of the Bear Lodge Mountains have received more attention than the disseminated deposits because they have distinct boundaries, have the most radioactivity, contain higher grades of rare earths and thorium, and have been explored in the past for these elements. The veins in this district, however, are smaller and less continuous than thorium- and rare-earth-bearing veins found in the Lemhi Pass district of Idaho and Montana, Wet Mountains and Powderhorn districts of Colorado, Diamond Creek and Hall Mountain districts of Idaho, and the Mountain Pass district of California (Staatz, 1974). The resources of the Bear Lodge veins were calculated on 26 veins, or all known veins over 5 cm thick. These veins are exposed along strike for about a meter to 137 m, and are as much as 2.5 m thick. All the data used in calculating resource data come from surface exposures. Lacking any data on the downward extension of these veins, none of the resources can be considered measured reserves. Resources are divided into indicated and inferred reserves. Indicated reserves in each vein are those found in a block consisting of the traceable length of the vein multiplied by the average thickness multiplied by a depth equal to one-third the length of the vein. Inferred reserves are extensions of the indicated reserves both laterally and at depth. For inferred reserves, the vein was extended on the surface a quarter of the known length in each direction. This distance was shortened where the vein could not be extended through areas of outcrop. Thickness was the same as that used in calculating indicated reserves. Depth of this block is one and a half times the trace of the vein. All veins regardless of length are included in these reserves. If the vein is exposed in only one place, it is assumed to have a length of 7.6 m. A tonnage factor of 2.38 m^3/t is used in converting vein volume to vein weight. The average grade of all veins ranges from 0.011 to 0.68 percent ThO_2 and from 0.23 to 9.81 percent total rare-earth oxides. Indicated reserves of all 26 veins are 50 t of ThO_2 and 1,360 t of total rare-earth oxides. Inferred reserves amount to 250 t of ThO_2 and 6,810 t of total rare-earth oxides. Reserves of most veins are small, and those of 17 of the 26 veins do not exceed 10 t of ThO_2. Most veins in this district are too small to support a viable mining operation. The ThO_2 content is lower, although the total rare-earth content is higher, than most other thorium- or rare-earth-containing veins in other districts. A discussion of the necessary size and grade of thorium veins in various districts to support a viable mining industry has been presented by Staatz and others (1979). They concluded that in a modern mining operation, a vein should contain a minimum of 32,000 t of mineable rock. Only two of the veins in the Bear Lodge Mountains have this much in total reserves. These two veins have indicated reserves of only 20 t of ThO_2 and 545 t of total rare-earth oxides. They also have inferred reserves of 125 t of ThO_2 and 3,140 t of total rare-earth oxides.

DISSEMINATED DEPOSITS

PHYSICAL AND RADIOMETRIC DESCRIPTION

The disseminated deposits occur entirely within the fractured Tertiary intrusive rocks that form the core of the Bear Lodge dome. Much of the intrusive rock in the core has been fractured and altered, but the greatest concentration of fracturing and the most mineralization occur in the central part of the core. Boundaries of disseminated deposits may be either gradational or sharp, and they commonly are erratic. The deposits can be roughly outlined by radioactivity that is concentrated in veinlets within the altered rock.

The radioactivity, however, of all the Tertiary intrusives is above that of the adjacent sedimentary rocks. These igneous rocks range from 120 to 3,500 counts/s on a model SC–1314 Mount Sopris scintillation counter.[1] The least altered parts of the main intrusive, the south and north ends, and the little-altered small intrusives that surround the main intrusive have the least radioactivity. The intrusive rocks in these areas commonly yield only 150 to 300 counts/s. The radioactivity of the surrounding sedimentary rocks is typically between 60 and 80 counts/s. Radioactivity is greatest near Bull Hill in the hydrothermally altered central part of the area that is seamed by many thin veinlets. As the central part of the intrusive body has been erratically mineralized and altered, measurements taken a meter apart may show considerable differences.

The size and extent of the disseminated deposits are not readily determinable by visual examination, and this must depend on either radiometric or chemical measurements. As a first step in determining the extent of mineralization, radiometric readings were taken over the entire central core of the Bear Lodge dome, an area of approximately 30 km^2, with a Mount Sopris scintillation counter. Plate 2*A* is a radiometric map made from measurements taken at 537 different localities. The contours on this map represent a generalized position of points of equal radiation.

The scintillation counter measures both gamma and high-energy beta-rays. These come from three sources, (1) thorium, (2) uranium, and (3) potassium, all three of which may have an appreciable effect on the total radioactivity. The radiation from potassium comes from the isotope ^{40}K, which only makes up 0.0119 percent of the total potassium. Hence, in high-grade thorium veins, the radioactivity due to potassium is insignificant when compared to the total radioactivity. In disseminated deposits, however, where the thorium content is relatively low and potassium content fairly high, radiation due to potassium makes up a much larger proportion of the total radiation. The potassium content of 354 samples was measured on a quantitative gamma-ray spectrometer (Staatz and others, 1980, table 1). An overall average of these samples is close to 9.1 percent potassium. The amount of radioactivity from a rock containing this amount of potassium is equal to that produced by 260 ppm thorium (John Stuckless, oral commun., 1978). The potassium occurs mainly in feldspar, both as an essential mineral in the igneous rocks and as a gangue mineral in the veinlets. Potassium is an important source of radioactivity in these rocks, and in some areas it may be the principal source of radioactivity. The radioactivity due to potassium changes much more gradually than that due to thorium or uranium, as it takes a major change in the amount of potassium to make an abrupt change in radioactivity. Thus, the effect of potassium is to give a generally high background radioactivity over all the Tertiary intrusive rocks. Abrupt changes in potassium content are most commonly due to changes in country rock.

The radioactivity in the Bear Lodge deposits due to uranium is greater than in most other thorium districts. The uranium content of 354 samples of rock from the Tertiary intrusive ranges from 2 to 346 ppm; most, however, contain less than 15 ppm. The radioactivity due to uranium is approximately 5.7 times that created by an equal amount of thorium. Thus, the radiation due to uranium would about equal that due to approximately six times as much thorium. Although the amount of uranium exceeds thorium in only 3 of the 354 samples, the amount of radioactivity due to uranium is greater than that due to thorium in a number of others.

Thorium is the principal source of radiation in most samples. In the other samples, uranium is the principal source. Potassium contributes a significant amount of radiation to all samples. The following questions need answering: Is the radioactivity due to thorium masked by radiation from uranium and potassium in many places? Can the overall pattern of thorium radioactivity be discerned on a radiation map (pl. 2*A*) made with a scintillation counter? The problem is twofold with part of the variation due to the presence of uranium and potassium and part due to differences between measurements made by the scintillation counter and data obtained from analyses. To separate the two problems, the proportionate amount of radiation obtained from

[1]Brand or manufacturers' names used in this report are for descriptive purposes and do not constitute endorsement by the U.S. Geological Survey.

thorium, uranium, and potassium in each sample was calculated from analyses. This was done by arbitrarily equating the radioactivity due to 1 ppm thorium to 1 count/s. Then, the radioactivity due to 1 ppm of uranium is 5.7 counts per second and that of 1 percent potassium is 28.5 counts/s. The thorium content of the samples is plotted against their calculated total count (fig. 14*A*)[2]. The well-defined linear trend formed by these points indicates that the thorium content is for the most part proportional to the total count. The one point to the far right that does not fit the general pattern contained 346 ppm uranium. The radioactivity due to uranium in this sample is about 15 times that due to thorium.

The difference obtained between the actual radiation measured by a scintillation counter and the thorium content of the sample from that locality is shown in figure 14*B*. The linear trend is still quite apparent for the samples with a low thorium content. The two graphs show that higher radioactivity, no matter what the source, indicates a greater thorium content. Furthermore, the total thorium content is roughly proportional to the radioactivity.

Although the contour map shown on plate 2*A* in general outlines the principal radiometric areas, it is of too small scale to define the size and grade of the disseminated deposits. In 1979 a more detailed radiometric measuring and sampling program was started. This program covered an area of about 10.6 km^2 of the most radioactive part of the igneous core. At each sample site a chip sample was collected and analyzed for thorium, uranium, and potassium on a quantitative gamma-ray spectrometer in the U.S. Geological Survey's Denver laboratory (Staatz and others, 1980). In addition semiquantitative spectrographic analyses were performed on a little over half of these samples. Radiometric measuring and sampling were made only on soil-free areas. Many of the sites were in pits, trenches, or on dumps, but some were of roadcuts and of outcrops along ridges. Samples and radiometric readings were taken so as to be as representative as possible; none contained material from any of the larger veins described in the previous section. These data were used to construct five contour maps: (1) a detailed total-count radiometric map, (2) a thorium map, (3) a uranium map, (4) a potassium map, and (5) a total rare-earths map.

The detailed radiometric contour map (pl. 2*B*) gives a more detailed picture of a smaller area than that shown on plate 2*A*. Differences between these two maps can largely be accounted for by having many more points on view *B*. The areas of greatest radioactivity on view *B* are concentrated in section 17 and adjacent parts of sections 18 and 20.

A thorium map (pl. 2*C*), which is based on thorium analyses of samples taken at 354 localities, fairly closely resembles the total count map. Differences are due to the fact that view *C* represents only the thorium content of the rock and that the two sets of measurements, although taken at the same locality, were not exactly the same sample. View *C* can be used to define the edge of the disseminated deposit as a thorium resource.

A thorium aeroradioactivity map or thorium gamma-ray intensity map of the same area at a scale of 1:62,500 was published in 1979 (Geometrics, 1979). This map and plate 2*C*, except for their difference in scales, are remarkably similar in the area of principal thorium concentration in sections 17, 18, and the north half of section 20. Away from the principal thorium concentration, the two show many differences. These differences are due to both the size of the samples and the difference in material measured. Plate 2*C* is a spot map, and each sample represents a small specific area of bedrock. The aeroradiometric measurements were made at an average elevation of 122 m at a flight speed of 112 km/hr, and each 1-second measurement corresponds to an oval area 213 m long by 183 m wide (Geometrics, v. 1, p. 47). The material measured includes both alluvial cover and bedrock, and most measurements represent more of the former.

The uranium contour map (pl. 2*D*) shows little resemblance to the thorium map (pl. 2*C*). A comparison of the two maps indicates that the few concentrations of uranium present are not closely associated with those of thorium. The uranium values of more than 60 ppm appear to represent scattered individual samples rather than part of a general increase in uranium in that area. Furthermore, except for the few scattered samples, the uranium tenor is fairly low and rarely exceeds 40 ppm. The uranium contour map shows little resemblance to a previously published aeroradiometric uranium gamma-ray contour map (Geometrics, 1979). The aeroradiometric contour map over the area of thorium concentration resembles the thorium contour map. The values used in constructing the aeroradiometric uranium map are corrected readings of gamma-ray spectrometer measurements. Correcting is done by using a complicated formula to remove excess radiation due to thorium or potassium in the uranium channel. The formulas for the instrument used by Geometrics were calculated from measurements made on the U.S. Department of Energy's sample areas in Grand Junction, Colo., which have known thorium, uranium, and potassium contents. These formulas, however, are apparently

[2]The analyses used in these graphs were those from samples collected between 1975 and 1977 and do not include those collected in 1979.

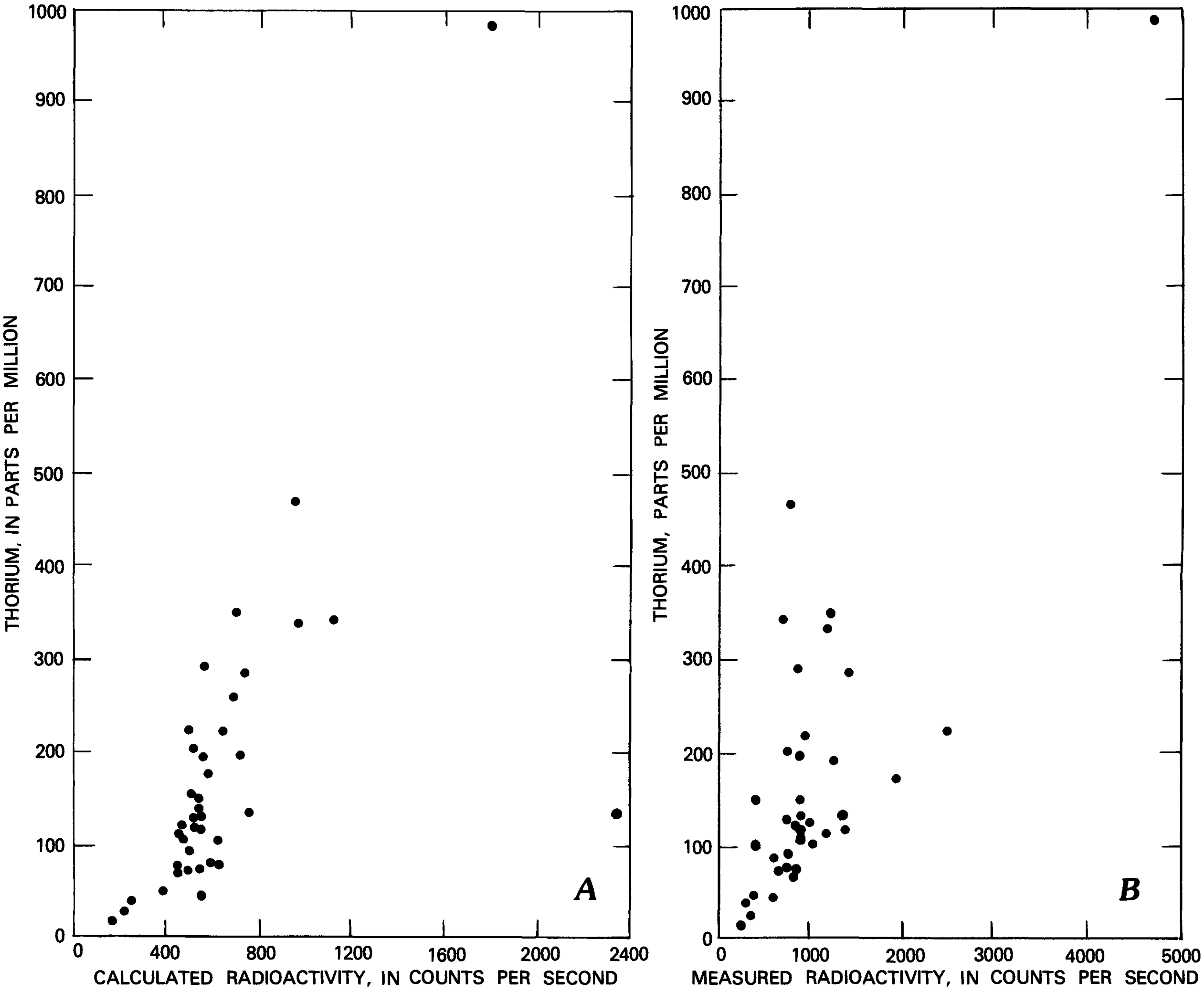

FIGURE 14.—Relation of thorium content to radioactivity in the core of the Bear Lodge dome. *A*, Radioactivity calculated from analyses. *B*, Radioactivity measured with scintillation counter at sample site.

not satisfactory for areas that have a high thorium content, as considerable thorium is apparently interpreted as uranium. I have also measured the thorium, uranium, and potassium content of the trachyte core with a portable gamma-ray spectrometer. My instrument was also calibrated on the U.S. Department of Energy's sample areas in Grand Junction, Colo. Results obtained were not satisfactory, and a uranium contour map constructed from this data also resembled that of thorium.

The potassium contour map (pl. 2*E*) shows little resemblance to the total count, thorium, rare-earth or uranium maps. Potassium is principally in the feldspar of the host rock, and changes in potassium content reflect changes in the amount of potassium-bearing feldspar. In some places, a change indicates different rock types, but in other places it is due to later alteration that has resulted in leaching of some of the original potassium from the rock.

The rare-earth contour map (pl. 2*F*) shows little resemblance to the other contour maps. The area in which the greater part of the rare earths occurs is the same general area in which the thorium is concentrated. In detail the major rare-earth concentrations are found in different places than those of thorium. The reason that rare earths and thorium are found in the same general area is that both occur in the veinlets that make up the disseminated deposits. Furthermore, both rare earths and thorium commonly occur in the same minerals. The amounts of rare earths in various minerals, however, show little correlation with the amount of thorium. Hence, although the amounts of rare earths may not correlate with those of thorium, those areas lacking veinlets will lack both rare earths and thorium.

MINERALOGY

The study of the mineralogy of the disseminated deposits was carried out in the same manner as that of the veins. The minerals identified in samples from 36 locations are given in table 8. Twenty-nine minerals have been identified. Although the altered trachytic rock and phonolitic country rock make up the bulk of the samples, most of the identified minerals were derived from the veins. Minerals from the country rock are now largely shown in table 8 as groundmass, which means very fine grained or aphanitic pieces in which individual minerals are not distinguishable under the binocular microscope. Minerals from the country rock also make up part of the feldspar and iron oxides. Thus, the gross mineralogy, as shown in table 8, is mainly derived from the veins, but the concentration of the various vein minerals has been diluted by the addition of the country-rock fraction.

The mineralogy of the disseminated deposits includes both that of the altered and fractured trachytic and phonolitic host rock, and that of the included tiny veinlets. The mineralogy of the veinlets is similar to and shows the same kind of variations as that of the previously described veins (p. D33–D34). The trachyte and phonolite consist principally of larger sanidine and smaller nepheline and mafic phenocrysts set in a fine-grained to aphanitic groundmass. The mafic minerals are commonly aegirine-augite but locally may be hornblende or biotite. Accessory minerals include sphene, rutile, apatite, zircon, and fluorite. The country rock, however, was altered during or preceding the mineralization. Nepheline and the mafic minerals have for the most part been completely altered, and the former sites of these minerals are now occupied by fine intergrowths of feldspar, clay, and iron and manganese oxides.

Feldspar is the principal mineral in the rocks containing disseminated deposits. As previously noted it is derived both from the country rock and from the veins. In unaltered trachyte or phonolite, sanidine is the principal feldspar. Fine-grained feldspar is abundant in most of the veinlets. The X-ray diffraction method of Bowen and Tuttle (1950, p. 493) was used to compare the variation in the angular separation between the ($\bar{2}$01) plane in feldspar and the (10$\bar{1}$0) plane in a quartz standard to that of known feldspars to determine relative amounts of potassium feldspar versus plagioclase. These data indicate that the six samples are made up of from 99 to 100 percent potassium feldspar. The relative amounts of potassium feldspar versus plagioclase were also obtained by using optical data on several samples. Although the feldspar in many samples was too microcrystalline to be analyzed by this method, E. J. Young was able to determine the β index of refraction of several samples. This index, which is 1.522, was compared by Young with the potassium feldspar content of this value on a diagram compiled by Tuttle (1952, p. 559). Potassium feldspar makes up approximately 100 percent of the total feldspar, where the β index is 1.522. These data corroborate those obtained by the X-ray diffraction method.

Iron oxide minerals are derived from the alteration of both iron-bearing veins and country-rock minerals. Goethite and hematite make up the greater part of the heavy minerals recovered in many samples. Goethite most commonly occurs in these rocks as a dark-brown, granular mineral. It may vary in color from nearly black to a light brownish yellow. In addition to granular the texture can be smooth or vesicular, and the luster may be either dull or shiny. Several different types may occur in a single hand specimen. The various types may reflect different modes of origin. Some of the goethite occurs as dark-brown striated cubes and is formed by pseudomorphous replacement of pyrite cubes. Other goethite occurs in small veinlets that crosscut earlier minerals, where the iron oxide has been transported at least a short distance before it was redeposited. Goethite was identified by its X-ray diffraction pattern in mineral separates from about half the samples. Although goethite was the only variety of limonite identified in the disseminated deposits, lepidocrocite probably also occurs in minor amounts, as small amounts of this mineral have been found in the veins. Hematite is generally a dark-reddish-gray, granular mineral commonly found in association with goethite. Magnetite is present in most samples, but in no place does it make up more than a few tenths of one percent of any sample. This mineral occurs in tiny crystals that are commonly intergrown with the other iron oxides.

Manganese oxide minerals were found in about two-thirds of the samples examined. The manganese oxide minerals range from dark gray to black, and their surfaces may be either dull or shiny. Most manganese oxide minerals are similar in appearance but can be identified by their X-ray diffraction pattern. Six of the

TABLE 8.—*Mineralogy of the disseminated deposits in the southern Bear Lodge Mountains*

[Minerals listed in italics were identified by their X-ray diffraction pattern]

Locality No.	Rock or minerals--relative amounts			
	Large	Medium	Small	Rare
27	Groundmass------	Feldspar, *goethite*.	Hematite, manganese oxide mineral.	*Quartz*, *anatase*.
28	Groundmass, sanidine.	Goethite---------	Magnetite, *pyrolusite*, *rutile*.	Fluorite.
29	*Sanidine*, groundmass.	---do------------	*Brookite*-----------	Magnetite, *rutile*, barite.
30	Sanidine, groundmass.	Goethite, hematite.		Magnetite, *zircon*.
31	Groundmass, *sanidine*.	Goethite, *cryptomelane*.	Hematite, *sphene*.	Magnetite.
32	Groundmass------	Feldspar, *hematite*.	Biotite, goethite.	Chalcedony, fluorite, *barite*.
33	Groundmass, feldspar.	Goethite---------	Hematite, magnetite, *rutile*, manganese oxide mineral.	*Brookite*, barite.
34	Groundmass------	---do------------	*Rutile*, hematite, magnetite, manganese oxide mineral.	Calcite.
35	Groundmass, sanidine.	*Goethite*---------	Hematite, *rutile*.	Barite.
37	---do-----------	Goethite---------	Hematite, *cryptomelane*.	Magnetite, barite, *rutile*.
38	Sanidine, groundmass.	*Goethite*---------	Biotite, magnetite.	*Barite*.
39	---do-----------	*Goethite*---------	Pyrite, *rutile*, magnetite, manganese oxide mineral.	Calcite.
40	Groundmass, manganese oxide mineral.	Feldspar, *goethite*.	Hematite, *bastnaesite*.	Magnetite, barite.
42	Groundmass, sanidine.	Hematite, *cryptomelane*.	Goethite-----------	Magnetite, barite.
43	---do-----------	*Goethite*, manganese oxide mineral.	Magnetite, *sphalerite*, *brockite*, *uraninite*, *rutile*.	Barite.
44	---do-----------	Goethite---------	Hematite, magnetite, *biotite*, manganese oxide mineral, *jarosite*, *apatite*, *sphene*.	Fluorite.
45	Sanidine, groundmass.	*Goethite*, manganese oxide mineral.	*Hematite*, *barite*.	Magnetite, *rutile*.
46	*Sanidine*, groundmass.	Goethite---------	*Pyrolusite*, *brookite*, *rutile*.	Magnetite, pyrite, calcite.
47	Groundmass------	Sanidine, *hematite*, *barite*.	Goethite.	
48	Sanidine, groundmass.	*Pyrolusite*, goethite.	Quartz, *barite*.	Magnetite, calcite.
49	Groundmass------	*Sanidine*, goethite.	Hematite, *cryptomelane*, *brookite*.	Magnetite, *rutile*.
53	Groundmass, sanidine.	*Goethite* hematite.	*Rutile*-------------	Barite.
54	---do-----------	*Goethite*---------	Hematite, biotite, *cryptomelane*, *barite*, *rutile*.	Magnetite.
55	Sanidine, groundmass.	Hematite, goethite.	*Rutile*, *barite*.	Magnetite, *brookite*.
56	Groundmass, sanidine.	Chalcedony, goethite, *hematite*.	*Rhabdophane*, *rutile*, *brookite*, *barite*.	
57	---do-----------	Quartz, *goethite*.	Hematite, barite, *sphalerite*.	Magnetite, *rutile*.
58	Groundmass, *sanidine*.	*Goethite*---------	Quartz, manganese oxide mineral, hematite, *monazite*, *kasolite*.	*Barite*, zircon, magnetite.
59	Groundmass, sanidine.	Hematite, *goethite*.	*Cryptomelane*, *barite*.	
109	Groundmass------	Sanidine, *goethite*, hematite, *brockite*.	*Barite*, manganese oxide mineral, *rutile*.	Biotite.
113	---do-----------	Sanidine, hematite.	*Goethite*, *barite*.	Magnetite, *rutile*.
133	Groundmass, sanidine.	Goethite---------	Magnetite, hematite, manganese oxide mineral, *barite*, *brockite*, *rutile*, *bastnaesite*.	
134	Groundmass------	Sanidine, *goethite*, hematite, manganese oxide mineral.	*Barite*-------------	*Uraninite*.
141	---do-----------	Sanidine---------	Manganese-oxide mineral, *barite*, *rutile*, *brockite*, *weinschenkite*(?).	
142	---do-----------	*Sanidine*, *goethite*.	Hematite, magnetite, *pyrolusite*, *rutile* *monazite* *barite*.	*Apatite*.
144	---do-----------	---do------------	Magnetite, hematite, *pyrolusite*, *rutile*, barite.	*Brookite*.
252	---do-----------	Sanidine, *goethite*.	*Barite*, *cerussite*, *sphene*, *bastnaesite*, *brockite*.	*Hematite*, magnetite, rutile.

manganese oxides gave a cryptomelane pattern, and five had a pyrolusite one.

In only 7 of the 36 samples are thorium minerals recognized. Brockite was identified at five localities and monazite at two. Rare earths also occur in these minerals and in several other minerals. Bastnaesite was found at localities 40, 133, and 144; rhabdophane at locality 56; and weinschenkite at locality 142 (table 8). The relatively high contents of rare earths and thorium found by the chemical analysis of those same samples indicate that minerals of these elements should occur in most of these samples, but iron and manganese oxides tend to mask them. Two uranium minerals, uraninite and kasolite, were identified in two samples and one sample respectively. Neither occurs in the most uranium rich samples. Uranium minerals in other samples are probably also masked with iron and manganese oxides. Although uraninite is a primary mineral, kasolite, $PBO_3UO_3 \cdot SiO_2 \cdot H_2O$, is a secondary one, and it probably formed along fractures during weathering from uraninite.

Other minerals that are fairly common in small amounts in these samples include barite, rutile, brookite, fluorite, biotite, and calcite. All of these minerals occur in the larger veins.

CHEMICAL COMPOSITION

The shape of the disseminated deposits, as stated previously, is determined by the grade of the rock. The shape and the grade of the disseminated deposits are generally not known until after analyses have been made. A total of 341 samples were taken in outlining the disseminated deposits (Staatz and others, 1980, fig. 1). These samples contain from 9.3 to 990 ppm thorium. Two hundred sixty-five samples of this group fell inside the 50 ppm contour (pl. 2*C*) and they contain from 51.1 to 990 ppm thorium. Although trachyte and phonolite of Tertiary age made up the bulk of the country rock sampled, granite of Precambrian age was also included along the edge of the disseminated deposits in the vicinity of Warren Peak and Smith Ridge. The granite in many places is cut by thin dikes of trachyte or phonolite, and some samples in these areas include both rocks. Nine samples that were made up of both granite and trachyte contain from 22.7 to 158 ppm thorium; nine samples made up only of granite contain from 9.3 to 87.4 ppm thorium. All but one of the samples made up entirely of granite had less than 50 ppm thorium. Granite does not appear to be a favorable host rock, although some abnormally high thorium values occur where cut by or immediately adjacent to trachyte or phonolite dikes.

In addition to the samples taken in and around the disseminated deposits, another 10 samples were collected in trachytic and phonolitic rocks that were not in or adjacent to the disseminated deposits. Three of these samples were taken in the southern part of the core of the Bear Lodge dome; the others came from separate intrusives that are bodies satellitic to the core. These 10 samples, which represent nonmineralized alkalic rocks, contain from 15.4 to 55 ppm Th.

The total rare-earth content of the disseminated deposits varies in 192 samples from 47 to 27,145 ppm (Staatz and others, 1980). One hundred seventy-one of these samples contain at least 500 ppm, 103 samples contain at least 1,000 ppm, and 54 samples contain in excess of 5,000 ppm. The distribution of the rare earths in the disseminated deposits is shown by contours on plate 2*F*. The overall amount of total rare earths in the 192 analyzed samples is 26.6 times greater than that of thorium. A plot of the amounts of rare earths and thorium found in various samples indicates no correlation between the amounts of one with those of the other. Total rare-earth content does correlate with that of uranium. A plot of uranium, excluding two values over 140 ppm, with total rare earths shows a general increase in one with that of the other (fig. 15). The amounts of most other elements that occur in anomalous amounts in this area show little correlation with the amounts of rare earths. These other elements include: niobium, barium, strontium, potassium, manganese, iron, copper, lead, zinc, and molybdenum.

The lanthanide distribution of the samples analyzed for rare earths is remarkably similar. The amounts of light rare earths greatly exceed those of the heavy rare earths. The principal rare earth in all samples containing as much as 5,000 ppm total rare earths is cerium or cerium with neodymium and (or) lanthanum. Yttrium, the principal heavy rare earth, makes up from 0.8 to 17.5 percent of the total rare earths in these same samples. In 52 of the 54 samples that contain as much as 5,000 ppm total rare earths, however, yttrium makes up only 0.8 to 8.6 percent of the total rare earths. The average yttrium content of the total rare earths in the 54 higher grade samples is only 3.2 percent.

The uranium content of the disseminated deposits ranges in 341 samples from 1.8 to 346 ppm (Staatz and others, 1980). The average uranium content of all samples is 16.5 ppm. Twenty-seven samples contained 40 or more ppm uranium, but only five samples contain as much as 80 ppm. Granite within the area of disseminated deposits contains only minor amounts of uranium, and nine samples taken of this granite yield from 1.8 to 7.0 ppm uranium. For comparison 10 samples of trachyte and phonolite were collected either in the Bear Lodge core away from the disseminated deposits or in

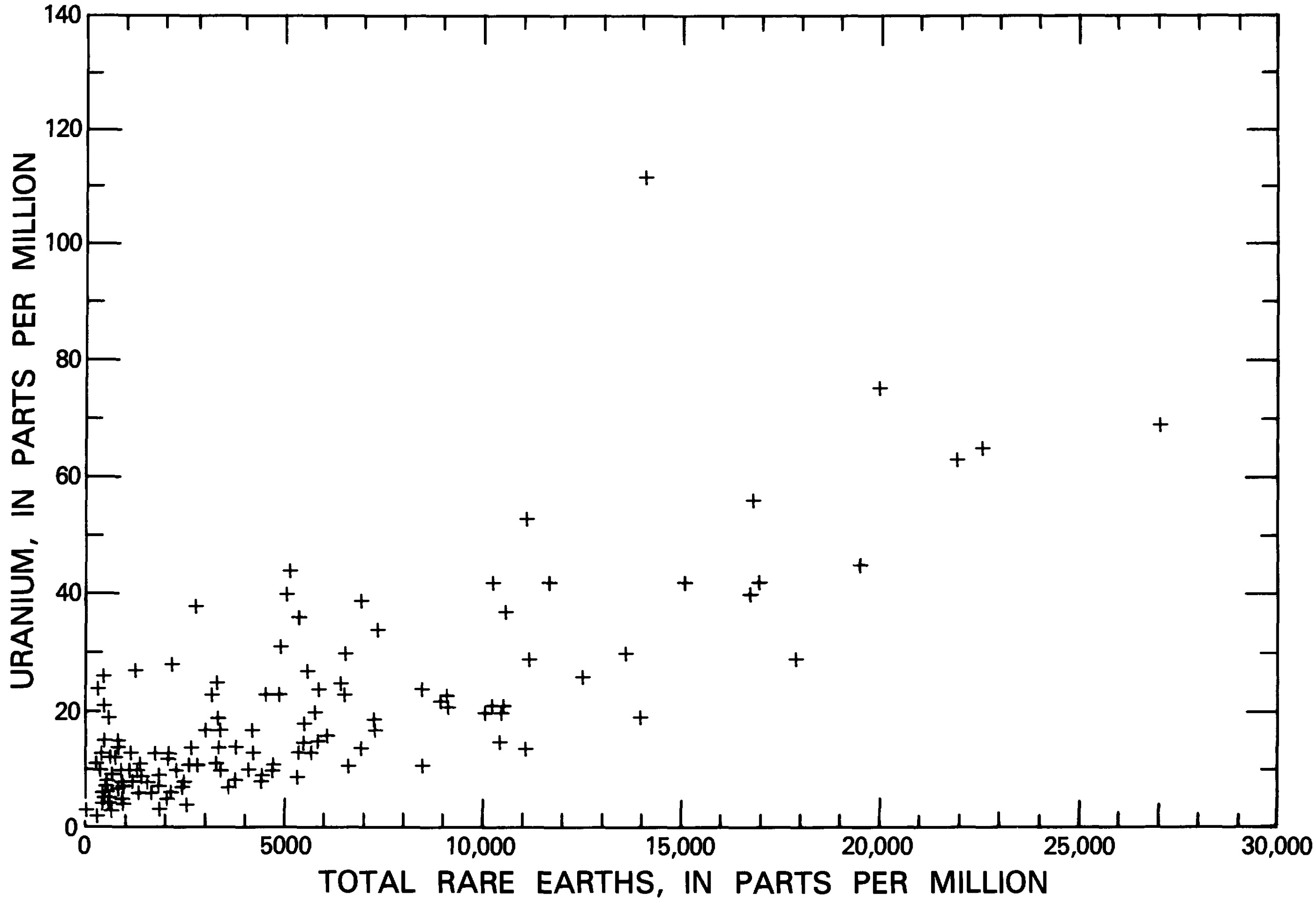

FIGURE 15.—Relation of uranium to total rare earths in samples from the disseminated deposits.

separate peripheral bodies. These nonmineralized rocks contain from 8.0 to 19.8 ppm uranium. Thorium to uranium ratios of samples taken in the disseminated deposits are highly erratic; they vary from 0.4 to 136. Most of this variation is due to later mineralization, as the thorium to uranium ratios of the 10 samples of trachyte and phonolite that were collected away from the sites of mineralization vary only from 2.1 to 3.4. The amount of uranium present at any place within the disseminated deposits has no relation to the amount of thorium. This can best be seen by comparing the contour map showing the distribution of uranium with that showing the distribution of thorium (pls. *2D*, *2C*).

The potassium content of trachyte and phonolite, the host rocks for the disseminated deposits, is generally high. In addition some potassium also occurs in the gangue minerals in the veinlets. Potassium content varies from 3.1 to 12.4 percent of the 354 samples. Three hundred and one of these samples, however, have more than 7 percent potassium. On the average, potassium content of all samples was 9.1 percent. This amount of potassium is equivalent to the rock's being made up of 65 percent sanidine. As the greater part of the potassium in disseminated deposits comes from the host rock, potassium content of various samples shows little relation to the metal content of various other anomalous elements.

Barium and strontium are also present in the disseminated deposits. Barium content ranges from 500 to 15,000 ppm and the strontium content from 150 to 7,000 ppm. Barium occurs in barite, which is a common mineral in some of the veinlets. Rare earths are also common in the veinlets. Most samples containing 5,000 ppm or more of barium are high in rare earths and many contain in excess of 1 percent total rare earths, although there is no direct correlation between the amount of barium and that of rare earths in the samples. A part of the strontium probably substitutes for barium in the barite. The amount of strontium, however, is unrelated to the amount of barium, and a plot of strontium and barium from the same samples shows no overall trend. Although a few samples that contain

5,000 ppm or more strontium also contain 5,000 ppm or more barium, most samples with a high strontium content contain 3,000 ppm or less barium. Strontium-high samples also generally have a fairly low rare-earth content. Most samples that have a strontium content of 5,000 ppm or more come from localities scattered along the periphery of the disseminated deposits. No mineral in which strontium is an essential component has been identified. Furthermore, strontium analyses of the light and heavy fractions of several samples separated in methylene iodide indicate that most of the strontium occurs in the light fraction. Hence, this element most likely proxies for one of the alkalies in feldspar.

Niobium makes up from less than 10 to 2,000 ppm of the disseminated deposits. Most samples contained from 30 to 70 ppm niobium, and only 15 samples had 200 or more ppm. The amount of niobium present in any sample shows little relation to the amounts of the following elements: thorium, rare earths, uranium, potassium, strontium, copper, molybdenum, lead.

Copper, molybdenum, lead, and zinc are anomalously high in many samples (Staatz and others, 1980, table 1). Copper content of 193 samples ranges from 3 to 10,000 ppm. The two samples that contained more than 500 ppm were taken from dumps of old copper prospects and contained green secondary copper minerals. Sixty-two samples, however, contain from 150 to 300 ppm copper. Molybdenum content of the samples ranges from less than 2 to 700 ppm, and 40 samples contain at least 100 ppm molybdenum. Lead content varies from 15 to 5,000 ppm, and 24 samples contain at least 700 ppm lead. Zinc content ranges from less than 200 to 2,000 ppm, and 17 samples contain at least 700 ppm zinc. The amounts of copper, molybdenum, lead, and zinc present in various samples in these rocks have neither a positive nor a negative correlation with the amounts of thorium, total rare earths, or uranium. Furthermore, the amounts of these four base metals show little correlation with one another. The samples are all taken from the surface where the rocks are oxidized. Few sulfides remain, and it is doubtful that the grade at the surface is representative of these metals at depth.

ECONOMIC GEOLOGY

The disseminated deposits, although lower grade than the veins previously discussed, are large and contain the bulk of the thorium and rare earths in this district. The entire central part of the Bear Lodge dome, which is anomalously radioactive, contains numerous crisscrossing veinlets over an area of approximately 10.6 km^2 as outlined by a scintillation counter (pl. 2*A*). As previously noted, the area of thorium and rare-earth mineralization has been further defined by a more detailed sampling program (pls. 2*C*, 2*F*). Although sampling has shown that in places grade boundaries are erratic, in many places, as shown by the maps of plate 2*C* and plate 2*F*, they are also gradational. These maps allow choosing an area with a specific grade. As ore is defined as a metal-bearing deposit that can be mined at a profit, the size and shape of any future mineable part of the disseminated deposits depend on the economic conditions at the time of mining. These conditions include whether thorium, rare earths, or both are being sought, the cost of mining at the time, and the price obtained for the commodities, as well as such nonmineral related problems as land ownership, environmental considerations, and mining company policies. Thus, the size and shape of the ore body in the disseminated deposits at any particular time can be defined by whichever grade contour fits the economic conditions of that time.

The bulk of the thorium and rare earths occur in sec. 17, the E½ sec. 18, and the N½ sec. 20 (pls. 2*C*, 2*F*). The most thorium rich parts of this area generally do not coincide with those richest in rare earths. A thorium content of 200 ppm was chosen as a likely lower limit of rock that would be mineable in the foreseeable future. The 200 ppm contour encloses several areas that total 1.69 km^2. The thorium content of these areas ranges from 200 to 990 ppm. Higher grade localities tend to be small and local and are scattered through the areas enclosed by the 200 ppm contour. Areas falling within the 500 ppm contours encompass only 0.09 km^2.

Rare earths are much more abundant than thorium in this region, and the greater part of the higher rare earth concentrations lie within a contour representing 2,000 ppm total rare earths (pl. 2*F*). This contour encloses one large area and a couple of small ones, which have a total area of 3.22 km^2. The grade of the total rare earths falling within this contour ranges from 2,000 to 27,145 ppm. Seven smaller areas containing 1 percent (10,000 ppm) or more of total rare earths fall within the 2,000 ppm contour. Total size of these smaller areas is 0.84 km^2. More than half of the area containing this higher grade rock occurs at one place along the west side of sec. 20 (pl. 2*F*). Two other areas that contain most of the rest of the higher grade rock lie along the northwest side of Bull Hill and astride the road along Taylor Divide in the northern part of sec. 20. Few data are available on the thorium and rare-earth content of these rocks at depth. Anomalous amounts of thorium or rare earths, however, are exposed at the surface over a difference of elevation of approximately 260 m. In addition, sparse drilling data from the W½ sec. 17 and the E½ sec. 18 indicate that the rock is mineralized in places at least 370 m below the surface.

Large low-grade deposits, like the disseminated deposits, which occur near the surface, can be mined by the open-pit method (Staatz and others, 1979, p. 20-21). Overburden covers much of the area, but is thin; it generally ranges from less than 1 to 5 m in thickness. Although the open-pit method is fairly cheap, not all the resources would be recovered. The walls of an open pit must be terraced with an overall slope of 45° or less. Furthermore, if the thorium and rare-earth resource continued to a depth greater than about 460 m, the deeper resources would have to be recovered by some other method. The Bear Lodge disseminated deposits have one of the largest resources of both thorium and rare earths in the United States. Although neither the thorium nor the rare earths are producible under 1980 market conditions and the grade of both commodities is lower than that of some other deposits in the United States, the disseminated deposits' large size and their cheap cost of mining makes them an important future economic resource.

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