Geology of the South Pass Area, Fremont County, Wyoming

By RICHARD W. BAYLEY, PAUL DEAN PROCTOR, *and* KENT C. CONDIE

GEOLOGICAL SURVEY PROFESSIONAL PAPER 793

Describes the stratigraphy, structure, and metamorphism of the South Pass area, and the iron and gold deposits

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1973

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 73-600101

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 – Price $1.10 (paper cover)
Stock Number 2401-02398

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GEOLOGY OF THE SOUTH PASS AREA, FREMONT COUNTY, WYOMING

By RICHARD W. BAYLEY, PAUL DEAN PROCTOR,[1] and KENT C. CONDIE[2]

ABSTRACT

The South Pass area includes five 7½-minute quadrangles near the south end of the Wind River Range in Fremont County, Wyo. Laramide uplift and erosion exposed the Precambrian rocks along the crest of the range for over 100 miles. About half of the South Pass area is underlain by Precambrian granitic and gneissic rocks that are about 2.7 billion years old. The other half is underlain by a large pendant of Precambrian metasedimentary and metavolcanic rocks that are older than the granite. Inasmuch as the oldest metamorphic rocks are on the northwest and the southeast side of the pendant, the original structural feature may have been a northeast-trending synclinorium. Gold and iron deposits are included in the pendant. The older rocks of the pendant probably correspond in age to the pregranite rocks (2.5 b.y.) of the Superior province of Canada, Minnesota, and northern Michigan.

The Precambrian rocks of the South Pass area are overlapped on the east by gently dipping Paleozoic rocks, and on the south and west by nearly flat-lying Tertiary rocks. Approximately half of the area is covered by a Tertiary pediment, which descends east, through canyons in the Paleozoic rocks, to the Wind River Basin and south and west into the Green River Basin.

The metasedimentary rocks of the pendant are underlain by gneiss, in which inclusions of greenstone and metagabbro amphibolite are abundant, and probably by some serpentinite. These lithologies suggest an ophiolite basement.

The pendant contains three formations: the basal Goldman Meadows Formation, composed of quartzite, schist, and iron-formation; the intermediate Roundtop Mountain Greenstone, composed mostly of ellipsoidal basaltic lavas; and the overlying Miners Delight Formation, composed mostly of metagraywacke, but including some meta-andesite, conglomerate, and graphitic schist. These layered rocks were intruded by igneous rocks in the following order: metagabbro dikes, metadiorite dikes, metaleucodacite dikes and tonalite stocks, metagabbro dikes, a granodiorite batholith and satellitic granitic stocks, and gabbroic dikes.

The intrusion of the batholith and satellite stocks caused refolding of the western part of the pendant. Differentiates of the batholith—pegmatites and aplites—were emplaced after the second folding.

Major faulting occurred before and after the batholith was emplaced. The early faults are on either side of the Roundtop Mountain Greenstone. They are apparently normal, with a large displacement. Most of the late faults postdate and cut the batholith and have caused extensive displacement of the gold belt. One major fault was reactivated during the Laramide uplift and caused extensive dislocation of the Paleozoic and Mesozoic rocks east of the Precambrian area.

The layered rocks of the pendant are mostly of amphibolite facies; only the volcanics at Roundtop Mountain are of greenschist facies. Andalusite and cordierite schist is widespread. Sillimanite occurs only at the graywacke-granodiorite contact in the northwest.

Gold was probably introduced into the Miners Delight Formation during the first folding. Gold-bearing quartz veins occur mostly in graphitic schists and metadiorite; however, a few are isolated in the graywacke. All known gold mines were discovered between 1867 and 1871. Most are now inactive or abandoned. A second weaker mineralization, in which copper accompanied gold, occurred during the late faulting and caused sericitic alteration of some fault zones.

Production and shipment of iron ore from the deposit in the Goldman Meadows Formation at Iron Mountain was begun in 1962 by the U.S. Steel Corp. About 1.3 million tons of pelletized ore is produced annually.

INTRODUCTION

GEOGRAPHY

The South Pass area lies close to the Continental Divide, near the south end of the Wind River Range in Fremont County, Wyo., about 28 miles south of the town of Lander (fig. 1). It contains chiefly National Forest and public rangelands, but includes some deeded ranch lands and mineral claims as well.

The topography is varied, but the dominant feature is a Tertiary pediment surface, a very gently dipping plain, of Tertiary sedimentary deposits, which blends the Precambrian core of the Wind River Range with the Green River Basin to the south and west. Low foothills beginning near the upper limit of the pediment, about lat 42°30′, grade into a glaciated mountainous terrain toward the northwest. Two photographs are included to show the variation in the topography and vegetation of the area. (See figs. 2 and 3.)

The country is high semidesert. Most of it lies between 7,200 and 8,500 feet above sea level. The relief in the foothills is 300–500 feet, and the north-

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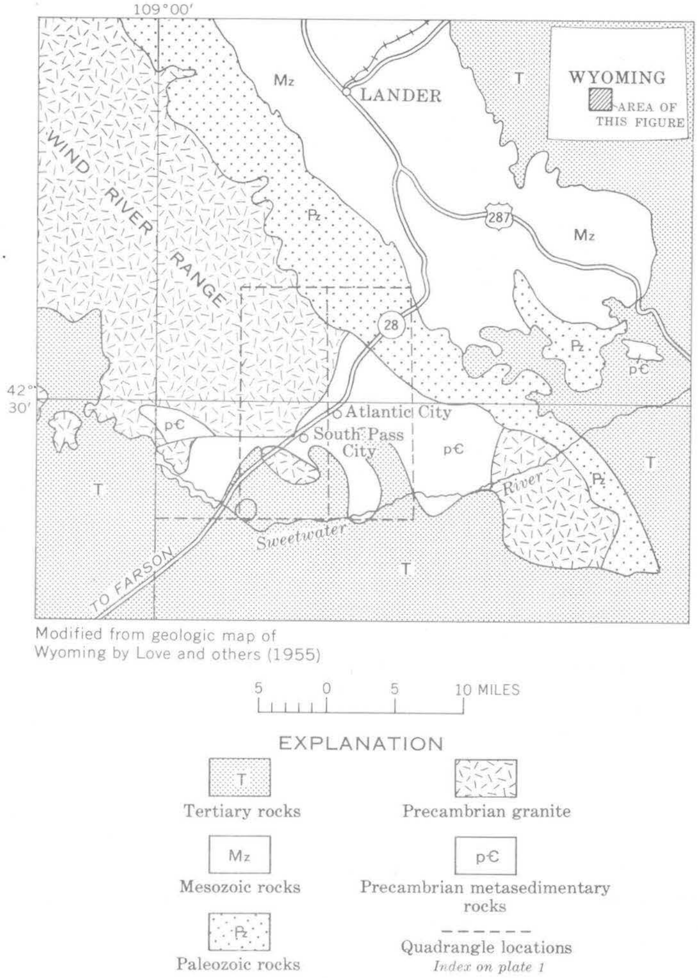


FIGURE 1.—Generalized geologic map showing the geographic and geologic setting of the South Pass map area, Fremont County, Wyo.

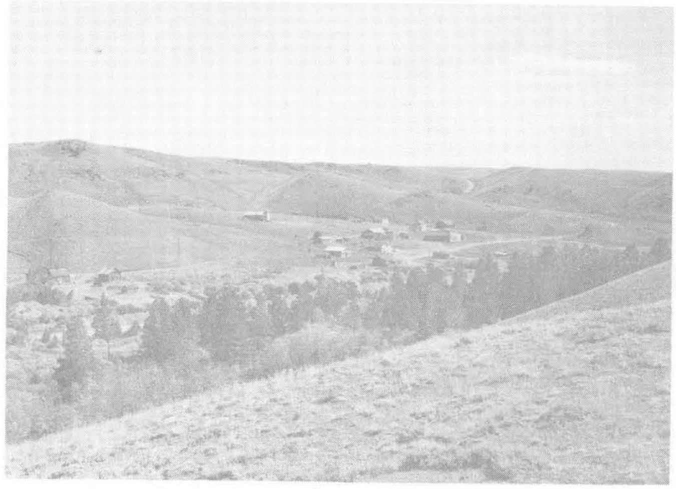


FIGURE 2.—View east across Rock Creek valley and Atlantic City. South-dipping Tertiary pediment surface on horizon.

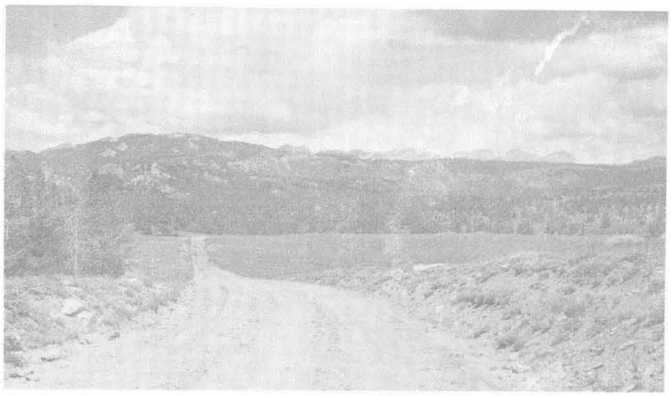


FIGURE 3.—View north from Tertiary pediment toward granite mountains. Taken on Louis Lake road in sec. 4, T. 29 N., R. 100 W.

ern mountains rise to 10,300 feet. Many small streams, tributaries to the Sweetwater and Wind Rivers, drain the area, and narrow, steep-sided gulches are common in the Tertiary pediment. Grass and sage cover most of the plains and the south-facing hill slopes; sage, willow brush, aspen, and pine grow in the creek valleys and on north-facing slopes; and most of the high country is sparsely pine covered. (See figs. 2 and 3.) The climate is semiarid. The weather in summer, between about mid-June and early October, is very pleasant; the winters are long and rigorous. The area is accessible at all times of the year by State Highway 28 from Lander to Farson. Numerous dirt roads and trails from this highway lead to almost all points of interest. The five mapped quadrangles (pl. 1) are the Miners Delight, Louis Lake, Atlantic City, South Pass, and Anderson Ridge.

HUMAN HISTORY

Indian artifacts are relatively plentiful throughout the area, attesting to centuries of occupation by the earliest inhabitants. When the first white man came is uncertain, but the emigrant trail to California and Oregon was established across the area and functioning before 1842. In that year, placer gold was found in the streams of the area, and in 1867, the first lode gold mine, the Carissa Lode, was discovered; shortly thereafter the area was stampeded. By 1869, there were reported to be 2,000 people in three gold camps: South Pass City, Atlantic City, and Miners Delight. By 1871, all the known major gold lodes had been found, and many placer deposits had been worked, but the boom was short lived, and 1875 found most of the mines idle and the area nearly deserted (Knight, 1901, p. 9; Nickerson, 1886, p. 14). Occasional gold mining has continued from 1875 to the present day (fig. 4).

FIGURE 4.—The Carrisa gold mine near South Pass City, Fremont County, Wyo.

Numerous unsuccessful attempts to resume operation of existing mines sums up the mining activity in general. A highlight of the period was the dredging of Rock Creek below Atlantic City, which produced $400,000 in gold (Armstrong, 1948, p. 63). Iron mining, begun in the area about 1959 by the U.S. Steel Corp., produced a brief flurry of activity during the development and construction stage, but it had no obvious lasting effects. Since completion of the mine facilities, the "ghost town" residents have resettled into their hundred-year-old groove, no better or worse off for the unsettling experience.

PREVIOUS INVESTIGATIONS

The earliest reports on the area deal mostly with the gold mines and prospects and contain very little information about the geology. Data on the early gold mining may be found in reports by Hayden (1871), Raymond (1870 and 1873), Aughey (1886), Ricketts (1888), Knight (1901), Henderson (1916), Jamison (1911), and Schrader (1915). Knight (1901) made the first geologic map of the area, which showed at least the major geologic framework. He noted the folded and metamorphosed character of the "Algonkian" schists and the close relationship of the gold deposits to bodies of mafic intrusive rocks. Trumbull (1914) refined the previous mapping by showing the location of the main masses of intrusive rocks and of the major quartz lodes and by better defining the north contact of the schists with the granitic rocks. Both Knight and Trumbull considered the granite to be Archean, that is, older than the Algonkian schists. Trumbull emphasized the close relationships of the lode gold deposits to the intrusive diorites and andesites. Spencer (1916) mapped the northern part of the area in greater detail than his predecessors did. He very precisely located the diorites and porphyry intrusives of the gold belt and recognized agglomerates and green schists, which he assumed to be of igneous origin. He discovered the quartzite and iron-formation in the northeastern part of the area and determined that the granitic rocks to the north and west are intrusive into the schist series. Spencer was the first to suggest that the diorite-gold belt was dislocated by faulting, a deformation which has since been verified. He spent only 3 weeks in the South Pass area, and Knight and Trumbull only a week to 10 days. It seems remarkable, considering the circumstances under which they worked, that they learned as much as they did. Bartlett and Runner (1926) reviewed the state of the gold mines and milling practices and commented briefly on the geology. Runner pointed out that the diorite dikes are metamorphic rocks, possibly derived from carbonate sedimentary rocks, and that the gold-quartz veins were emplaced after the dikes had been sheared and metamorphosed. He suggested that the gold veins might be related to the granite batholith. The next mapping of note was done by De Laguna (1938), who mapped the northern part of the South Pass area with considerable skill. He found several important faults, and although his map is not as detailed as later ones, all major geologic units are shown in approximately their proper configurations. In 1946 and 1947 a small area near South Pass City and the Carrisa mine was mapped by Armstrong (1948). The most significant contributions of this investigation were a detailed surface and underground map of the Carrisa property and the observation of graded bedding in the graywacke, a finding which enabled Armstrong to map many new folds. R. H. King mapped and sampled the iron deposits in the Miners Delight quadrangle in 1949, under the auspices of the Chicago and Northwestern Railway Co., and the Natural Resources Research Institute, University of Wyoming. (See King, 1949.)

RECENT INVESTIGATIONS

The investigations leading to this report were begun in 1958 by R. W. Bayley. In that year, Bayley made a geologic and magnetic survey of the iron deposits in the Miners Delight quadrangle (Bayley, 1963), and in the field seasons 1959 to 1962 he mapped the four quadrangles that cover most of the area (Bayley, 1965a–d). He reported that anomalous values of arsenic in soils may be a clue to the location of gold deposits (Bayley and Janes, 1961), and he commented on other mineral deposits of the area (Bayley, 1968). A quadrangle adjacent to the four mapped by Bayley (the Anderson Ridge quadrangle) was mapped by Worl (1963), who mapped only the northwestern part in detail, and by Proctor and El-Etr, who mapped the whole in detail in 1962 and 1963. A contiguous area northwest of the Anderson Ridge quadrangle was mapped by Hodge (1963). A special study of the pegmatites of the Anderson Ridge quadrangle was made by El-Etr (1963) and by Proctor and El-Etr (1968). Condie (1967a) made a geochemical study of the graywackes of the area. Geochronological investigations in the area have been carried out by Giletti and Gast (1961); Cannon, Bayley, Stern, and Pierce (1965); by Naylor, Stiger, and Wasserburg (1967); and by Condie, Leech, and Baadsgaard (1969). The publications noted above cover only certain aspects of the geology of the region. The present report gives a summary of the previous published results, presents the remaining unpublished results, and provides a compilation of the geologic mapping.

ACKNOWLEDGMENTS

We are grateful to the friendly residents of the South Pass area, who made our sojourn a pleasurable experience. Special mention is due the U.S. Steel Corp., which freely gave information on the geology of its Atlantic City iron project. Part of the research of K. C. Condie was supported by Washington University NASA Multidisciplinary Research Grant NaG–581. The work of P. D. Proctor was supported in part by the V. H. McNutt Memorial Fund of the Geology Department of the University of Missouri at Rolla.

GEOLOGIC SETTING

The geologic setting of the South Pass area is shown in figure 5. The area is near the south end of the Wind River Range, which was uplifted during the Laramide orogeny. The range is a narrow block mountain over 100 miles long, uplifted and tilted eastward on a west-flank reverse fault that has a maximum displacement of about 35,000 feet. For nearly its full length the crest of the range has been stripped of its cover of Paleozoic and Mesozoic strata to reveal the Precambrian core, which is mainly granitic; it has also been much dissected by Tertiary and later erosion. The erosional edge of the Paleozoic strata lies along the east flank of the range, and these strata dip gently eastward into the Wind River Basin. The northern half of the South Pass area is a maturely dissected Precambrian erosion surface, the southern half a partly denuded and slightly dissected Tertiary pediment surface. Except for a few granite monadnocks, the pediment surface is nearly a perfect plane beginning at about lat 42°30′ at an altitude of about 8,500 feet and descending south and southwest at approximately 100 feet per mile into the Green River Basin. It is connected to an accordant east-dipping erosion surface which descends into the Wind River Basin by canyons through the upturned edge of Paleozoic rocks.

The Precambrian sedimentary and volcanic rocks underlying the South Pass area are a small remnant of a once widespread system of layered rocks, probably more than 3 b.y. old, now limited to widely separated clots and pendants in what is virtually a sea of younger, intrusive granitic rocks, 2.7–3.3 b.y. old. Elsewhere in Wyoming, pendants of similar rocks occur in the northwestern part of the Granite Mountains, the Seminoe Mountains, and the Owl Creek Mountains southeast of Thermopolis. Still others occur at several places in Montana. In the South Pass area, the old stratified system is cut by a variety of dikes and sills and small stocks, all probably related to local volcanism; and all the strata plus the intrusive rocks, with the exception of the Louis Lake batholith and later diabase dikes, are tightly folded and metamorphosed to amphibolite grade. Gold mineralization accompanied the folding. The Louis Lake batholith intrusion of the folded rocks caused broad-scale refolding and contact metamorphism. Faulting occurred before and after the emplacement of the batholith and after the emplacement of the late diabase dikes. Spotty, retrograde metamorphism has affected all the rocks of the area.

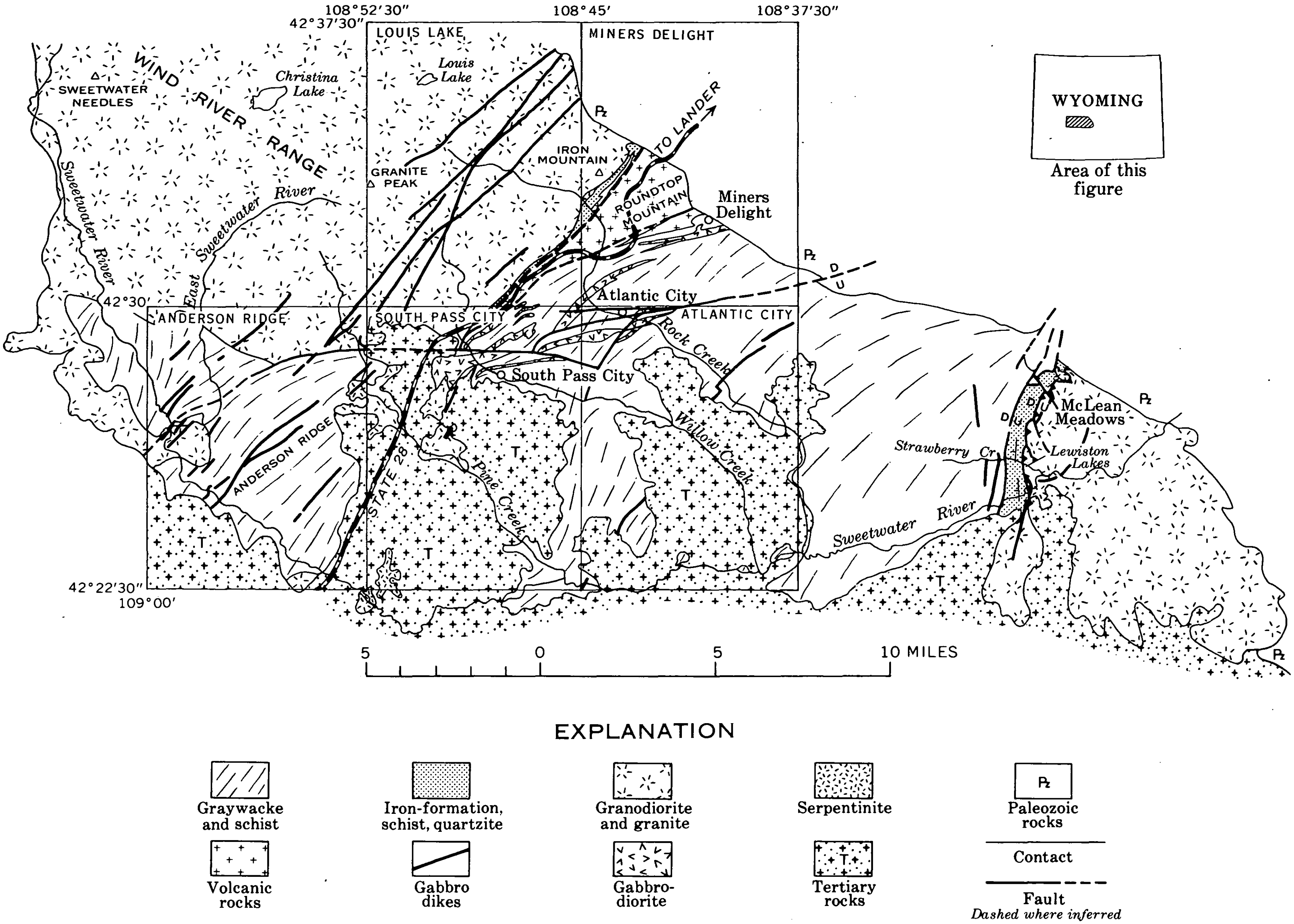


FIGURE 5.—Generalized geologic map of the southern part of the Wind River Range. Reconnaissance mapping on the east granite contact by Bayley.

STRATIGRAPHY

The stratified rocks of the area include two distinct suites of different origins: the basal suite—composed of orthoquartzite, schist, and oxide iron-formation—indicates sedimentation in a stable marine shelf environment of considerable duration, and the overlying suite—composed mainly of submarine volcanic rocks and graywacke turbidites—indicates deep-water deposition in a tectonically unstable basin, or eugeosyncline, also probably of long duration. The basal suite rests against intrusive granitic rocks and migmatite. The country-rock part of the migmatite consists mostly of amphibole schist, amphibolite (metagabbro), and serpentinites—possibly remnants of a mafic volcanic basement upon which the shelf suite was deposited. The stratified rocks have been divided into three formations, two of which contain a number of unnamed members. The stratigraphic succession is given in table 1.

TABLE 1.—*Lower Precambrian sedimentary and volcanic rocks*

Suite	Units
Eugeosynclinal suite	Miners Delight Formation: Metagraywacke, schist, conglomerate, metatuff, and meta-andesite. About 5,000 feet
	FAULT CONTACT
	Roundtop Mountain Greenstone: Metabasalt, green schist, and amphibolite. About 5,000 feet
	GRADATIONAL OR DISCONFORMABLE CONTACT
Shelf suite	Goldman Meadows Formation: Quartzite, iron-formation, and schist. 700–800 feet
	UNCONFORMITY
	Metabasalt, metagabbro, serpentinite(?).

GOLDMAN MEADOWS FORMATION

The Goldman Meadows Formation was named for exposures along the northwest side of Goldman Meadows in sec. 26, T. 30 N., R. 100 W. (Bayley, 1965a). It occurs only in a narrow belt, about 5 miles long, along the southeast margin of the Louis Lake batholith in the above-mentioned township (see Bayley, 1963, 1965a, b). The most complete exposures are in secs. 13, 24, and 26 (pl. 1). The formation is primarily a schist unit containing three distinct nonschist members—a quartzite member and two iron-formation members. The stratigraphic succession of members (unnamed) of the Goldman Meadows Formation, from youngest (top) to oldest, is as follows:

Mica-andalusite schist
Biotite (chlorite)-garnet schist
Chlorite-garnet schist
Iron-formation
Chlorite-amphibole-magnetite-garnet schist
Quartz-mica-andalusite schist
Quartz-mica schist
Iron-formation
Chlorite-amphibolite-garnet schist
Quartz-mica-andalusite schist
Quartzite
Mica-andalusite schist
Feldspathic quartz-biotite schist

At the extreme northeast end of the belt, some metabasalt intervenes between the quartzite and the upper iron-formation member, but nowhere else.

Metasedimentary schist that has become isolated from the lower part of the formation forms concordant inclusions in schistose and gneissic granite that also contains sill-like inclusions of metagabbro. The lower limit of the formation has been arbitrarily set where granite is the dominant rock. The schist inclusions are tabular, 10–50 feet long and 1–10 feet thick. Their attitudes conform to the attitude of the main part of the formation. Most are composed of light-colored feldspathic quartz-biotite schist, which is well foliated and has medium-sized eyes of quartz and plagioclase and relict fragments of sedimentary rocks set in a fine-grained matrix of quartz, plagioclase (An_{30}, approximately), biotite, and microcline. The plagioclase in eyes is commonly sericitized and partly replaced by microcline. A less common variety of schist inclusion is composed of biotite, quartz, and untwinned plagioclase. The schist above the granite, near the base and top of the quartzite member, differs from the schist interlayered with granite in that it is apparently nonfeldspathic. Commonly it contains biotite and muscovite, quartz, and andalusite, partly replaced by sericite. In most of this schist, the biotite has been replaced by chlorite. The upward transition from quartzite to schist appears gradational.

The quartzite is a distinct mappable unit. Outcrops are found chiefly in the central and southwestern parts of the outcrop belt, but a single small exposure was found in the extreme northeastern part of the belt. In the extreme northwestern exposures of the formation, massive granitic rocks are in contact with the upper iron-formation member, and the lower schist units and the quartzite unit have been cut out. To the southwest from sec. 35, T. 30 N., R. 100 W., the granitic rocks cut progressively higher in the formation until the quartzite is virtually gone, except for a few resistant inclusions in granitic gneiss. The quartzite is 20 to 40 feet thick. Individual beds are less than an inch to as much as several feet thick. Most commonly, the rock is light colored, white to gray, but in some outcrops it appears pale bluish green because chrome muscovite (fuchsite) colors the bedding surfaces and forms thin schist layers. The quartzite is fine to medium grained, totally recrystallized and vitreous, and shows no primary sedimentary features other than bedding. In thin sections it shows a simple quartz mosaic with numerous minute flakes of colorless mica and a trace of bluish-gray tourmaline.

About 20–80 feet above the quartzite, the quartz-mica-andalusite schist grades into chlorite-amphibole-magnetite-garnet schist containing a few thin metachert layers, and this unit, in turn, grades upward into the lower banded metachert-magnetite iron-formation member, which is similar to the main iron-formation member above it. This lower iron-formation is 20–60 feet thick. Exposures are limited to the west limb of the formation in a 2-mile segment between secs. 35 and 24. It apparently pinches out to the southwest and is apparently cut out by granitic rocks to the northeast. No evidence of this lower iron-formation was found along the southeast limb of the formation in secs. 24 and 25.

Quartz-mica schist, 20–100 feet thick, some of which contains sericitized andalusite, overlies the lower iron-formation member. This schist grades upward into and is interlayered with chlorite-amphibole-magnetite-garnet schist that forms the basal part of the upper (main) iron-formation member. Much of the biotitic schist is entirely chloritized. Some schist is dark gray and carbonaceous. Andalusite occurs in the quartz-mica schist in peanutlike forms, up to 1 cm long and 2–3 mm wide, elongated in the foliation parallel to the plunging axes of minor folds. Nearby all crystals are sericitized, and the sericite pseudomorphs contain concentration of carbonaceous dust.

Near the base of the upper iron-formation member, thin beds of magnetite and metachert are interlayered with quartz-chlorite schist, chlorite-garnet schist, and chlorite-amphibole-garnet-magnetite schist. These selvage rocks are well foliated and show a strong alinement of metamorphic quartz, chlorite, and amphibole, whereas the garnets transect the foliation. The large quartz grains form augen. The amphibole in the schist ranges from common blue-green hornblende to nearly colorless grunerite.

The upper and lower iron-formation members are chiefly dense, hard, laminated rock, composed principally of quartz, magnetite, and amphibole. The layers are commonly plicated and range in thickness from less than 1 mm to more than 6 cm, but layers 1 mm to 1 cm thick are most common. Magnetite-rich layers alternate with quartz-rich layers, or rarely, jasper layers. The rock is generally gray or black and is fine grained; the microtexture is hornfelsic. The quartz-rich layers, which presumably were originally chert, are fine-grained mosaics of quartz with intergranular euhedral magnetite and amphibole; the magnetite-rich layers contain chiefly euhedral magnetite and crystalline magnetite aggregates, and a few quartz grains and amphibole euhedra as well. The average size of quartz crystals is 0.2 mm; of magnetite, 0.12 mm. The amphibole, generally colorless, is bluish green or bluish gray in some specimens. The colorless variety is grunerite; the colored varieties are apparently hornblende. Magnetite and quartz, about equally abundant, make up about 90 percent of the rock. The average Fe content is about 33.5 percent (Bayley, 1968). A complete analysis of the iron-formation is shown in table 2, with an average ($n=12$) analysis of the

TABLE 2.—*Chemical analysis of iron-formation in the Goldman Meadows Formation and analysis of iron-formation from the Biwabik Iron-formation for comparison*

[n.d., not determined; est, estimated]

	A	B
SiO_2	56.23	47.32
Al_2O_3	.45	.24
Fe_2O_3	34.96	26.72
FeO	5.67	14.87
MgO	1.13	2.16
CaO	.81	1.26
Na_2O	.15	n.d.
K_2O	.12	n.d.
H_2O+	.52	1.39
TiO_2	.02	n.d.
P_2O_5	.05	.067
MnO	.07	.4 est
CO_2	.06	4.18
Cl	----	n.d.
F	----	n.d.
S	----	n.d.
C	n.d.	.05
Total	100.24	98.66

A. Analysis (weight percent) of iron-formation from sec. 23, T. 30 N., R. 100 W., Fremont County, Wyo., by Dorothy F. Powers, U.S. Geological Survey (Bayley, 1963).

B. Weighted average of 12 analyses (weight percent) of banded magnetite iron-formation, from Biwabik Iron-formation, Mesabi district, Minn., from Gruner (1946, tables 5, 7, and 8).

Biwabik Iron-formation in Minnesota for comparison. Oxidation of the surface of the Goldman Meadows iron-formation probably accounts for the high Fe_2O_3 value.

The rocks represented by these analyses are approximately equivalent iron-formation facies (magnetite-banded iron-formation of James, 1954, p. 261), but the magnetite-banded Biwabik probably contains more iron silicates than the Wyoming rocks, and probably primary carbonate, which the Wyoming rocks lack.

Close above the upper iron-formation the rocks are biotite or chlorite schist that is similar to the schist below the iron-formation. Some schist beds are garnetiferous and interbedded with thin magnetite-rich layers and layers of metachert, which decrease in number away from the iron-formation. These transitional rocks are as much as 60 feet thick in the vicinity of Iron Mountain, but are absent in the northeastern part of the formation. Mica-andalusite schist, 40–60 feet thick, overlies garnetiferous chlorite schist and forms the top of the Goldman Meadows Formation. This topmost schist is absent in both the northeastern and southwestern parts of the belt, and in its place are volcanic rocks of the overlying Roundtop Mountain Greenstone.

Contact relations.—The base of the Goldman Meadows Formation is everywhere in contact with intrusive granitic rocks, some massive and some migmatitic. The country rock of the migmatite is in most places amphibolite, but in some places, it is greenstone or metagabbro. These mafic rocks could represent remnants of the basement upon which the Goldman Meadows Formation was deposited, or they could be pregranite intrusives. The upper contact of the formation is irregular. Schist units above the upper iron-formation member are discontinuous along strike, and the volcanic rocks of the Roundtop Mountain Greenstone are in contact with the upper iron-formation member at most places. The contact between the formations is either disconformable or gradational.

ROUNDTOP MOUNTAIN GREENSTONE

The Roundtop Mountain Greenstone was named for Roundtop Mountain, secs. 30 and 31, T. 30 N., R. 99 W. (Bayley, 1965a). The most instructive exposures are in the synclinal trough at Iron Mountain and on Roundtop Mountain. Southwestward from these localities the unit is so sheared and altered that the original character cannot be determined. The formation is composed principally of greenstone, ellipsoidal (pillow) metabasalt, and a small amount of massive vesicular metabasalt, and green schist, sheared greenstone and a little metatuff. These greenstones and green schists are of two metamorphic facies, amphibolite and greenschist. The greenschist facies rocks are limited mainly to the Roundtop Mountain area, the amphibolites to the synclinal trough at Iron Mountain and to the southwestern part of the outcrop belt, near the gneissic contact of the Louis Lake batholith. The greenschist facies rocks are composed of actinolite, chlorite, epidote, and minor apatite. The original plagioclase is entirely saussuritized. The amphibolite facies rocks are composed of blue-green hornblende, untwinned plagioclase (probably oligoclase), epidote group minerals, some chlorite, and locally, a little diopsidic pyroxene. Structurally competent, massive beds are most commonly hornfelsic or igneous textured amphibolites, whereas strongly sheared beds are hornblende schist. Primary ellipsoidal structures preserved in the rocks of both metamorphic facies, are much elongated along foliation planes, but despite the elongation, tops of flows can be accurately determined in a few places.

The lower contact of the Roundtop Mountain Greenstone is either gradational or disconformable. The upper contact is not exposed anywhere in the area. On the southeast the formation is in fault contact with the overlying Miners Delight Formation, which we assume is younger. These two formations face each other across a major fault; that is, tops of beds in each face toward the fault separation. This structural configuration does not give any clues to the relative ages of these formations. The Miners Delight Formation is assumed to be younger because of its central position in the South Pass pendant, which is believed to be synclinorial, and because it is totally different from all rocks known to be older than the Roundtop Mountain Greenstone.

MINERS DELIGHT FORMATION

The Miners Delight Formation was named for the old mining camp of Miners Delight in sec. 32, T. 30 N., R. 99 W., where exposures are exceptionally good (Bayley, 1965a). The formation underlies about 85 percent of the South Pass area and is estimated to be more than 5,000 feet thick. It is composed mainly of metagraywacke and schist isoclinally folded first on east to northeast axes and then on south to southeast axes. In what is assumed to be the lower part of the formation, at Peabody Ridge, and in the belt between Miners Delight and South Pass City, the formation contains a variety of rocks not found anywhere else in the area. These include ellipsoidal and vesicular meta-andesite flows and trachytic meta-andesite porphyry flows, or possibly sills, tuffaceous metagraywacke and volcanic conglomerate, and graphitic schist. This particular part of the formation is also host to numerous thin sill-like dikes of metadiorite and metagabbro and to dikes and small stocks of leucodacite porphyry.

The metagraywackes are most abundant, and all are graded turbidites. By the grain-size gradation, tops of beds may be determined on almost any outcrop (fig. 6).

In areas remote from the Louis Lake batholith.

FIGURE 6.—Graded metagraywacke from the Miners Delight Formation. Top direction toward southeast corner of picture.

mainly the southeastern part of the area, primary clastic textures in the metagraywackes are well preserved, and metamorphic foliation is absent or only poorly developed. Slaty, argillaceous beds that interweave between the graywacke beds, however, are strongly foliated.

METAGRAYWACKES

The metagraywackes beds are gray to dark brown. Individual beds range in thickness from a few millimeters to more than 2 m; the average thickness is about 10 cm. The beds are generally fine to medium grained and massive, and they have sharp bottoms and fairly sharp tops (fig. 6).

Slaty argillaceous tops are uncommon, and sole markings are rare. Although graded, the metagraywackes are poorly sorted. They contain angular to subangular grains of quartz and plagioclase (mostly oligoclase) and rock fragments in a recrystallized matrix of biotite, untwinned plagioclase, and quartz, and commonly some garnet, chlorite or chloritoid, and sericite. The rock fragments rarely compose more than 10 percent of the rock, and most fragments are sedimentary types—such as chert, quartzite, or phyllite. Fragments of igneous rocks are rare except in the metatuffs and conglomerates of the Peabody Ridge area, described below.

GRAYWACKE SCHIST

The graywacke schist interbeds are mineralogically like the metagraywacke but are more micaceous; many also differ by being carbonaceous. The schist beds are as much as 100 feet thick and continue on strike for several miles. Abundant black almond-shaped porphyroblasts elongated in the foliation (fig. 7) are a characteristic feature, particularly in the carbonaceous schists. In all respects the porphyroblasts, or "peanuts" as they are called locally, resemble the andalusite in the Goldman Meadows Formation; however, almost all are totally sericitized and contain poikiloblastic inclusions of quartz and biotite. The porphyroblasts may have originally been either of two minerals. Close to the granitic rocks on both the north and south sides of the South Pass pendant they were doubtless andalusite; however, according to Condie, the X-ray pattern of some "peanuts" from near the Rose mine, north of Atlantic City, indicates cordierite. Apparently the rocks contained cordierite and andalusite of the same growth habit. Because of the sericitic alteration, the original distribution of these two minerals is indeterminable.

FIGURE 7.—Altered andalusite schist from the Miners Delight Formation.

Southwest of South Pass City and in the western and northwestern parts of Anderson Ridge quadrangle, the metagraywackes and metagraywacke schists lie close to the Louis Lake batholith and its pegmatite swarm; hence, they are coarser grained and somewhat more schistose. Very close to the granite they are strongly schistose to gneissic. Despite the higher metamorphic grade of these rocks, the structure is easily defined by the primary bedding, and tops of beds can be determined in the graded metagraywackes to within 1,000 feet of the intrusive granite.

Beyond the metamorphic aureoles of the granite, which are as much as a quarter of a mile wide, the predominant mineralogy of the metagraywackes and metagraywacke schists is quartz-biotite-plagioclase-

(garnet), with minor magnetite, amphibole, and apatite. The common plagioclase is calcic oligoclase, An_{28} to An_{30}, and the garnet is almandite (Worl, 1963). As in the eastern area, the so-called "peanut" schists are abundant, but they form stratigraphic zones 100–1,000 feet thick and are therefore thicker than the eastern schists. These schists also differ from those to the east in that the pesudomorphs of andalusite or cordierite are poikilitic paragonite instead of sericite.

Within the contact aureoles of the granite, the metagraywackes and schists have been affected in several ways: (1) the grain size increases to about 0.5 mm, (2) the plagioclase is well twinned, (3) the amount of biotite decreases, and (4) pale-green hornblende or actinolite and porphyroblastic microcline, paragonite, and muscovite are commonly present. The mica porphyroblasts are overprinted on the original rock fabric. Microcline replaces the metamorphic plagioclase. Graywacke in contact with a large pegmatite in the NW¼ sec. 30, T. 29 N., R. 100 W., is totally converted to a hornfels composed of twinned microcline, minor biotite, and sphene. Contact metagraywacke gneisses along the northwesternmost granite-graywacke contact zone are composed chiefly of quartz, biotite, garnet, and sillimanite. The "peanut" porphyroblasts in the aureoles most commonly form coarse sheaves of paragonite and muscovite and give no clue as to their original mineral composition. Twinned coarsest grained plagioclase in the aureoles shows positive evidence of zoning. The composition is mostly sodic andesine. Pendants of metagraywackes and schist within the granite show the same mineralogy as the contact aureole rocks (Worl, 1963).

Partial chemical analyses and modal analyses of 23 metagraywackes specimens are presented in table 3 (Condie, 1967a).

To facilitate identification of potassium feldspar, the thin sections were etched for 20 seconds in HF and then stained with sodium cobaltic-nitrite solution. Even after staining, however, some fine-grained feldspar could not be distinguished from quartz, and it was necessary to include a corresponding category in the modes (table 3). Rock fragments are not counted as such in the modes because all gradations exist between rock and mineral fragments. Fragments that are obviously lithic compose from 1 to 5 percent of the metagraywackes.

Although only approximately 4–20 percent quartz could be confidently identified in thin sections, X-ray diffraction studies and the relatively high SiO_2

TABLE 3.—*Chemical and modal analyses of graywackes of*

[Oxides, in weight percent; trace elements, ppm; modes, in volume percent. $\bar{x}$, mean values;

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G11	G12	G13	G14
SiO_2	66.90	66.68	64.31	61.14	68.04	65.30	61.35	71.70	67.91	67.03	60.79	66.86	62.77
TiO_2	.635	.576	.583	.645	.585	.599	.687	.501	.559	.602	.731	.579	.558
Al_2O_3	14.41	15.53	14.96	16.38	15.40	15.07	15.30	14.96	15.30	15.26	16.18	14.94	15.92
Total Fe as Fe_2O_3	6.25	4.87	6.29	8.13	4.96	5.74	8.22	3.43	4.90	5.58	7.51	6.11	6.20
MgO	2.95	2.28	4.28	3.93	2.26	2.62	3.94	1.94	1.93	2.28	3.37	2.67	2.84
CaO	.85	1.54	1.96	2.23	2.48	3.19	2.10	2.65	2.39	2.05	2.23	2.57	1.25
K_2O	2.81	2.03	1.13	2.86	2.06	2.51	3.37	1.79	2.11	2.41	2.83	2.10	2.54
Na_2O	3.99	4.81	4.31	3.23	3.60	3.79	3.63	3.56	3.77	4.11	4.69	3.67	4.93
Mn	430	408	870	580	340	510	790	333	390	460	560	450	460
Ni	86	76	93	111	59	68	115	54	68	62	90	77	103
Rb	97	50	32	126	73	79	123	62	77	77	110	79	114
Sr	159	268	341	492	496	528	421	411	330	304	608	558	236
Zr	144	159	201	221	197	216	193	163	171	163	254	208	186
Rb:Sr	.61	.19	.09	.26	.15	.15	.29	.15	.23	.25	.18	.14	.48
K:Rb	241	337	293	188	234	264	227	240	228	260	214	221	185
Na:K	1.3	2.1	3.4	1.0	1.6	1.3	1.0	1.8	1.6	1.5	1.5	1.6	1.7
Ca:Sr	47	41	41	32	36	43	36	46	52	55	26	33	38
$\frac{Al_2O_3}{Na_2O}$	3.6	3.2	3.5	5.1	4.3	4.0	4.2	4.2	4.1	3.7	3.4	4.1	3.2
Quartz	20.5	20.6	33.2	4.1	29.6	15.5	------	11.6	10	13.5	7.9	22.8	21.5
Plagioclase	11.1	14.6	5.3	1.0	12.5	14.2	------	8.1	------	9.4	4.0	9.0	tr
An	(28–29)	(25–31)	------	------	------	(30–33)	(30–33)	(24–28)	(32–35)	(30–33)	(26–33)	(32–34)	------
Fine-grained quartz or feldspar	16.9	20.6	36.9	44.0	34.7	31.3	44.6	40.2	42	28.3	41.8	34.0	24.1
Potassium feldspar	------	.7	.3	------	------	------	1.5	------	------	------	.3	------	------
Biotite[1]	45.4	41.2	2.9	50.9	20.8	38.7	53.2	39.2	48.0	45.4	45.5	34.2	53.1
Muscovite	5.3	.2	2.4	tr	.7	------	------	tr	------	.5	tr	tr	tr
Chlorite	.5	.4	17.6	tr	1.7	------	------	------	------	------	.5	------	tr
Magnetite (and ilmenite)	.2	1.8	tr	tr	tr	tr	tr	.3	tr	2.4	tr	tr	.7
Hematite and limonite	.5	------	.3	------	tr	.3	.7	.3	------	.5	tr	------	.3
Accessory minerals[2]	tr	------	1.1	------	------	tr	------	.3	tr	------	------	tr	tr

[1] Includes chloritized biotite.
[2] Chiefly zircon, apatite, and epidote.

contents of the metagraywackes indicate that quartz is much more abundant than feldspar. The low quartz modes result from the difficulty in distinguishing quartz from plagioclase.

COMPOSITIONAL VARIATION OF THE METAGRAYWACKES

Each metagraywacke sample (table 3) represents an individual bed. The analyses thus clearly show significant compositional variations between beds. Intrabed variation is much less than interbed variation. Similar findings were reported for other graywackes by Weber and Middleton (1961). The smallest bed-to-bed variation involves changes in the amount of the two most abundant oxides, SiO_2 and Al_2O_3 ($C = 5$). All other elements, regardless of their concentrations, have relative deviations >10 percent. Rubidium is particularly variable ($C = 38$). Of the element ratios, the Rb:Sr ($C = 57$) and Na:K ($C = 43$) ratios vary most.

METATUFF, CONGLOMERATE, AND META-ANDESITE OF PEABODY RIDGE

In the vicinity of Peabody Ridge in the Miners Delight quadrangle and in the area on strike to the west, the Miners Delight Formation contains a variety of rocks not found elsewhere in the South Pass area. The meta-andesites are lava flows that interfinger with the conglomerates and metatuffs. The flows are mostly massive, but some are ellipsoidal, some are trachytic porphyries, and some are vesicular. The massive meta-andesite is a porphyry or glomeroporphyry with altered plagioclase and green amphibole phenocrysts in a fine-grained matrix of plagioclase, blue-green amphibole, biotite, and quartz. The plagioclase shows both albite and carlsbad twinning; it is heavily charged with mineral dust, mostly biotite, amphibole, and possibly clinozoisite, and the extinction angles and indices suggest it is probably oligoclase. Both biotite and the blue-green amphibole are products of metamorphism that occurred after the lavas were deformed. Both replace the original plagioclase and hornblende and the fine-grained groundmass. Because the lavas were previously foliated, both minerals show mimetic growth in the folia; however, the crystals are randomly oriented, and crystals of both cross the original foliation and have not been disturbed.

The trachytic meta-andesite porphyries are dark-brown to black rocks with white plagioclase phenocrysts 0.5–3 cm long oriented parallel to the strike

the Miners Delight Formation (after Condie, 1967a)

S, standard deviations from mean; *C*, relative deviations, in percent; n.d., no determination; tr, trace]

G15	G17	G18	G19	G20	G21	G22	G23	G24	G25	$\bar{x}$	*S*	*C*
58.38	65.42	60.94	64.15	60.65	68.26	65.20	63.74	59.97	64.33	64.43	3.30	5
.677	.636	.692	.632	.703	.576	.618	.652	.651	.585	.620	.06	10
14.92	14.78	16.30	15.28	15.30	14.74	15.97	15.49	17.50	16.09	15.48	.71	5
10.66	7.18	6.96	7.40	8.61	4.95	5.84	6.60	7.60	6.37	6.54	1.39	21
4.78	3.86	3.46	3.41	4.09	1.86	2.50	3.29	3.94	3.24	3.12	.82	26
1.96	2.76	1.80	2.15	1.82	2.10	2.46	3.21	2.18	3.07	2.22	.57	26
1.37	1.80	3.96	2.46	2.98	2.20	2.35	2.80	2.74	2.82	2.44	.63	26
3.75	3.30	3.27	3.44	3.91	4.19	3.25	3.13	2.91	2.79	3.74	.57	15
871	560	570	540	580	400	446	520	570	530	529	146	28
148	88	107	83	135	64	80	100	124	92	91	25	27
36	65	n.d.	107	106	73	n.d.	107	145	114	88	33	38
375	529	418	348	467	324	500	530	458	650	424	123	29
183	193	205	192	213	171	208	250	207	219	196	27	14
.10	.12	------	.31	.23	.23	------	.20	.32	.18	.23	.13	57
316	230	------	191	233	250	------	217	157	205	230	43	19
2.4	1.6	.7	1.2	1.2	1.7	1.2	1.0	1.0	.9	1.4	.6	43
37	37	31	44	28	46	35	43	34	34	37	8	22
4.0	4.6	5.0	4.4	3.9	3.5	4.9	4.9	6.0	5.8	4.2	.8	19
13.9	9.2	8.7	1.7	2.5	15.3	3.5	12.2	11.5	10.3	------	------	------
1.9	.5	------	1.7	------	2.5	1.0	8.2	1.5	------	------	------	------
------	(30–33)	------	(32–35)	------	------	(32–35)	------	(32–35)	------	------	------	------
58.3	53.1	31.5	34.7	39.1	31.9	39.3	24.3	45.5	30.5	------	------	------
tr	tr	------	------	------	1.1	------	------	------	------	------	------	------
23.1	35.6	57.6	60.7	56.9	47.5	42.1	53.8	38.2	59.0	------	------	------
1.9	tr	1.9	tr	tr	------	1.5	------	3.1	tr	------	------	------
------	------	tr	tr	tr	------	12.5	------	tr	tr	------	------	------
tr	tr	tr	1.2	tr	1.2	tr	1.1	tr	tr	------	------	------
.9	1.6	.3	tr	1.5	tr	tr	.3	tr	tr	------	------	------
tr	tr	------	------	------	tr	------	tr	------	tr	------	------	------

of the flows (fig. 8). The plagioclase is now oligoclase; it may have originally been more calcic. Green hornblende phenocrysts occur sparingly in some flows and abundantly in a few. The flow matrix is dense and microlitic, composed originally of feldspar microlites and a little quartz, which in some flows were oriented into trachytic flow patterns. In the matrices, metamorphism has produced randomly oriented brown biotite and blue-green hornblende and a fine-grained granular residue, probably feldspar and quartz (fig. 9).

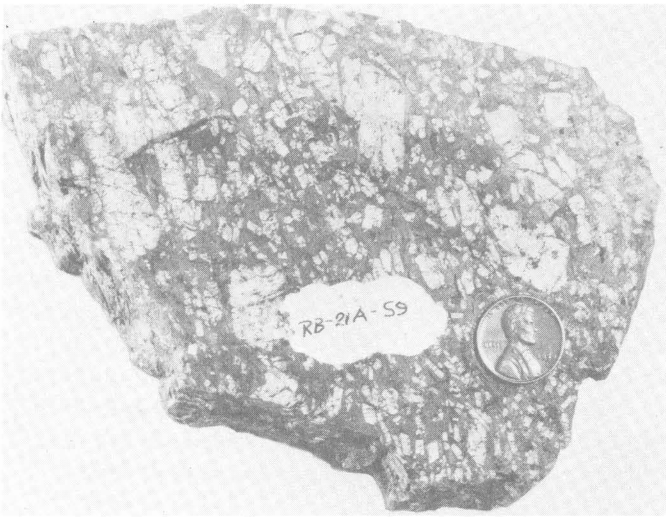
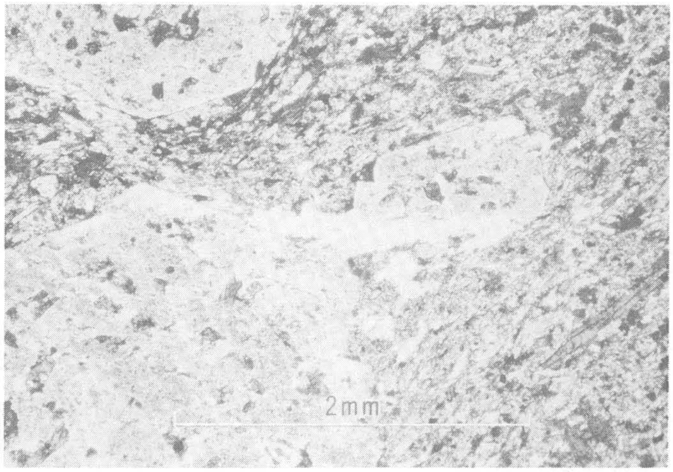


FIGURE 8.—Hand specimen of trachytic meta-andesite porphyry.

Mineralogically these flows closely resemble andesite described from other localities; chemically they show a close kinship to the diorite-andesite class, as shown by the analyses in table 4. There is also a close chemical relationship to the so-called mangerite-doreite clan of Nockolds (1954), which seems a little baffling inasmuch as the original mangerite of Kolderup (Johannsen, 1937) is a microperthite-pyroxene rock containing only 47.34 percent of silica.

The metatuffs and conglomerates associated with the meta-andesite are composed almost entirely of well-foliated, lenticular andesite debris. They grade from very fine grained to very coarse grained rocks, the coarsest, the conglomerates, being composed of cobbles that may be close to 12 inches long. In sec. 31, T. 30 N., R. 99 W., the conglomerates rest directly on the meta-andesite, and most cobbles are identical with the underlying rock, except for a few composed of quartzite and high-grade hornblende schist of unknown origin. The metamorphic grade of the tuffs and conglomerates is identical



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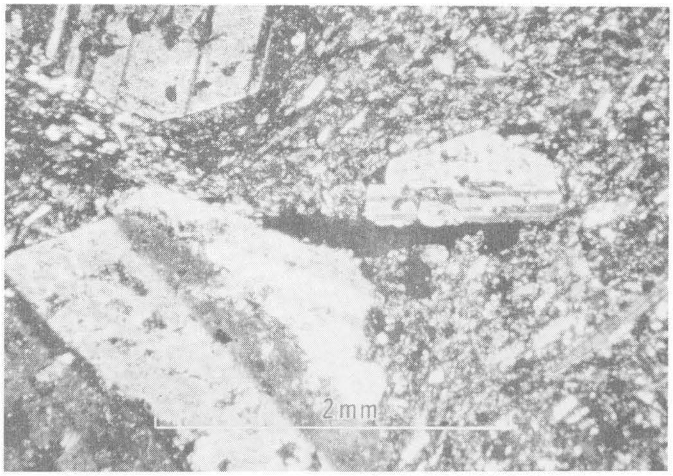


B

FIGURE 9.—Thin section of trachytic meta-andesite porphyry. *A*, Plane light; *B*, crossed nicols. Phenocrysts are oligoclase. Matrix: feldspar, quartz, biotite, and blue-green hornblende.

TABLE 4.—*Partial analyses of meta-andesite porphyry (weight percent) and average compositions of andesite and doreite from other publications for comparison*

	Meta-andesite porphyry		Average andesite (Daly, 1933, p. 16)	Average doreite (Nockolds, 1954, p. 1018)
	Sec. 6, 29–99	Sec. 32, 30–99		
SiO_2	59.55	57.75	59.59	56.0
TiO_2	1.45	.96	.77	1.29
Al_2O_3	17.49	19.05	17.31	16.81
Fe_2O_3	.75	1.83	3.33	3.74
FeO	3.61	3.53	3.13	4.36
MgO	2.30	2.26	2.75	3.39
CaO	4.68	6.18	5.80	6.87
Na_2O	4.07	4.37	3.58	3.56
K_2O	2.83	1.38	2.04	2.60

with that shown by the meta-andesite; biotite and blue-green amphibole are the principal metamorphic minerals.

A second belt of tuff, conglomerate, graphitic schist, and minor lava flows lies 4,000 feet south of Peabody Ridge and is separated from the first by north-facing graywacke and schist. This belt is coincident with the belt of metagabbro sills, which lies north and south of Atlantic City, as shown on plate 1. Most of the gold mines in the area are within this belt. The intense metamorphism and recrystallization of the rocks of this belt make it difficult to separate the volcaniclastic rocks from the igneous. However, there is some recognizable ellipsoidal and vesicular metabasalt near the east end of the belt south of Atlantic City and some trachytic metadacite porphyry in the belt north of Atlantic City, as shown on plate 1. The volcaniclastic rocks are composed chiefly of debris from dacite or andesite porphyry. Like the similar rocks on Peabody Ridge, they were strongly foliated and metamorphosed. Also the metamorphic minerals are the same: biotite and blue-green and green hornblende. The hornblende forms rosettes in some of the rocks and is rather coarse. In the field such rocks look like salt-and-pepper diorites or gabbros. The metabasalt in the belt is diabasic, with green hornblende and thoroughly saussuritized plagioclase. The metadacite porphyry matrix is composed of randomly oriented biotite, granular untwinned plagioclase (probably oligoclase), and minor quartz grains. The plagioclase phenocrysts are sericitized or replaced by larger muscovite plates, and all plagioclase remnants have broken down to granoblastic aggregates of new untwinned plagioclase crystals, probably oligoclase.

Black very fine grained graphitic schists lie on both sides of the north belt and along the north side of the south belt for about half its length (Bayley, 1965a–d). They are composed of clastic grains, plus abundant powdery intergranular graphite, and are severely sheared and cut by abundant quartz veins, some of which carry a little gold.

RELATIONSHIPS TO OTHER FORMATIONS

The Miners Delight Formation is assumed to be the youngest Precambrian sedimentary formation in the area because of its central location with respect to the Goldman Meadows and Roundtop Mountain Formations in the South Pass pendant. Neither upper or lower contacts have been found. The formation is in fault contact on both flanks with the older formations. Moreover, because of the complex folding, it has not been possible to distinguish the upper parts of the formation from the lower.

ENVIRONMENT OF SEDIMENTATION AND PROVENANCE

The occurrence of commonly graded, poorly sorted graywacke beds in the Miners Delight Formation suggests that much of the detritus in the formation was deposited by turbidity currents in a tectonically unstable basin or trough. Large intrabed compositional variations reported by Condie (1967a) are most easily explained by one or more of the following mechanisms:

1. Slumping and turbidity current generation at different sites on a submarine slope. The difference in turbidity current composition would result from original differences in the sediments deposited on the slope. Such original differences may result from the segregation of minerals as a function of transport distance from the shoreline due to differing grain sizes and settling velocities.
2. Turbidity current generation on opposite sides of a partly enclosed basin (bay or lagoon). The composition of the sediment arriving at the basin's edge would vary from one point to another along the shoreline, depending on the composition of the rocks in the immediate source area.

The volcanic rocks and associated volcaniclastic rocks suggest that volcanic islands emerged within the basin from time to time and were subjected to subaerial or shallow submarine erosion.

The graywackes are characterized by a relative abundance of quartzite, chert, and metagraywacke rock fragments and, unlike many graywackes, a sparsity of igneous rock fragments, except those generated within the sedimentary basin. Although, because of the difficulties in evaluating preferential losses during weathering and erosion, it is not possible to reconstruct quantitatively the lithologic composition of the graywacke source areas, it is probable that quartzite, chert, and graywacke were important source rocks. On the other hand, major- and trace-element compositional data suggest that in bulk composition the rocks of the source area were similar to quartz diorite or granodiorite. Such a composition would require that the source area contain significant amounts of calcium-rich granitic rock or that large amounts of contemporary volcanic detritus of dacite to rhyodacite composition be mixed with the quartzite, chert, and graywacke source materials. Such volcanic detritus was certainly available locally, but the nearly complete absence of volcanic rock fragments in most of the graywacke indicates that these volcanic sources were of minor importance. A sparsity of granitic rock fragments in the graywacke is a necessary consequence of the overall fine grain size of these rocks, and hence the abundance of granitic rocks in the graywacke source areas cannot be directly evaluated. However, in terms of existing mineralogical and geochemical data, it seems likely that the source area contained significant amounts of calcium-rich granitic rock, in addition to the quartzite, chert, and graywacke already mentioned.

Condie (1967a) has suggested that if diagenetic and low-grade-metamorphic compositional changes have been small, the composition of the graywackes of the Miners Delight Formation may be representative of the composition of the continental crust, which appears not to have changed appreciably during the last 3.0–3.5 b.y.

INTRUSIVE IGNEOUS ROCKS

The intrusive igneous rocks in the area are of various kinds and ages, but all belong to either the basalt-gabbro or the andesite-dacite clans and are thus closely related. Their origin therefore presents no serious problem. The submarine basalts and andesites attest to the underlying basalt magma source. The dacites, tonalites, and granodiorites are possibly differentiates of that source. The fact that the granodiorite batholith is cut by basalt dikes indicates that the basalt magma persisted at depth, for a very long time. Heavy loading and depression of the general area, or a subduction, could have generated the magma. The approximate order of emplacement of the igneous rocks is as follows:

1. Serpentinite (metaperidotite).
2. Metagabbro (diabase), dikes and sills.
3. Metadiorite, dikes or sills.
4. Metaleucodacite and metatonalite, dikes and small stocks.
5. Metagabbro (diabase) dikes.
6. Louis Lake batholith (granodiorite-granite).
7. Gabbro (diabase) dikes.

SERPENTINITE

Asbestos-bearing serpentinite, possibly metaperidotite, forms a sill-like body about 200 feet thick in the lower part of the quartzite unit of the Goldman Meadows Formation, west of Iron Mountain. Smaller bodies, probably dislocated from the main body by faulting or isolated from it by the intrusion of younger metagabbro, crop out both north and south of Iron Mountain (pl. 1).

The bulk of the rock is massive reddish-brown-weathering serpentinite containing disseminated magnetite. Less abundant but important rock types are black and gray magnetic serpentinite, chrysotile asbestos-bearing serpentinite, and serpentine and talc schists.

The black and gray magnetic serpentinites, which possibly represent gravity segregations from a magma, appear to be chiefly confined to a narrow zone close to the quartzite—that is, near the east margin of the serpentinite, and this zone of magnetic rocks is repeated by faulting in at least the four easternmost of the fault slices shown on the map.

The chrysotile asbestos-bearing rock is found extensively throughout the outcrop area of the serpentinite, but natural exposures are rare. It is best known from the dump of an abandoned asbestos mine on the north side of the body and from the dumps of many test pits in the same area. Color and texture are variable—shades of green are most common, but some parts are blue gray or nearly black. It ranges from intensely sheared to massive. Cross-fiber chrysotile forms discontinuous subparallel veinlets through the rock, commonly three or more to the inch. Most veinlets are less than a quarter inch in width, but 1 inch widths are not uncommon. Fine-grained crystalline serpentine makes up the bulk of the rock. The chrysotile-bearing rock seems to be limited to shear zones in the serpentine body, but this conclusion is based on only a few observations.

The serpentine and talc schists are best developed along the southeast margin of the main serpentinite body close to the boundary between the serpentinite and the quartzite, but they also are found throughout the serpentinite in the southernmost exposure. The schists are dark green, soft and soapy, and contain tiny disseminated crystals of magnetite.

The age of the serpentinite in relation to the Goldman Meadows Formation is uncertain. If older, it could represent part of the volcanic basement. The fact that the quartzite of the Goldman Meadows Formation is chromiferous suggests an unconformable relationship, but the pertinent field relationships are not clear. The serpentinite is cut by dikes of the late metagabbro (No. 5 on the list given at the beginning of this section on "Intrusive Igneous Rocks") and must therefore be older than the metagabbro; it must also be older than the Louis Lake batholith, which was emplaced after the metagabbro.

METAGABBRO

Diabasic metagabbro is rather common in the northeastern part of the South Pass pendant and in the frontal gneisses of the Louis Lake batholith. The bulk of it forms concordant sills in the Roundtop Mountain Greenstone, but it cuts all older formations. Two, possibly three, generations are represented. The metagabbro in the gneiss below the Goldman Meadows Formation could be older than that formation and, if so, would belong to a first generation. The second generation (No. 2 in the list given at the beginning of this section on "Intrusive Igneous Rocks") was probably contemporaneous with the Roundtop Mountain volcanism, or at the latest may be younger than the Miners Delight Formation, but it antedates intrusion of the metaleucodacite and metatonalite and any folding; whereas the third generation (No. 5) was intruded into fault zones after most of the early folding had taken place. Southwest of Atlantic City the metagabbro is cut by metatonalite; hence, some is older than the metatonalite, and all of it is older than the Louis Lake batholith.

The original intrusive rocks were apparently common diabasic gabbro composed of augite, calcic plagioclase, and minor accessory minerals. Although the rock was thoroughly reconstituted by metamorphism, its basaltic kinship is still evident. (See table 5.) The present fabrics and modes reflect mild to extreme deformation and metamorphism of the gabbro to greenschist and amphibolite facies.

The greenschist facies metagabbro forms concordant sills and dikes in the Roundtop Mountain Greenstone at Roundtop Mountain and southwestward to at least Rock Creek. Southwestward from Rock Creek the metamorphic grade increases as the edge of the Louis Lake batholith is approached. The greenschist metagabbro is massive to semischistose, dark green to black, and medium to coarse grained.

TABLE 5.—*Chemical analysis (weight percent) of South Pass metagabbro and data on average oceanic tholeiitic basalt for comparison*

	South Pass metagabbro [1] (sec. 1, T. 29 N., R. 100 W.)	Average oceanic tholeiitic basalt (Engel and others, 1965, p. 721)
SiO_2	49.44	49.34
TiO_2	.83	1.49
Al_2O_3	15.00	17.04
Fe_2O_3	1.44	1.99
FeO	9.19	6.82
MgO	7.76	7.19
CaO	10.80	11.72
Na_2O	2.29	2.73
K_2O	.37	.16
H_2O+	1.89	.69
H_2O-	.11	.58
MnO	.18	.17
P_2O_5	.24	.16
CO_2	.25	----
Total	99.79	100.08

[1] Analysis by Dorothy F. Powers, U.S. Geological Survey.

The original texture, probably diabasic, has been much modified. The only abundant metamorphic minerals are pale-green amphibole, probably actinolite, and saussurite, composed mainly of epidote group minerals (fig. 10). Metagabbro in the fault zone on the south side of the Roundtop Mountain Greenstone has the appearance of plicated chlorite schist; however, it contains mainly pilitic actinolite and has only a minor amount of chlorite and only a trace of biotite and calcite.

The metagabbro of all other areas is of amphibolite facies but is not all of the same metamorphic grade. In general, all metagabbro south of the main

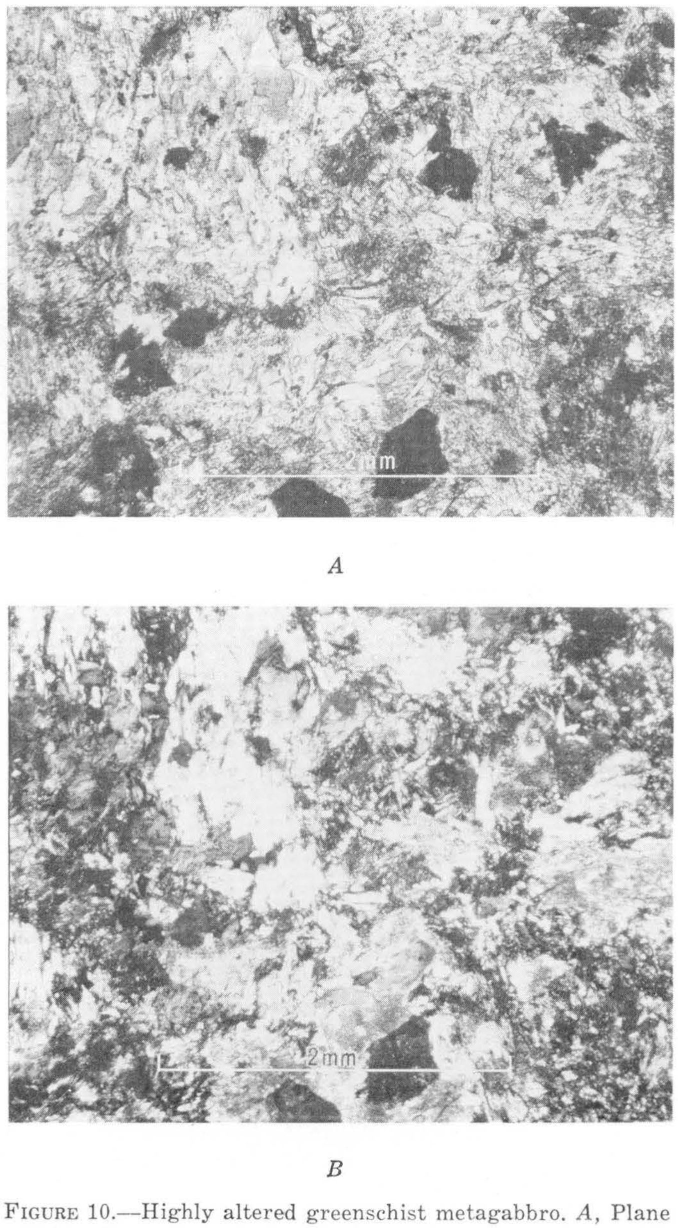
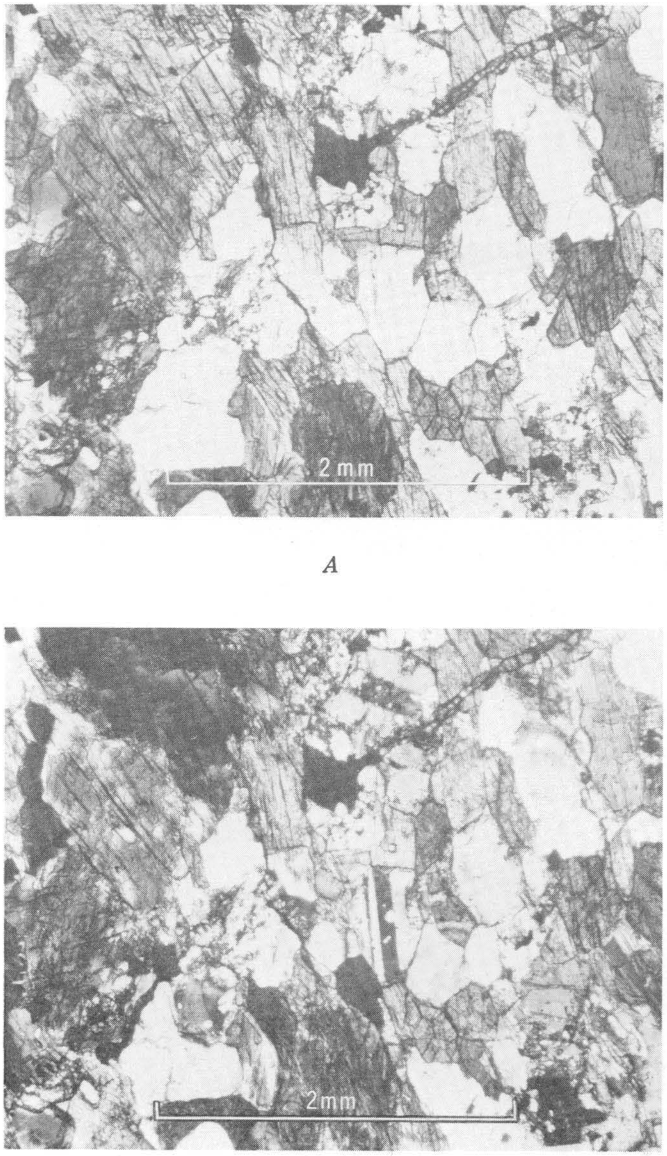


FIGURE 10.—Highly altered greenschist metagabbro. *A*, Plane light; *B*, crossed nicols. Most abundant minerals are actinolite, chlorite, saussurite, calcite, and magnetite.

fault that separates the Roundtop Mountain Greenstone and Miners Delight Formation contains inclusion-loaded granoblastic untwinned oligoclase and fibrous, plumose, or rosetted blue-green amphibole, whereas the metagabbro north of Roundtop Mountain and along the general fracture zone of the Louis Lake batholith contains granoblastic twinned and untwinned oligoclase or sodic andesine and mostly sharply crystalline blue-green and green hornblende (fig. 11). Epidote occurs sparingly throughout, and magnetite and apatite are the common accessory minerals. Minor and local retrograde metamorphic effects are indicated in some of the metagabbro by the occurrence of sericite, chlorite, and clinozoisite. In the gneiss zone of the Louis Lake batholith, at a number of localities, the metagabbro grades into banded gray granitic gneiss. The nature of the transition is uncertain, but the change appears to occur at the inclusion boundaries and involves the coarsening of metamorphic plagioclase and the introduction of quartz and microline, which in effect dilutes the original hornblende component of the metagabbro and reduces it to intergranular remnants, possibly partly altered to biotite.



A

B

FIGURE 11.—Amphibolite facies metagabbro. *A*, Plane light; *B*, crossed nicols. Minerals mainly hornblende and plagioclase (oligoclase or andesine).

METADIORITE

The only true metadiorite intrusive bodies occur in the Peabody Ridge area just south of the main mass of meta-andesite and are probably genetically related to that mass. The metadiorite forms two sill-like bodies that trend northeastward across the ridge crest. The northern sill contains large inclusions of meta-andesite porphyry and graywacke—evidence of its intrusive character. The rock is massive to slightly schistose, with a medium-grained salt-and-pepper appearance that distinguishes it from the commonly dark metagabbros.

Mineralogically, the metadiorite resembles the meta-andesites, the primary minerals being plagioclase and green hornblende, but its texture is more nearly holocrystalline. Also, as in the meta-andesites, the metamorphic minerals are mainly biotite and blue-green hornblende. These igneous rocks may be extrusive and intrusive rocks from the same source, as suggested by the analyses in table 6.

TABLE 6.—*Partial chemical analyses of Peabody Ridge meta-andesite and metadiorite*

[Analyses by Dorothy F. Powers, U.S. Geological Survey]

	Meta-andesite (average of three analyses)	Metadiorite (SW¼ sec. 32, 30–99)
SiO_2	58.16	54.63
TiO_2	1.16	1.09
Al_2O_3	17.44	17.40
Fe_2O_3	1.22	2.70
FeO	4.31	5.72
MgO	3.01	3.71
CaO	5.81	8.54
Na_2O	4.17	3.34
K_2O	1.74	.94
H_2O+	1.49	1.30
H_2O-	.10	.06
P_2O_5	.46	.24
MnO	.11	.13
CO_2	.40	.03
Total	99.58	99.83

METALEUCODACITE AND METATONALITE

Light-colored intrusive metaleucodacite and metatonalite form two dikes and a few small stocks. The dikes are metaleucodacite. One occurs near the south edge of the Roundtop Mountain Greenstone and the other near the east end of the metagabbro belt south of Atlantic City (pl. 1). The stocks, metatonalite, have intruded the same metagabbro belt southwest of Atlantic City. The metaleucodacite is porphyritic, with crystals of oligoclase and quartz in a dense sericitized groundmass, which in some specimens also contains biotite (fig. 12).

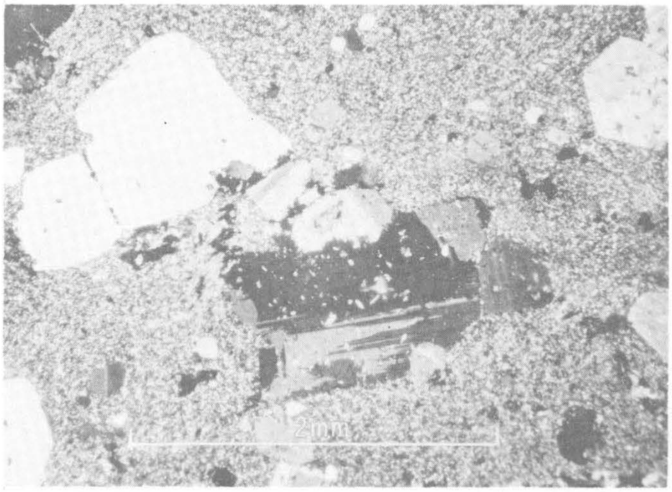


FIGURE 12.—Porphyritic metaleucodacite. Crossed nicols. Phenocrysts are oligoclase and quartz. Dense sericitized matrix.

Chemical analyses of the two widely separated dikes are given in table 7. The rock which specimen A (table 7) represents contains quartz veins, apparently in joints, and disseminated crystals of arsenopyrite. A fire assay indicates 0.01 oz per ton Au and 0.01 oz per ton Ag.

TABLE 7.—*Chemical analyses of metaleucodacite porphyry*

	A	B
SiO_2	69.64	72.9
TiO_2	.35	.31
Al_2O_3	15.43	14.7
Fe_2O_3	.92	.8
FeO	.89	1.3
MgO	.63	1.0
CaO	1.89	1.1
Na_2O	5.12	5.7
K_2O	2.21	1.0
H_2O	1.11	.88
P_2O_5	.10	.11
MnO	.03	.04
CO_2	1.18	<.05
Cl	----	n.d.
F	----	n.d.
S	.02	n.d.
Total	99.52	100.0

A. Dike in Roundtop Mountain Greenstone, sec. 36, T. 30 N., R. 100 W. Analysis by Dorothy F. Powers, U.S. Geological Survey.

B. Dike in Miners Delight Formation, sec. 7, T. 29 N., R. 99 W. Rapid analysis by P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe, U.S. Geological Survey.

The metatonalite stocks are small. Exposures of the largest cover about 10 acres at the Mary Ellen mine in sec. 14, T. 29 N., R. 100 W. This stock and two smaller ones to the west have intruded the metagabbro, and the stock margins and surrounding metagabbro were strongly sheared by the accompanying deformation. The metatonalite of the Mary Ellen stock is massive to slightly foliated and is well jointed. It is a medium-colored medium-grained hypautomorphic-granular rock composed of sodic oligoclase and quartz and a little brown biotite. In specimens of the sheared rocks from the margins of the stock, the oligoclase is thoroughly granulated and interspersed with eyes and lenticles of quartz. The Mary Ellen mine is in a north-dipping blanket quartz vein which was probably emplaced in a gently dipping joint of the stock. Parallel joints probably underlie the vein and may also be gold bearing.

LOUIS LAKE BATHOLITH

The Louis Lake batholith is exposed over about 250 square miles in the northern part of the mapped area (pl. 1). It is a relatively uniform igneous body with conspicuous primary foliation throughout and rather severe deformational foliation along the south margin; weathering along the foliation causes a sheeting effect (fig. 13). An aureole zone that contains layered granite and amphibolite gneiss with two included bodies of granite marks the southeastern contact. From the U.S. Steel iron mine southwestward to Willow Creek the gneiss cuts progressively higher into the Goldman Meadows Formation until it finally reaches the base of the Roundtop Mountain Greenstone. At the contact, greenstones are generally of amphibolite grade. In the west the

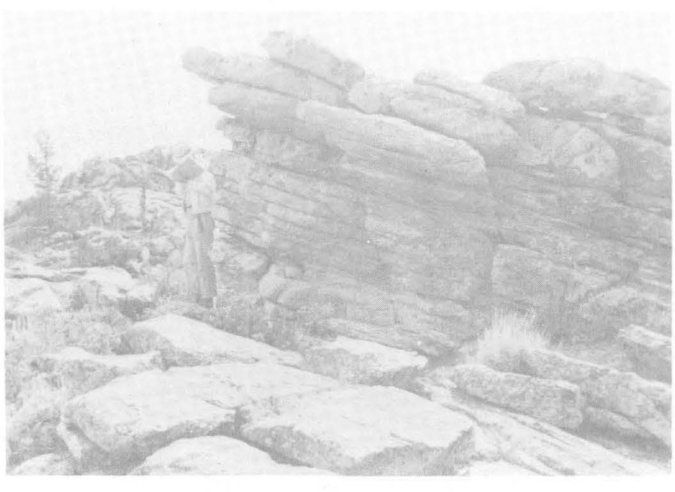


FIGURE 13.—Sheeting in granite exposed near the west side of Anderson Ridge quadrangle.

batholith is in fault contact with graywackes of the Miners Delight Formation along the Anderson Ridge fault, and northwest of that fault it is in intrusive contact with the graywackes. The sheared gneissic rocks at this northwest intrusive contact are of sillimanite grade. Isolated granitic plutons related to the batholith occur just west of South Pass City and at the west border of the Anderson Ridge quadrangle (fig. 14). The South Pass pluton is porphyritic and domical with primary foliation, and it grades westward into pegmatitic granite. Pegmatites related to the batholith are confined mostly to the western part of the area. Dikes of fine-grained aplite cut the batholith in the east. The main mass of the batholith encloses widely separated discus-shaped clots of metagabbro which parallel the primary foliation. The foliation, vertical to steeply south dipping on the south, nearly horizontal near the middle of the batholith, and east dipping on the north side, suggests that the batholith is shaped like an elongated east-trending dome.

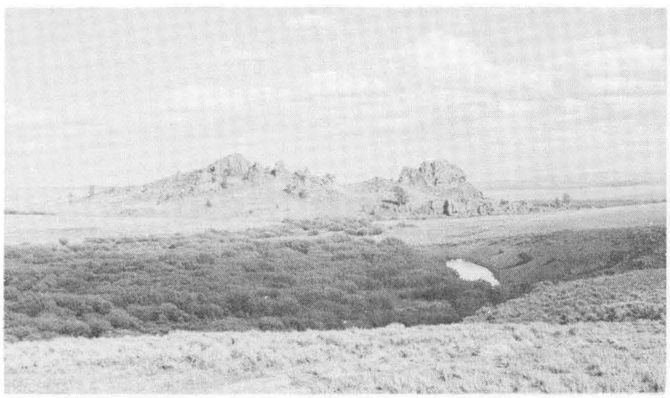


FIGURE 14.—Part of satellitic pluton west of South Pass City viewed from northwest.

The contact gneiss in the east is composed mainly of pink, white, and brown layers of foliated granitic rock and amphibolite. The amphibolite seems to be partly greenstone and partly metagabbro. The amphibolite is abundant in the south but diminishes in quantity toward the north. All amphibolite layers are parallel to the trend of the gneiss belt. These amphibolites underlie the Goldman Meadows Formation and probably constitute the basement for that formation. The serpentinite west of the U.S. Steel mines could be a part of this basement, but the field evidence is not conclusive.

Specimens collected in all parts of the batholith indicate that it is a rather uniform granodiorite. The averages of eight modes are as follows: plagioclase, 48.4 percent; microcline, 15.9 percent; quartz, 23.5 percent; and the mafic minerals, 12.2 percent. The granodiorite is commonly gray, its texture monzonitic—that is, the anhedral microcline usually includes crystals of euhedral plagioclase. The plagioclase is oligoclase, about An 25 to 30, and the primary mafic minerals are biotite, hornblende, sphene, and magnetite. Low-grade alteration has affected most of the specimens. The plagioclase is commonly sericitized and contains some epidote minerals. The mafic minerals are partly chloritized, and epidote is disseminated through the rock. Veins of epidote a few inches wide are not uncommon in the areas of intense epidotization.

The isolated plutons south of the batholith are monzonitic to granitic and partly porphyritic; microcline is much more abundant and blebs of granophyre are common. The pluton west of South Pass City, which is porphyritic granite, grades westward into coarse-grained pegmatitic granite. Most of the main batholith is cut here and there by aplite dikes. The dikes contain more microcline than the batholith and approach quartz monzonite in composition; the mafic minerals generally make up less than 1 percent of the rock. Pegmatites related to the batholith occur mainly in the southwest (pl. 1). They have been studied principally by Proctor and El-Etr (1968). They are concordant and discordant and of various sizes and shapes. Some are layered. They cut the batholith, the adjacent plutons, and the folded metasedimentary rocks. Elongation of these pegmatite masses was mainly controlled by bedding in the metasedimentary rocks. Round to oval crosscutting bodies are common in the crests of tight folds. A size-shape analysis of the pegmatites is shown in figure 15.

At least five mineralogical types of pegmatites have been observed: (1) magnetite; (2) graphic granite; (3) tourmaline-garnet, consisting of (a) very coarse grained garnet-tourmaline-beryl and (b) tourmaline-garnet; (4) garnet; and (5) biotite. The mineralogical modifier indicates that the mineral named is abundant enough to be readily recognized in outcrop. The major minerals of the pegmatites are subhedral potassium and alkaline feldspars, perthite, mica, and anhedral quartz. Film, string, and vein-type perthite (Andersen, 1928) are abundant. The network and patchy varieties are less abundant. The feldspar crystals, which, naturally, are the largest crystals, are as much as 1.5 feet long. Garnet, beryl, magnetite, and tourmaline, where present, form euhedral to subhedral crystals. Some minerals found in small quantities are arsenopyrite, columbite-tantalite, beryl, lepidolite, spodumene, and sky-blue tourmaline. The pegmatite minerals are

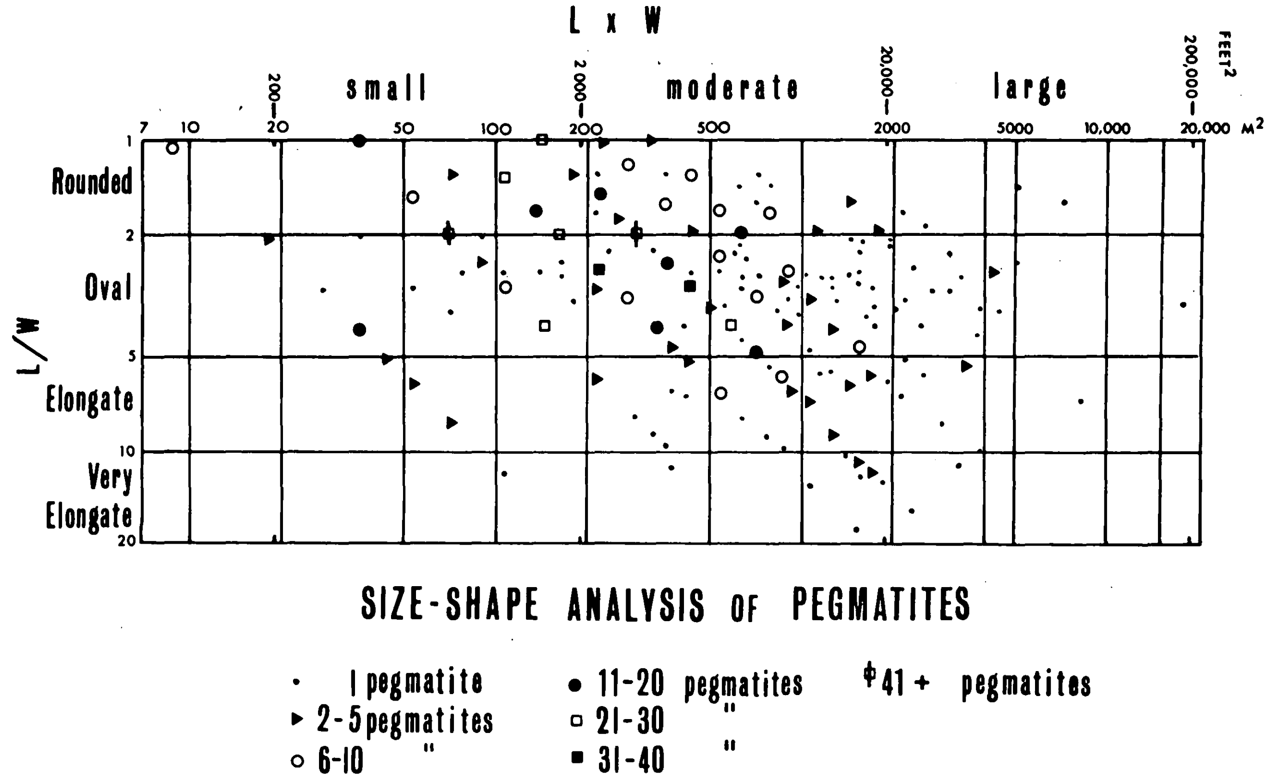


FIGURE 15.—Size-shape analysis of layered pegmatites, South Pass area. From Proctor and El-Etr (1968).

commonly fractured, and some pegmatites are foliated in the axial planes of the secondary folding. The layered pegmatites are commonly elongate, and the parallel to subparallel tabular layers may be either of monomineralic or polymineralic composition. Layered pegmatites are illustrated in figures 16, 17, and 18.

The chemical compositions of four pegmatites were determined by spectrochemical analyses (table 8). Normative albite, orthoclase, and quartz percentages for three pegmatites, an albite-rich marginal rock, and four granite specimens from the pegmatite area were calculated and plotted in figure 19. These analyses are compared to the trend of the isobaric minimum in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O under water pressure ranging from 0.5 to 4 kilobars. The normative albite, orthoclase, and quartz plot for the average of 571 previously analyzed granites (Tuttle and Bowen, 1958; Jahns and Tuttle, 1963) is also shown. Except for the sodic marginal rock, 3P, each of the normative pegmatite analyses fall below the curve for granite toward the Or apex. The four analyzed granites fall both above and below the curve toward the Or–SiO_2 join. The compositions of the pegmatites and granites therefore closely approach the composition of the average felsic granite.

TABLE 8.—*Spectrochemical analyses of granite pegmatites, Anderson Ridge area*

[From Proctor and El-Etr (1968). Analyst: K. Govindaraju, Centre de Recherches Pétrographiques et Geochimiques, Nancy, France, with kind permission of Prof. Dr. M. Roubalt, Director]

	Mineralogical type and sample number			
	Garnet pegmatite 22–P–62	Garnet pegmatite 44–P–62	Banded garnet-albite-quartz layer 48–P–63	Garnet pegmatite 24–P–62
SiO_2	72.80	73.50	72.80	73.40
Al_2O_3	13.30	14.00	16.20	13.75
Fe_2O_3	2.69	.99	1.79	.74
MnO	[1].20 (.40)	.09	[1].20 (.50)	.03
CaO	.69	.89	tr	.74
MgO	tr	tr	tr	.19
Na_2O	4.28	4.28	7.67	3.63
K_2O	5.33	4.83	.29	6.07
TiO_2	.12	.03	tr	.07
P.F.	.12	.39	.29	.38
Total	99.53+	99.00	99.24+	99.00

[1] Estimated MnO, amount exceeds established standards for analytical technique.

Note: Methods, accuracy, precision, reproducibility are discussed in Govindaraju (1963).

22–P–62.
Garnet granite pegmatite, east-central sec. 27, T. 29 N., R. 101 W.

44–P–62.
Garnet granite pegmatite, NE¼ sec. 34, T. 29 N., R. 101 W.

48–P–63.
Garnet-albite-quartz "line-rock," SW¼ sec. 6, T. 28 N., R. 101 W.

24–P–62.
Garnet granite pegmatite, NE¼ sec. 28, T. 29 N., R. 101 W.

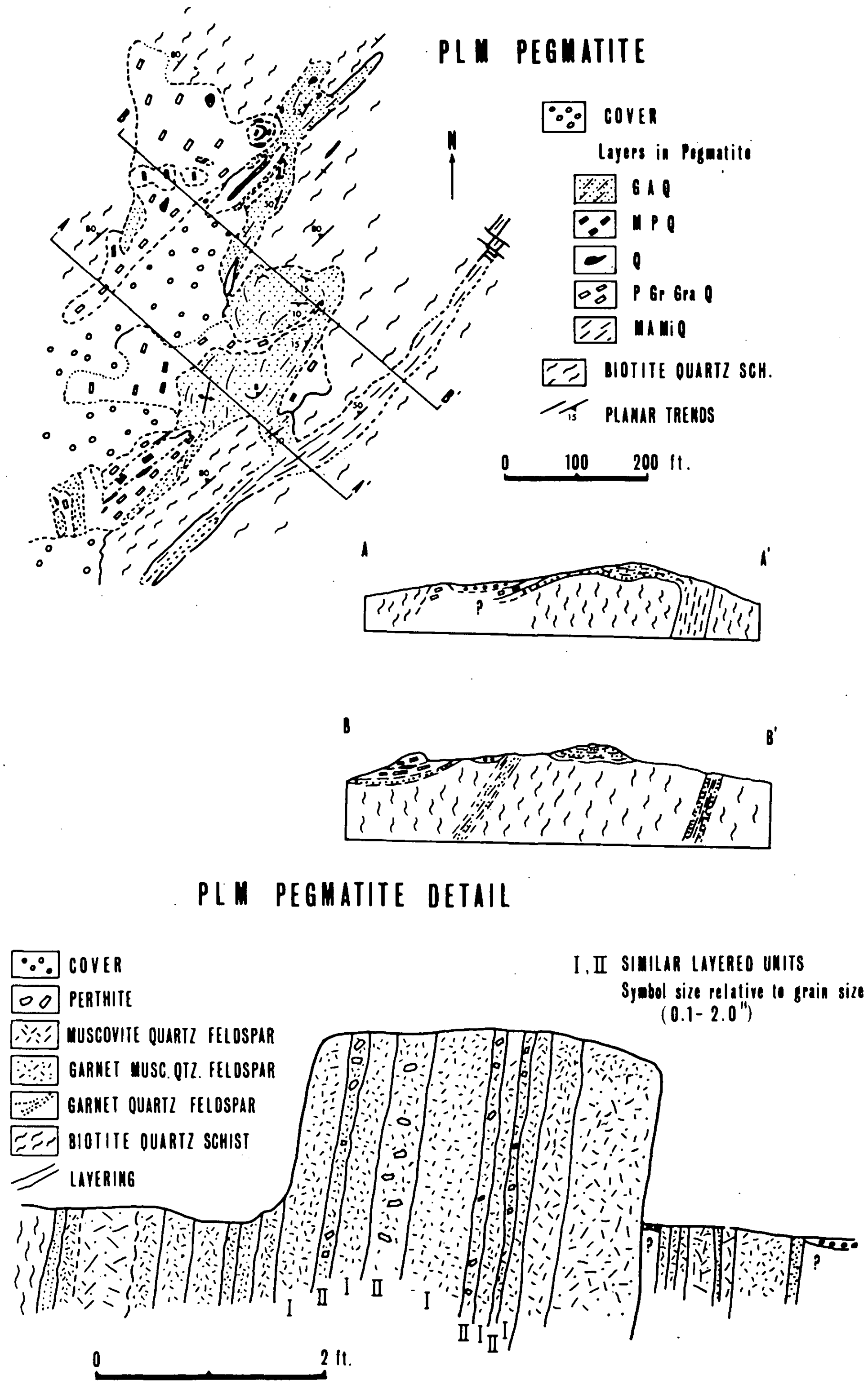


FIGURE 16.—PLM discordant pegmatite (SW¼ sec. 12, T. 28 N., R. 102 W.). G, garnet; A, albite; Q, quartz; M, muscovite; P, perthite; Gr Gra, graphic granite; Mi, microcline. From Proctor and El-Etr (1968).

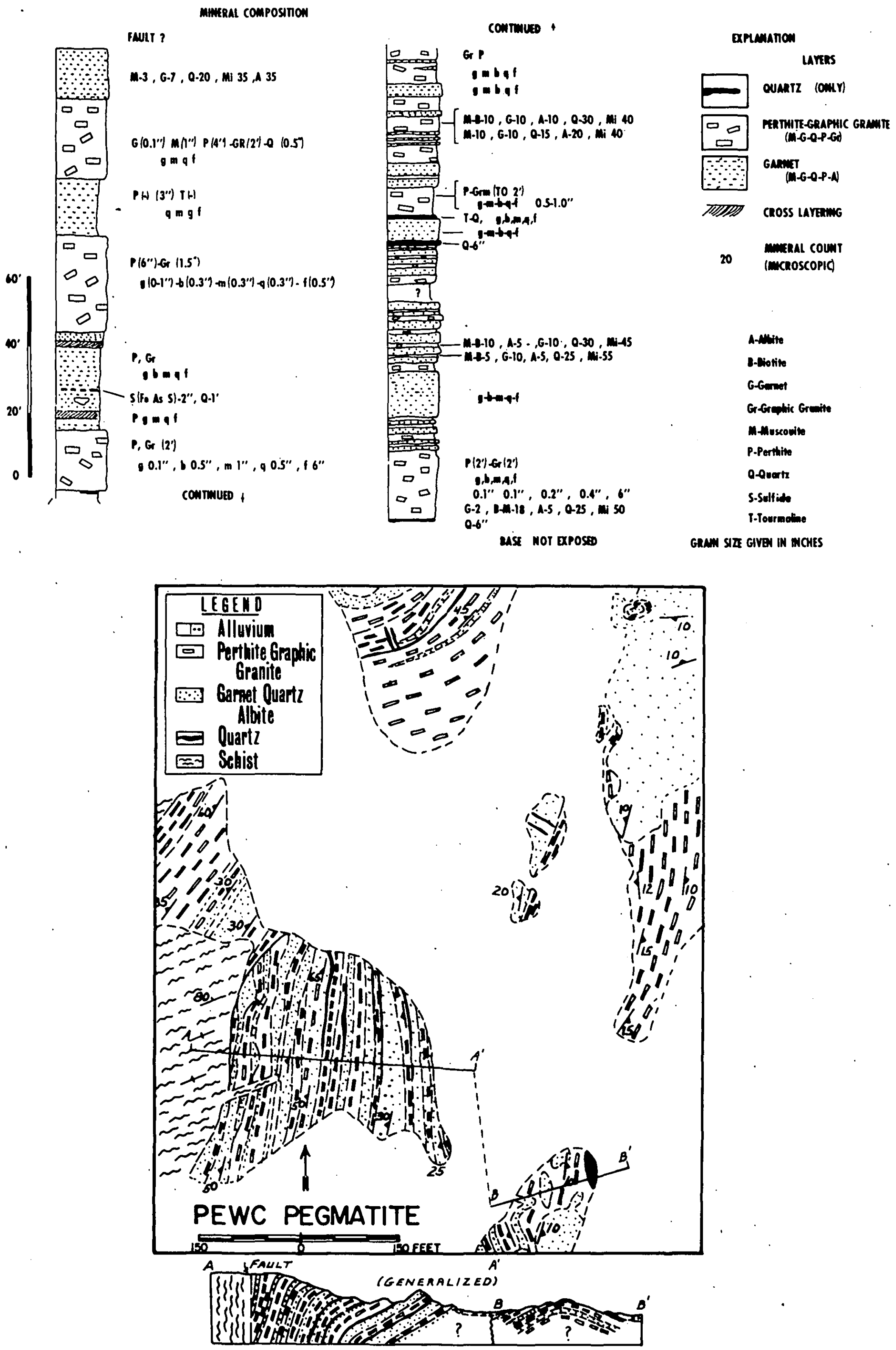
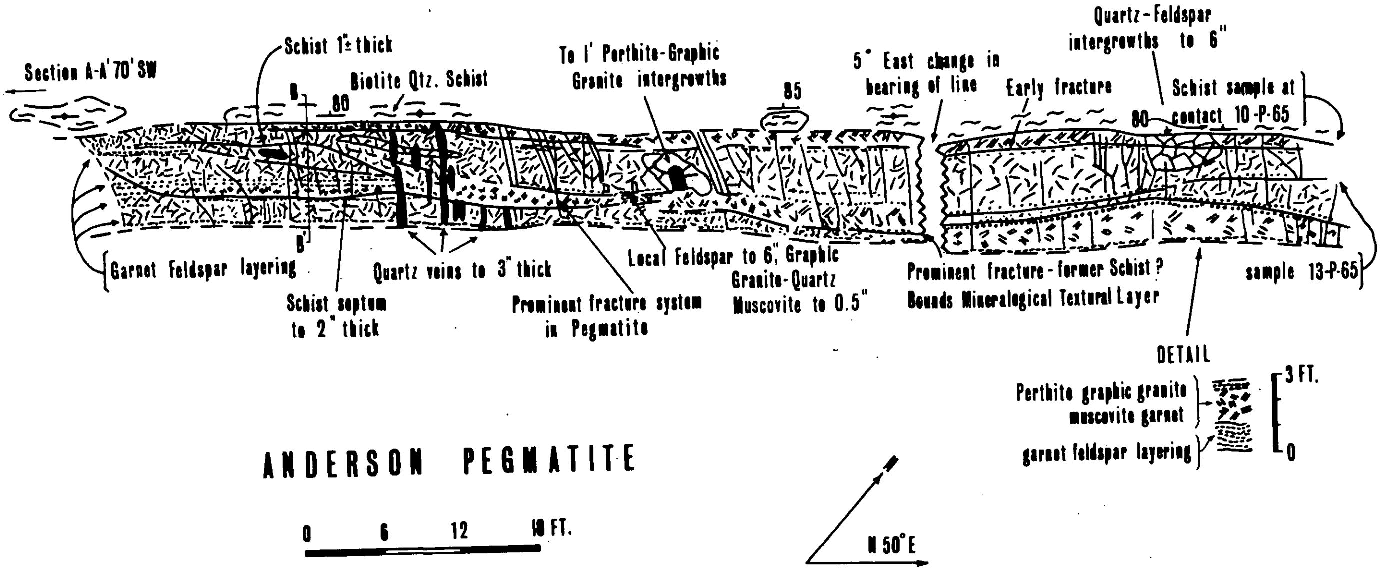
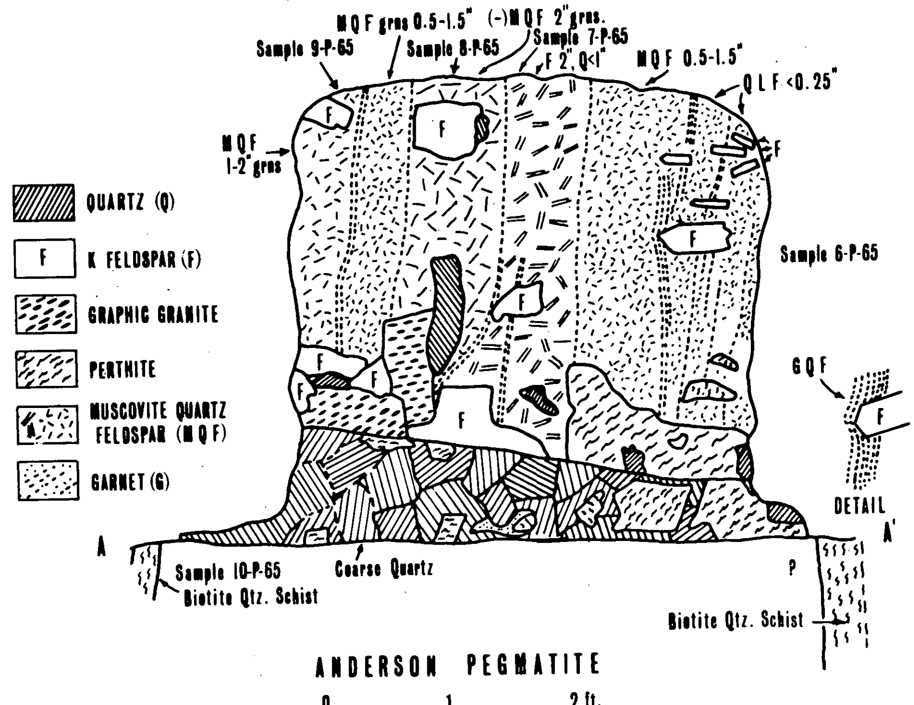


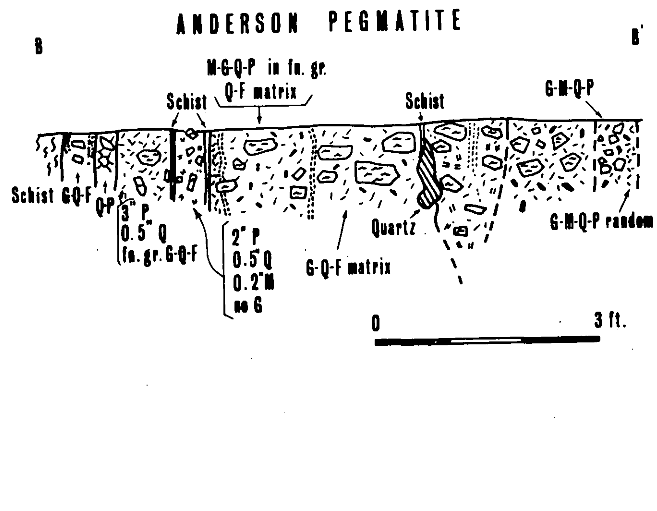
FIGURE 17.—Lithologic vertical section (top) and generalized geologic map and cross sections of the PEWC pegmatite (bottom), NE¼ sec. 1, T. 28 N., R. 102 W. From Proctor and El-Etr (1968).



Section A-A' 70' SW
Schist 1'± thick
Biotite Qtz. Schist
To 1' Perthite-Graphic Granite intergrowths
5° East change in bearing of line
Quartz-Feldspar intergrowths to 6"
Early fracture
Schist sample at contact 10-P-65
Garnet Feldspar layering
Schist septum to 2" thick
Quartz veins to 3" thick
Prominent fracture system in Pegmatite
Local Feldspar to 6", Graphic Granite-Quartz Muscovite to 0.5"
Prominent fracture-former Schist? Bounds Mineralogical Textural Layer
sample 13-P-65
DETAIL
Perthite graphic granite muscovite garnet
garnet feldspar layering
3 FT.
0
ANDERSON PEGMATITE
0 6 12 18 FT.
N 50° E



M Q F grns 0.5-1.5"
(-) M Q F 2" grns.
Sample 9-P-65
Sample 8-P-65
Sample 7-P-65
F 2", Q<1"
M Q F 0.5-1.5"
Q L F <0.25"
M Q F 1-2" grns
QUARTZ (Q)
K FELDSPAR (F)
GRAPHIC GRANITE
PERTHITE
MUSCOVITE QUARTZ FELDSPAR (M Q F)
GARNET (G)
Sample 6-P-65
G Q F
DETAIL
A
A'
Sample 10-P-65
Biotite Qtz. Schist
Coarse Quartz
P
Biotite Qtz. Schist
ANDERSON PEGMATITE
0 1 2 ft.



ANDERSON PEGMATITE
B
B'
M-G-Q-P in fn. gr. Q-F matrix
Schist
Schist
G-M-Q-P
Schist G-Q-F
Q-P
3" P 0.5" Q fn. gr. G-Q-F
2" P 0.5" Q 0.2" M no G
G-Q-F matrix
Quartz
G-M-Q-P random
0 3 ft.

Analyses of 33 pegmatites for beryllium by the U.S. Bureau of Mines proved negative (actually less than 0.03 percent BeO), except for two pegmatites of the group known to contain beryl. Beryl is generally confined to the tourmaline-garnet-bearing pegmatites that trend southwest through the central part of the pegmatite area.

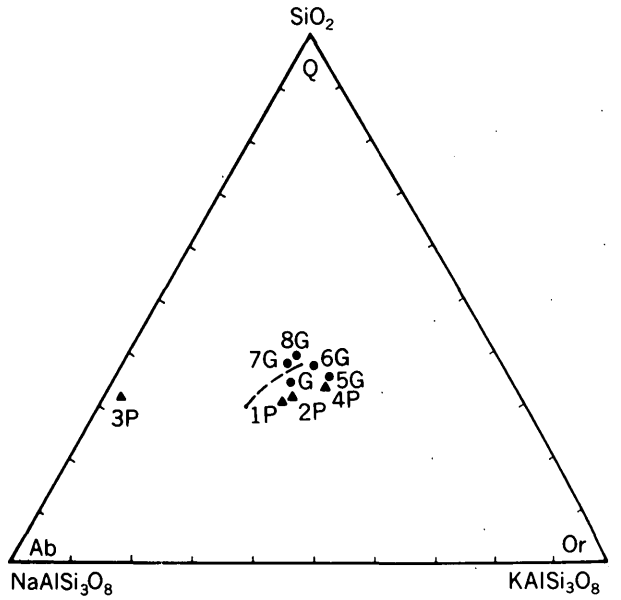


FIGURE 19.—Plot of normative albite, orthoclase, and quartz in pegmatites and granites from the Southern Wind River Range, Wyo. Sample data: samples 1P=22–P–62, 2P=44–P–62, 3P=48–P–63, 4P=24–P–62, all in table 8. Samples 5G and 7G are from east granite stock and 6G and 8G from west granite stock (pl. 1). From Proctor and El-Etr (1968).

The chemical composition of the Louis Lake batholith and its differentiated parts is summarized in table 9 and figure 20. Three specimens from the interior of the batholith are granitic, but the remaining 16 are granodiorite with a SiO_2 range between 63.62 and 69.67 percent. Ten specimens of the south marginal facies of the batholith average out as biotite granodiorite (Nockolds, 1954); however, three of the ten have a granitic composition. The outlying satellitic plutons are granitic, as indicated by the average of nine analyses (table 9). The satellitic plutons apparently represent a product of filter pressing, inasmuch as they are syntectonic. Filter pressing seems probable, because one of the satellitic plutons grades into pegmatitic granite. The late differentiates—the aplite dikes and pegmatites—cut the main batholith, the satellitic plutons, and the metasedimentary rocks. Their average compositions are quite similar, and both probably represent the last phase of the differentiating granodiorite. The average analyses of all phases of the batholith are plotted in figure 20, which shows the trend of differentiation.

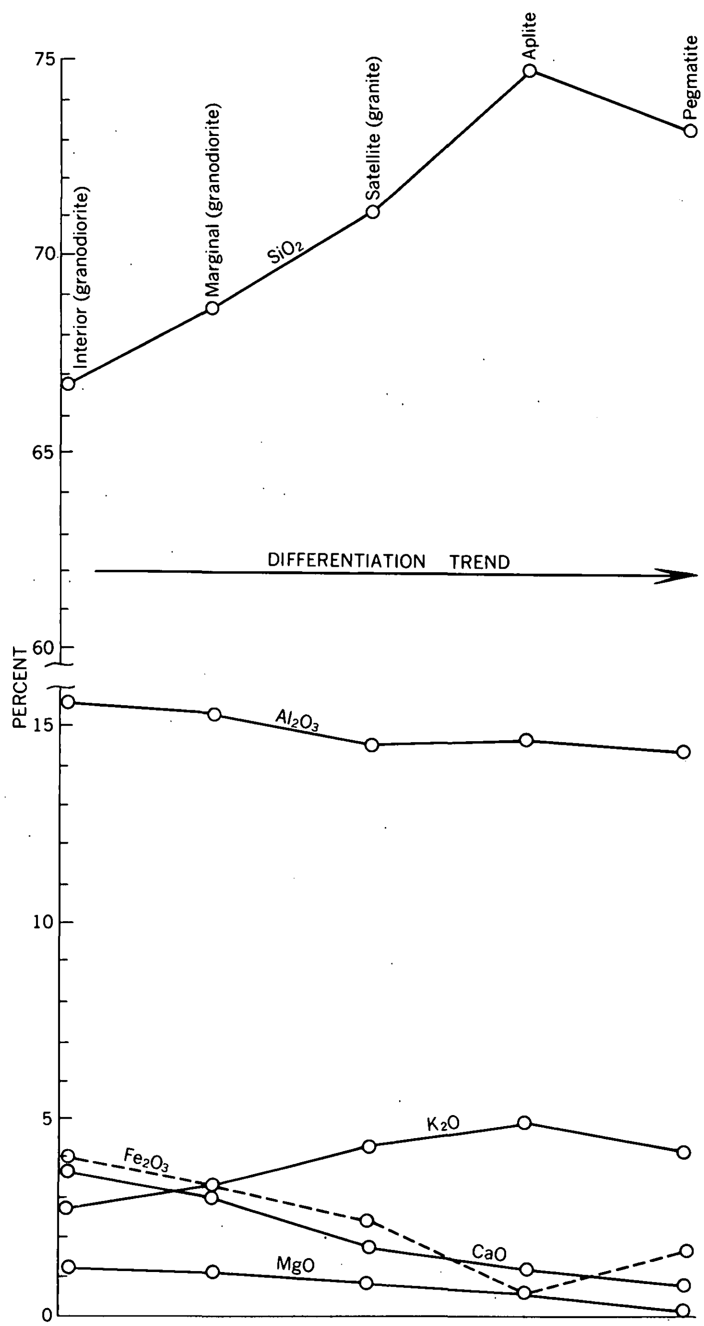


FIGURE 20.—Diagram showing differentiation trend of Louis Lake batholith.

FIGURE 18.—Anderson pegmatite (NW¼ sec. 7, T. 28 N., R. 101 W.), showing plan view and cross sections of the concordant pegmatite and its mineralogical characteristics. From Proctor and El-Etr (1968).

TABLE 9.—*Chemical analyses of the Louis Lake batholith and related differentiates—arithmetic averages*

[(3) number of analyses; tr, trace]

	Lo (1970) Interior (19)[1]	Lo and Proctor (1970) Margin (10)[1]	Proctor (unpub.) Satellites (9)	Lo (1970) Aplites (5)[1]	Proctor and El-Etr (1968) Pegmatites (4)[2]
SiO_2	66.76	68.28	71.05	74.75	73.12
Al_2O_3	15.67	15.32	14.52	14.68	14.31
Fe_2O_3	4.14	3.46	2.43	.51	1.55
MnO	(3)	(3)	(3)	(3)	.13
MgO	1.22	1.11	.82	.56	tr
CaO	3.64	2.99	1.74	1.03	.58
Na_2O	[3]3.69	3.90	3.84	?	[4]4.96
K_2O	2.81	3.47	4.27	4.94	4.13
TiO_2	.53	.43	.26	.07	.05
Total	98.46	98.96	98.93	96.54	98.83

[1] Analyses by Lo (1970), probably by X-ray fluorescence.
[2] From table 8.
[3] No Na_2O in interior analyses. Value taken from Nockolds (1954), average biotite granodiorite.
[4] Probably excessive because of one albite pegmatite.

DIABASIC GABBRO DIKES

The youngest Precambrian intrusive rocks in the South Pass area are relatively fresh gabbro dikes that show chilled selvages; these dikes are apparently part of a large swarm which crosses the Precambrian cores of several of the ranges in Wyoming: the Sweetwater uplift, the Owl Creek Range, and the Bighorn Range. In the Wind River Range the dikes generally trend northeastward or eastward. They are younger than the Louis Lake batholith, the pegmatites, and the refolded sedimentary rocks, but older than some east-west faults. The dikes have been described by Nold (1964) and dated by the whole-rock K-Ar method by Condie, Leech, and Baadsgaard (1969). They are 10–200 feet thick and are best exposed in the Louis Lake batholith, where they form conspicuous ridges (pl. 1). They are composed of tholeiitic gabbro and are commonly diabasic, except on the margins, where they are glassy, porphyritic, or pilotaxitic. The primary minerals are plagioclase (An_{50}–An_{60}), augite, magnetite, and ilmenite. Slight low-grade alteration is common in all the dikes, and alteration is nearly total in some. The alteration minerals are sericite (in plagioclase), chlorite, carbonate, uralite (in augite), epidote, iron oxide, and leucoxene. This low-grade alteration is not confined to the dikes but affects the metasedimentary rocks and Louis Lake batholith as well—which explains why every dike of this contemporaneous swarm that has been dated yields a different age, from 900 to 2,060 m.y. The oldest ages are from the tightly folded metasedimentary rocks, the youngest from the Louis Lake batholith, so environmental factors could have regulated the amount of alteration and the argon loss.

STRUCTURE

The Precambrian rocks of the South Pass area show clearcut evidence of two periods of folding and several periods of faulting. A northeastward-trending synclinorium, apparently the master structure of the South Pass pendant, seems generally to pitch southwestward; however, there are numerous reversals. The rocks of the synclinorium assumed to be the oldest, the Goldman Meadows Formation, occur on both flanks of the synclinorium. Intrusive granite occurs on both flanks as well but is in fault contact on the southeast flank. (See fig. 5.)

The first folding of the synclinorium preceded intrusion of the Louis Lake batholith. A classical synclinorial folding, it produced tight upright and recumbent folds, all of which probably trended northeastward. The principal fold on the older sedimentary rocks near Iron Mountain (Goldman Meadows and Roundtop Mountain Formations) is a large dragfold whose orientation suggests an anticlinal structure on the north. The iron-formation in this fold is thoroughly plicated with steep-plunging minor folds, and the beds are stretched down the plunge direction by boudinage. Most of the numerous faults that cut both limbs have been intruded by dikes of metagabbro. The anticlinal part of the dragfold was torn in half by the Hidden fault, apparently by considerable elevation of the north block.

The folds in the graywacke are upright or recumbent throughout the greater part of the graywacke area. These folds were defined on the basis of graded beds (turbidites). The beds and the axial planes of folds dip 60°–90°. However, near the south margin of the graywacke area, the dips of the beds and axial planes are lower, that is, from about 60° to about 30°, and the dips are generally northward. The more horizontal dips in this southern area are possibly due to deformation of the beds and axial planes during the intrusion of granitic rocks, for the rocks emplaced show a north-dipping foliation of 25°–40°.

Folding of the gabbroic and dioritic rocks of the South Pass gold belt occurred in two stages. The best displayed original fold is at Miners Delight. The second best, now thoroughly dislocated by faulting, is at Atlantic City. It apparently formed a synclinal loop of folded gabbro adjacent to the well-defined anticline just north of the Rock Creek and Atlantic faults. At Atlantic City and Miners Delight, the intrusive gabbros appear to parallel the metagraywackes. North of South Pass City the same intrusive gabbro belt cuts obliquely across the metagraywacke at about 20°–30°. Here independent folding of the metagraywacke caused a severe shear zone where the folds impinged on the gabbro (pl. 1). In the second stage of folding the gabbros and metagraywacke folds west of South Pass City were refolded as synforms by the intrusion of granite.

The second folding of the synclinorium was synchronous with the emplacement of the Louis Lake batholith. The folds of the original synclinorium were strongly deformed into broad arches of synform-antiform types. This folding is most pronounced west of South Pass City, where an isolated domelike pluton moved upward and southeastward into the graywackes. It produced a tight synform on the east of east-dipping recumbent folds, a broad antiform south of the domed pluton, and a broad arched synform on the west side of the pluton.

Faulting occurred in several stages. The major northeast-trending faults on either side of Roundtop Mountain appear to have developed after the first folding and before intrusion of the batholith. The fault north of the mountain is hidden and was inferred from the results of a magnetometer survey. It truncates the iron-formation of the Goldman Meadows Formation. The fault south of Roundtop Mountain, the Roundtop fault, is well marked by a platy strung-out tectonic breccia and by strongly foliated and plicated chloritized gabbro and greenstone. The greenstones of Roundtop Mountain face south, whereas the graywackes, adjacent on the south, face north; therefore, if our stratigraphy is correct, it must be assumed that the greenstone block was upthrown against the graywackes. To explain the absence of a strong magnetic anomaly over the iron-formation on the south side of the hidden north fault, it must be inferred that the north block of that fault was upthrown a considerable distance; thus, the north sides of both faults must have been elevated, but the northernmost block much more than the Roundtop Mountain block. Apparently the two faults on either side of Roundtop converge to the southwest; however, the extension of the north fault (because it parallels bedding) could not be found. Other minor faults in the area seem to be contemporaneous with the intrusion of the batholith and the second folding. A few faults in the southwest, in graywacke, appear to be shear zones caused by tight folding. Just west of South Pass City some minor tension faults in the synform that have slight displacements have been intruded by pegmatites and the late, fresh diabase (pl. 1). The major Anderson Ridge fault is possibly left lateral, as indicated by the disturbance of the granite on the north side, and it was probably upthrown on the north side; however, the evidence is inconclusive. If left lateral, it would have had to move north on the Willow fault or override the east block of the Willow fault at a very high angle, or it may have branched to move along the Roundtop or Atlantic faults. Between the Roundtop, Rock Creek, Atlantic, and Anderson Ridge faults, there are several displaced fault blocks which seem to have been rotated counterclockwise. Left-lateral movement in the bounding faults, the Rock Creek, Atlantic, and Anderson Ridge faults, could possibly have caused the rotation. The age of the movement on these faults, however, is uncertain. Although the part of the Atlantic fault that extends east into the area of Paleozoic rocks was reactivated during the Laramide uplift and upthrown on the south side, evidence for Laramide uplift in the Precambrian of the South Pass area is inconclusive.

The timing of the faulting in the iron-formation at Iron Mountain is difficult to assess. The faults that contain dikes of metagabbro were probably intruded during the first deformation. After or during the intrusion of the batholith, some of these faults were reactivated, so that now they displace the edge of the granite body to the west. The faults to the east that cut and displace the iron-formation syncline seem to be late; the eastern one displaces the edge of the batholith. These faults apparently impinge on the earlier Hidden fault. The eastern fault blocks have possibly been rotated counterclockwise, perhaps by reactivation of the Hidden fault. Reconstruction of the trend and areal distribution of the eugeosynclinal suite represented at South Pass is nearly impossible because of pervasive intrusion and fragmentation; however, part of the geologic history can be determined from the fairly large fragments of the suite that occur in the Granite Mountains, the Seminoe Mountains, the Owl Creek Mountains, the Beartooth Mountains, and probably in southwestern Montana as the Cherry Creek Group and Pony gneiss of Giletti and Gast (1961, p. 454). The key beds in this lithologic correlation are oxide iron-formation and green, fuchsite-bearing quartzite, and the intrusive granitic rocks, 2.7 b.y. old or more. The trend of the depositional basin was probably northeastward or eastward, as in the Superior province of Canada and Minnesota. The shoreward facies seems to have been northwest of South Pass, for abundant marble is present in the Cherry Creek Group near Dillon, Mont., and a granitic gneiss basement underlies Goldman Meadows quartzite in the Owl Creek Mountains. At South Pass and the Seminoe Mountains the basement was probably greenstone, metagabbro, and serpentine (ophiolite), which suggests sedimentation on oceanic crust. The whole master continent at this time, the so-called Pangaea, was probably composed of continental crustal nodes interspersed with large areas of oceanic crust. General stabilization of the continental kernel did not take place until the widespread batholithic intrusions 2.5–2.7 b.y. ago, and even thereafter tectonism continued about the nucleus of the North America plate until, and after, the alleged breakup of "Pangaea" 200 m.y. ago. The energy for this pre-breakup tectonism possibly represents interaction between plates within the continent and perhaps subductions or abductions from sea-floor spreading about the continental margins.

METAMORPHISM

The Precambrian rocks of the metasedimentary and metavolcanic terrane in the southern Wind River Range appear to have had a complex metamorphic history, involving at least three periods of metamorphism. (See table 10 and, for isograds, pl. 1.) The earliest was accompanied by isoclinal folding. It preceded intrusion of granite and was therefore probably regional. Nearly all the rocks of the area were raised to amphibolite grade except the greenstones and metagabbro dikes of the Roundtop Mountain area; they show greenschist facies characteristics. These Roundtop Mountain volcanic rocks are chlorite grade, the common mineral assemblage being chlorite-actinolite-albite-epidote, whereas most of the surrounding pelitic rocks and graywackes of the amphibolite facies contain plagioclase (oligoclase)-quartz-biotite-garnet-andalusite or cordierite. The andalusite occurs most commonly in schistose carbonaceous beds and seldom in graywacke. Some andalusite is the size of wheat grains, and some the size of almonds; almost all grains are oriented in the foliation of the enclosing rock and are nearly totally sericitized. Only andalusite remnants have been seen in these sericitized pods; however, according to Condie, X-ray analyses of some pods indicate the presence of cordierite. Apparently, then, both andalusite and cordierite are present, although the andalusite appears to be the more abundant of the two.

The second period of metamorphism coincided with emplacement of the Louis Lake batholith. The batholith caused only contact metamorphism and refolding of already folded rocks. Some contact rocks were merely upgraded, and some were metasomatized and are now microcline rich. In the northeastern part of the area the upgrading was very subtle and metasomatism slight; therefore that part of the batholith probably was relatively dry compared with the part west of South Pass City, in the area of pegmatitic granite and pegmatites, where some contact rocks were totally recomposed to microcline hornfels that contain biotite and quartz. The rocks at the northwest contact, in the Anderson Ridge quadrangle, are gneissic, with abundant ribbon quartz, and the metagraywacke contact rocks there bear quartz-sillimanite-almandite-biotite-microcline. Table 11 shows mineral assemblages for the area, and the ACF diagram, figure 21, shows the subfacies plot of 25 chemically analyzed metagraywackes and schists. The contact gneiss belt, which extends from Iron Mountain to Willow Creek, contains banded granitic rocks, amphibolites (greenstones and metagabbros), a small amount of quartz-pebble conglomerate, and quartz-mica schist. The amphibolite layers are abundant on the south side of the gneiss but diminish in number northward toward the batholith. The granitic gneiss layers are pink to gray and fine grained and contain abundant ribbons of quartz. Their composition is granodioritic. Partly chloritized biotite is the common mafic mineral in the gneiss.

The amphibolite interlayered in the granitic gneiss shows a well-crystallized high-grade fabric of horn-

TABLE 10.—*Proposed metamorphic history of the Precambrian rocks in the southern Wind River Range*

	I Regional	II Contact		III Retrograde
Time, billions of years	Greater than 2.8	About 2.7		Less than or about 1.4
Metamorphic mineral paragenesis (graywacke-schist rocks).	Biotite, andalusite (cordierite), plagioclase, garnet.	Sillimanite, garnet, microcline, muscovite.	--------------------	Chlorite, muscovite, actinolite, chloritoid, epidote.
Igneous activity	Diabase intrusion	Intrusion of granitic batholith and pegmatites.	Diabase dike intrusion.	
Extent of metamorphism	Widespread	Localized around granite contacts.	--------------------	Widespread but not ubiquitous.
Deformation	Isoclinal folding and faulting.	Open folding; minor faulting.	--------------------	Major faulting.
Intensity of metamorphism.	Amphibolite facies	Amphibolite facies (high-grade).	--------------------	Greenschist facies (retrograde).

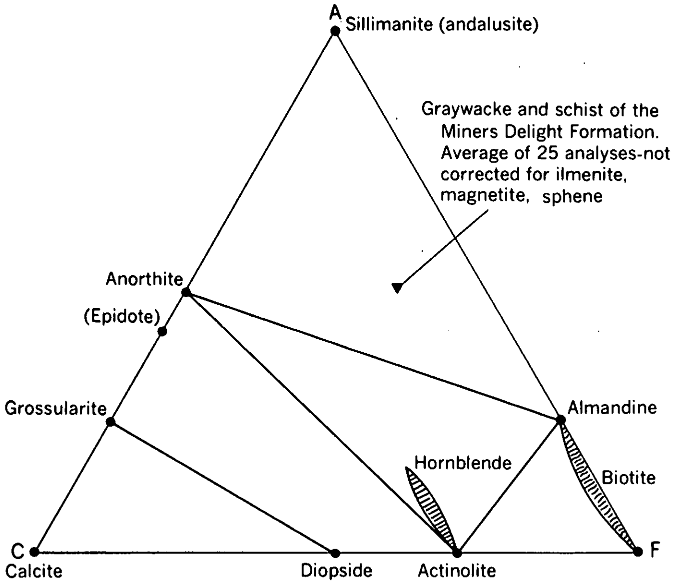


FIGURE 21.—Amphibolite facies, sillimanite-almandine subfacies: ACF diagram for rocks with excess SiO_2 and K_2O (from Turner and Verhoogen, 1951).

TABLE 11.—*Metamorphic mineral assemblages of contact-metamorphosed rocks*

Goldman Meadows Formation (amphibolite facies):
- quartz-plagioclase-biotite (±microcline)
- quartz-biotite-andalusite
- quartz-biotite-hornblende-garnet
- quartz-biotite
- quartz-muscovite
- quartz-magnetite-grunerite (±hornblende)

Roundtop Mountain Greenstone (greenschist facies):
- chlorite-actinolite-albite-epidote

(amphibolite facies):
- plagioclase-hornblende-epidote

Miners Delight Formation (amphibolite facies):
- quartz-biotite-plagioclase[1] (±muscovite, chlorite, chloritoid)
- quartz-biotite-cordierite-muscovite (±plagioclase, chlorite, chloritoid)
- quartz-plagioclase (±muscovite)
- quartz-biotite-plagioclase (±muscovite)
- quartz-biotite (±muscovite)
- quartz-biotite-plagioclase-microcline (±muscovite)
- quartz-biotite-plagioclase-andalusite (±muscovite, almandite, microcline)
- quartz-biotite-plagioclase-almandite
- quartz-hornblende-plagioclase-biotite (±almandite)
- quartz-biotite-muscovite-sillimanite (±microcline)
- quartz-muscovite
- quartz-plagioclase
- quartz-graphite

[1] Listed in order of decreasing abundance.

blende and plagioclase. Some of the hornblende is replaced by biotite, and the plagioclase is generally altered to sericite or epidote minerals. It is assumed that the amphibolite developed from country rock that was in close contact with the batholith and that the late retrograde alteration of the plagioclase occurred during the third period of metamorphism.

A suggested facies series (as defined by Miyashiro, 1961) for the first and second periods of metamorphism is shown in figure 22. Although the location of the triple point (andalusite-sillimanite-kyanite) in the Al_2O_3–SiO_2 system is still uncertain, many experimental studies seem to be converging on a temperature of 400°–500°C and a pressure of 3–4 kb. The exact position does not, however, significantly affect the proposed facies series in the South Pass area. The proposed facies series suggests that the early period of regional metamorphism (I) occurred at temperatures of 500°–550°C and burial depths of 8–10 km. The contact metamorphism (II) appears to represent approximately the same depths of burial, but the temperatures seem to have been in the range 550°–650°C, the extra heat being supplied by the Louis Lake batholith. The microcline in the contact areas may have resulted from the chemical reaction of muscovite and quartz at about 600°C (fig. 22); however, the sparsity of muscovite in the graywacke suggests that potassium-rich metasomatizing fluids from the batholith were most important in the production of microcline.

The metamorphism of the third period, as previously mentioned, was retrograde. It was widespread in the area—most rocks are retrogressive to some degree. The Louis Lake batholith has been epidotized and chloritized in broad areas. The late diabase dikes that cut the batholith show actinolite-chlorite-epidote alteration in every specimen. The gneisses south of the batholith are sericitized and chloritized, and the schists and graywackes show

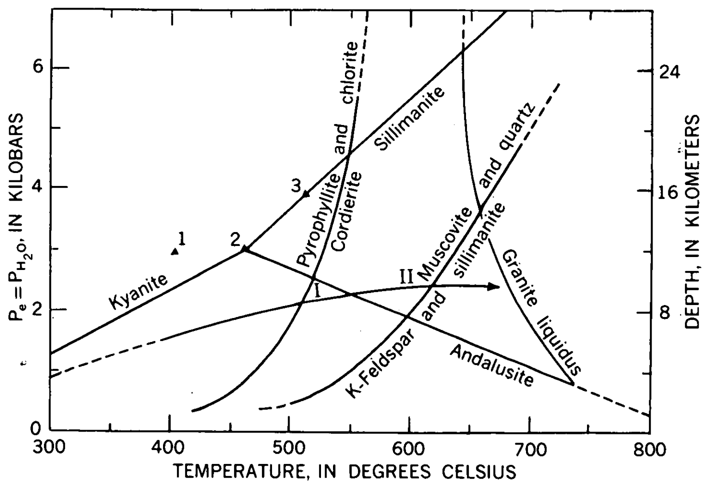


FIGURE 22.—Proposed facies series for Precambrian metamorphism of the southern Wind River Range. Triple points in the Al_2SiO_5 system after Weill (1966)–1, Fyfe and Turner (1966)–2, and Newton (1966)–3; other experimental data from Evans (1965), Schreyer and Yoder (1964, p. 303), and Tuttle and Bowen (1958, p. 122). The arrow indicates typical temperature versus rock-pressure relations in regional metamorphism of the andalusite-sillimanite type facies series.

varying degrees of sericitization and chloritization. The retrograde metamorphism is assumed to have taken place about 1.4 b.y. ago, probably during a period of major faulting. A biotite from a fault zone in the granite west of Iron Mountain gives the 1.4 b.y. (K-Ar) age. Also, along some faults, particularly the Atlantic and Anderson Ridge, the rocks are sericitized intensely and cut by numerous quartz veins, some bearing chalcopyrite. Probably the faulting provided access to alteration fluids from below.

GEOCHRONOLOGY

Sedimentary rocks in the South Pass area are very old. They correspond in age to the oldest formations of the Lake Superior region and the Superior province of Canada. The South Pass strata correlate approximately with Precambrian rock groups such as the Coutchiching Series, Keewatin Series, and Knife Lake (Seine) Group, and the Dickinson Group of the Felch district of Michigan, all of which predate the 2.7 b.y. old Algoman granitic "sea" that makes up the major part of the Canadian Shield in that region. There is an analogous granitic "sea" in the Wyoming province represented by the Louis Lake and other batholiths. The Louis Lake batholith has been dated by a number of investigations using several different techniques, and a fairly broad range of apparent ages has been obtained. (See table 12.)

TABLE 12.—*Age determinations of the Louis Lake batholith*

Investigators	Mineral or whole rock	Method	Age (b.y.)
Giletti and Gast (1961)	Biotite	Rb-Sr	2.37
U.S. Geological Survey:			
H. H. Thomas, R. F. Marvin, Paul Elmore, and H. Smith.	Biotite	K-Ar	2.21
	Hornblende	K-Ar	2.64
T. W. Stern	Zircon	Pb-α	3.0–3.3
Naylor, Stiger, and Wasserburg (1967).	Whole rock	Rb-Sr	2.65
	Zircon	Pb-U	2.68

A structurally disturbed body of granite on the south edge of the Louis Lake batholith, in sec. 34, T. 30 N., R. 100 W., gave seemingly spurious results, which, however, may reflect a time of deformation by faulting. The K-Ar biotite age is 1.42 b.y., the zircon Pb–α 1.24 b.y.

Several attempts to date the metasedimentary rocks have proved unsuccessful. However, one of the gold mines (Snowbird mine) in the Miners Delight Formation has yielded galena with the oldest model lead age yet found, 2.8 b.y. (Cannon and others, 1965). The apparent ages of the granitic rocks, despite large plus or minus factors, indicate the probable Algoman age of the major Wyoming intrusive event. The geology of the area and the galena date by Cannon indicate that the metasedimentary rocks are much older than that event, but how much older remains to be determined. For this area probably the leucodacites and tonalites would be most suitable for further investigation. But to determine the maximum age of the metasedimentary rocks dating must be done in the Owl Creek Range, where the quartzite and iron-formation rest unconformably on granitic gneiss.

The youngest diabase dikes of the area have been dated recently by Condie, Leech, and Baadsgaard (1969) using the whole-rock K-Ar method. Their results suggest two periods of late diabase intrusion, one 1.4–1.5 b.y. ago for dikes intruded into the Louis Lake batholith and one 1.8–2.0 b.y. ago for dikes in the sedimentary rock terrane.

In Bayley's opinion, this arbitrary grouping of numbers ignores the fact that these dikes belong to a single swarm. He therefore assumes that these altered dikes lost different amounts of argon and that the amount lost depended on where the dike is located. Those in the tight schistose metasedimentary rocks seem to have lost the least argon and therefore probably indicate a minimum age for the dike swarm, 2.06 b.y.

ECONOMIC GEOLOGY

GOLD

No reliable records exist for the early period of gold mining in the district, probably the most productive. On the basis of published total gold production figures for the State of Wyoming, Spencer (1916, p. 27–28) concluded that less than $1 million of gold was produced in the district to 1913. However, the total of estimates of individual mine outputs by Jamison (1911) greatly exceeds Spencer's estimate, as the figures below show:

Lode mines		*Placers*	
Miners Delight	$1,200,000	Meadow Gulch	$1,000,000
Carissa	1,000,000	Yankee Gulch	500,000
Caribou	500,000	Spring Gulch	30,000
Garfield	400,000	Promise Gulch	30,000
Victoria Regina	350,000	Smith Gulch	20,000
Franklin	300,000	Red Canyon	20,000
Mary Ellen	125,000	Atlantic Gulch	15,000
Lone Star	40,000	Beaver Creek	10,000
Carrie Shields	35,000	Others	140,000
Other mines	187,000		$1,725,000
	$4,137,000		

Spencer, who was aware of Jamison's estimate, conceded that the total value probably exceeded that indicated by the State's statistics, but not by millions. Reasoning that as much was produced before 1875 as after, he arrived at $1,500,000 as a fair estimate of total gold production to 1916. De Laguna (1938) accepted this figure as a starting point and estimated production to 1938 at $2 million. The total had not changed significantly by 1945, according to Armstrong (1948, p. 37), nor has it changed significantly to the present day.

The gold mined in this district has come from quartz veins and from placer deposits derived from them.

QUARTZ VEINS

The quartz veins generally follow the grain of the wallrocks and occupy zones of shearing and very commonly are extremely sheared themselves. The major shear zones dip steeply at most places, as do the enclosing strata. Almost all the gold-bearing veins are restricted to a narrow interrupted belt of sill-like metagabbro bodies that trends northeast across the district. (See mine locs. 1 to 15, fig. 23.) This close spatial relationship of veins to the metagabbro belt is structural rather than genetic. During folding, shearing occurred between the metagabbro and adjacent graphitic and micaceous schists and along schist inclusions in the metagabbro, thereby providing access ways for the quartz solutions. The gabbroic magma may have preferred this particular belt of rocks because the schists (graphitic and otherwise), basaltic flows and agglomerate, and graywacke conglomerate of the belt were easier to assimilate than the surrounding even-bedded graywacke. At other places, however, particularly in the vicinity of the Gold Dollar and Miners Delight mines (locs. 16 and 17, fig. 23), the gabbro intruded the graywacke. The point to be stressed is that most veins occupy shear zones formed within the structurally very competent metagabbro belt or between the metagabbro and the less competent schist and graywacke on its flanks. These shear zones are, at most places, demonstrably older than the major faults, which even though they caused extensive shearing and brecciation, contain only very local and minor copper-gold deposits. Locally, as at locations 1, 3, and 11 (fig. 23), gold-bearing quartz veins in the graywacke are distant from any metagabbro.

The quartz veins have been classified as to shape and attitude in various ways; we will not add to the already complicated terminology. Geologic mapping has shown that almost all veins of any economic interest are strike veins; that is, they conform in strike to the trend of the country rocks. Moreover, they occur in zones of shearing, faults, and joints that are mappable on the surface and underground.

The veins generally do not represent fracture fillings; they display neither crustification nor zoning. Although shearing subsequent to emplacement has almost everywhere obscured their original relations to the country rocks, replacement of country rocks by quartz is indicated in a few places, particularly where the veins cut metagabbro. The main production of gold has been from lodes composed of numerous sheared veins 2–7 feet thick. Some veins are large, up to 60 feet wide, particularly along the north margin of the gold belt, but their gold content is low, and although extensively prospected, they have not been mined.

MINERALOGY OF VEINS

Although hundreds of veins were examined during geologic mapping, little can be added to previous mineralogic descriptions. Surface exposures show mainly quartz, some of it massive and clean but most interlayered with splits of weathered country rock of various kinds (mainly ferruginous or graphitic dirt) and the whole very much iron stained. Some quartz is cellular and vuggy; some shows limonite-filled pits, the sites of oxidized sulfide crystals. During sampling, the amount of iron oxide in surface exposures was thought indicative of the amount of sulfides once present, and hence the gold content, but the results of 100 assays refute such a relationship. Quite unoxidized specimens of vein material from stock piles and mine dumps show white or gray or black quartz, pyrite, arsenopyrite, and calcite in some areas, and uncommonly chalcopyrite or green copper oxides. Most of the ore specimens examined have been exposed to the weather for many years. They smell of arsenic and show a dusty yellow efflorescence, presumably an arsenic compound. A few samples showing this efflorescence were assayed and found to contain gold, as much as $50 per ton in one. Tourmaline, though generally in microscopic grains, is common in the gold veins and the wallrocks close to veins and in places is abundant enough to blacken the vein quartz. Spencer (1916) reported that pyrrhotite and galena are subordinate minerals in the ore; however, he observed galena only at the Mary Ellen mine. Cannon, Bayley, Stern, and Pierce (1965) found a little galena at the Snowbird mine. Neither pyrrhotite nor galena were found during this investigation, and spectrographic analyses of 100 vein samples indicate no extraordinary concentrations of lead.

CHEMICAL COMPOSITION OF VEINS

Amounts of major elements in the quartz veins sampled differ extremely because of contamination of the vein material by wallrocks. The concentrations of certain minor elements, however, display a rather distinctive signature, as indicated by combined spectrographic analyses, colorimetric analyses

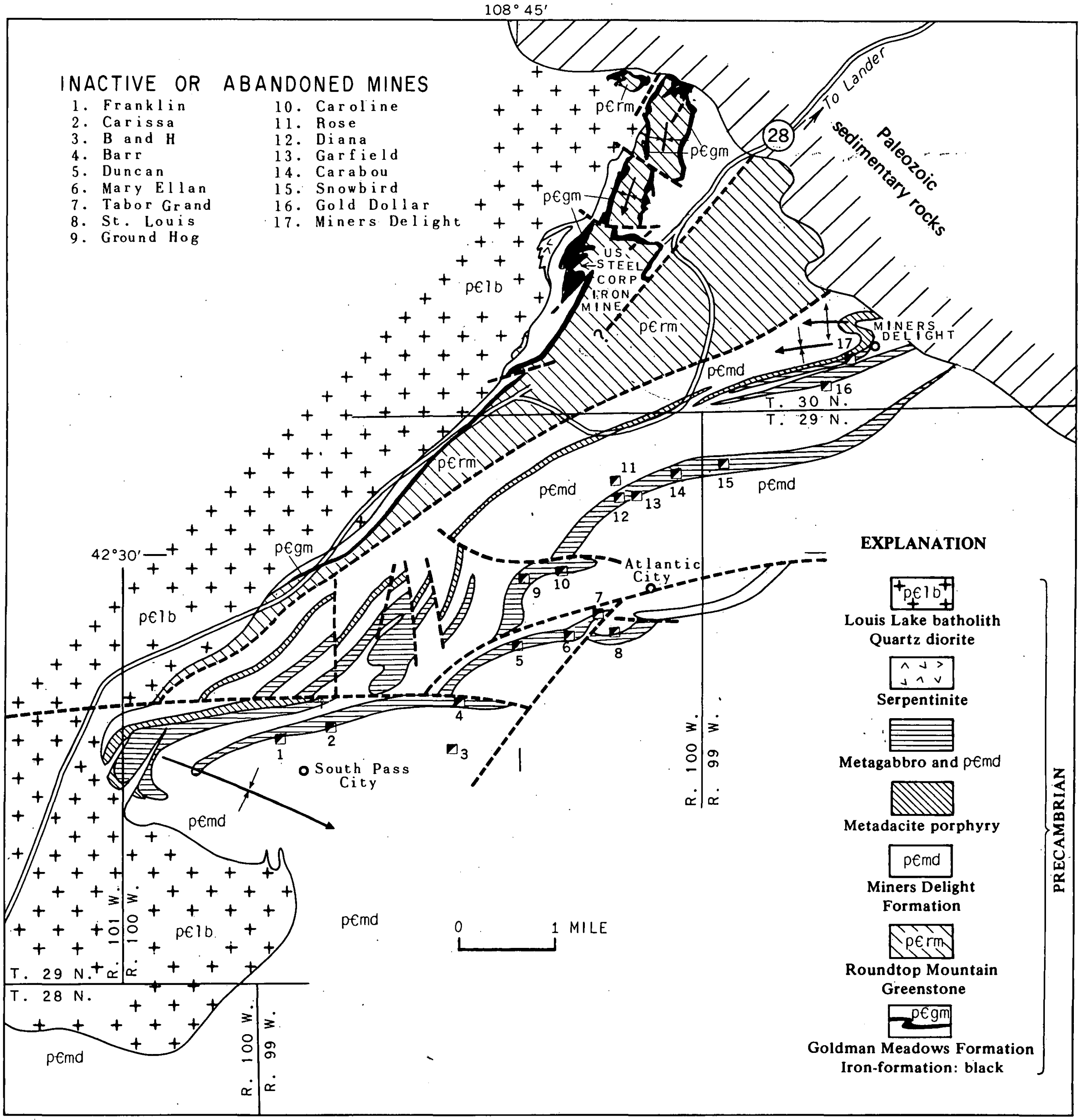


FIGURE 23.—Generalized geologic map of the Atlantic City district, Fremont County, Wyo., showing mine locations. Tertiary and Quaternary deposits omitted. Heavy dashed lines indicate major faults (Bayley, 1963).

(As), and fire assays (Au, Ag) for 18 samples that contain gold. In table 13, the signature is expressed in terms of observed ranges of enrichment of certain elements with respect to average amounts of those elements in silicic igneous rocks.

NATURE OF MINERALIZING SOLUTIONS

Five of the minor elements listed, Co, Cr, Ni, Sc, and V, could have been present in the metagabbro and other mafic country rocks in the maximum concentrations shown; thus, they need not have been imported. A few major elements, Si, Fe, and K, and the minor elements, Au, As, Ag, Bi, B, Cu, and Mo, would have had to be introduced by the mineralizing solutions, which probably consisted mainly of water vapor plus other gases. Thus, the major components of the vein material suggest that the mineralizing solutions were derived from a differentiating pri-

TABLE 13.—*Amounts of certain minor elements in gold-bearing veins compared with average amounts in silicic igneous rocks*

Element	Average percent in silicic igneous rocks, from Vinogradov (1956)	Minor-element signature of 18 gold-bearing veins (minimum and maximum times)
Au	0.000001	60x–4,600x
As	.00015	<2x–10,000x
Ag	.000015	<2x–>70x
B	.0015	2x–100x
Bi[1]	.0002	? –10x
Co	.00051	>1x–5x
Cr	.0025	>1x–5x
Cu	.0031	5x–10x
Mo	.0002	>1x–10x
Ni	.0008	10x–20x
Sc	.0007	>1x–10x
V	.004	>1x–5x

[1] Four samples from area of Carissa mine.
NOTE.—Other minor elements such as Pb, Sr, Y, Yb, and Zr occur consistently in the ores in amounts not exceeding those normally found in silicic igneous rocks.

mary igneous source. That all the igneous rocks of the district, except for the Louis Lake batholith and some late diabase dikes, were emplaced before metallization and regional metamorphism suggests that the batholith, at some stage of development prior to intrusion, caused the metamorphism and supplied the mineralizing solutions. Alternatively, some other subterranean body, not exposed anywhere, could have been responsible for either process or both.

It should be noted here, for the purpose of comparing this district with others, that the leucodacite dikes and stocks, mentioned earlier, are closely associated with a few of the gold deposits and are locally mineralized themselves. Some of the leucodacite is quartz-oligoclase porphyry, and the sodic feldspar content is unusually high. (See table 7). These porphyries probably correspond to the quartz-albite porphyries commonly found in other, similar gold districts (Gallagher, 1940; Ward, 1958). They are undoubtedly older than the ore deposits in this district, though they are probably the last material intruded before the gold mineralization.

WALLROCK ALTERATION

Wallrock alteration is slight and not megascopically apparent. Thin sections of wallrocks from several veins show mainly either sericitization or replacement of all preexisting feldspar by untwinned microcline and some rock replacement by quartz, calcite, and tourmaline. At the B and H mine, where wallrocks were sampled in detail, oligoclase is totally replaced by microcline in the metagraywacke close to the quartz vein. The alteration decreases outward and disappears about 6 feet from the vein, itself 1–6 feet wide.

Thin sections from many veins and their wallrocks show that generally the wallrock septa within the veins are mineralogically similar to the wallrock adjacent to the veins, except that the in-vein metamorphic minerals, mainly biotite, feldspar, and hornblende, are in much larger grains and show better developed crystal forms.

TEMPERATURE OF ORE FORMATION

The wallrock alteration suggests that the temperature of the mineralizing solutions was high, but not much higher than the temperature of the contemporaneous middle-grade regional metamorphism that affected all the rocks. The mineralogy of the metagraywackes suggests that they recrystallized near the low-temperature limit of the amphibolite facies, about 400°C (Rosenquist, 1952); the in-vein minerals suggest no higher temperature, but the environment was doubtless more fluid, hence the larger grain size of metamorphic minerals.

AGE OF DEPOSITS

The gold veins were emplaced early in the deformational history of the district and very probably before emplacement of the Louis Lake batholith, even though the batholith may have been the source of the gold. A galena sample from the Snowbird mine (loc. 15, fig. 23), analyzed by Cannon, Bayley, Stern, and Pierce (1965), gave the oldest model lead age yet found in the United States, 2.85 b.y. The Louis Lake batholith, which is postkinematic with respect to the early folding and synkinematic with respect to the second folding and definitely younger than the gold mineralization, has been dated by various methods at 2.2–3.3 b.y. old.

TENOR OF VEINS

As in most lode gold districts of this type, the Atlantic City lodes are commonly lean but locally contained rich ore shoots. It is generally accepted that the oxidized near-surface ores were somewhat enriched. The early production records would seem to indicate extreme enrichment of the oxidized shallow ores, but much of the early mining may have been done by very selective "gophering" on rich veins—thus, the apparent value of the surface ores is too high. Spencer's (1916, p. 32–34) comments on the gold content of the ores and the persistence of veins seem still valid and are repeated here (values $20 per oz.):

Very little definite information can be given concerning the amount of gold carried by the ores that have been mined from the veins of the district. Notes in Raymond's reports indicate that the ores mined prior to 1872 returned as a rule from $20 to $40 a ton under treatment by stamp milling and simple amalgamation. Some ores were worked that yielded only $15 a ton, and occasional lots yielded as high as $200 a ton. "The average yield of several thousand tons of ore from different lodes has been from $30 to $40 per ton." [Raymond, 1870, p. 330.] Among the mines mentioned by Raymond in 1870 are the Carrie Shields, Young America, Carissa, Golden Gate, Wild Irishman, Gold Hunter, Calhoun, Duncan, Mary Ellen, Barnaba, Buckeye State, Soules & Perkins, Cariboo, Miners Delight, and Bennet Line.

"Between July 20 and November 1, 1868, the original Hermit mill, near South Pass City, treated 1,040 tons of ore yielding an average of $36 a ton; and between April 20 and July 1, 1869, it crushed 480 tons of ore, averaging $47 a ton." [Raymond, 1870, p. 330.]

Ore from the Miners Delight vein is said to have yielded from $16 to $200 a ton, the average having been about $40.

Perusal of old reports relating to the district leaves an impression that many of the lodes occurring in the district might be expected to yield ores carrying on the average as much as $20 a ton. It is believed, however, that as a general rule this expectation will not be realized, though with little doubt shoots of rich ore will be found. It is more likely that assays will show averages of $6 to, say, $15 a ton.

The records of production in possession of the Geological Survey, which are held as confidential with respect to individual mines, indicate that 11,105 tons of ore produced by eight mines since 1902 yielded an average of $8.15 a ton. (See list of assays, p. 40.) On the face of the returns, if a few tons of exceptionally high-grade ore are left out of consideration, the yield appears to have ranged from $5 to $9.18 a ton. The figures given represent the metal recovered, and there is no way of ascertaining the actual gold content of the ores as mined. In so far as gold and silver yields are both given the ratio of gold to silver is found to vary from 5.03 to 10.02, the weighted mean ratio for 8,958 tons of ore being 6.79, which corresponds to a fineness in gold of 0.871.

From a practical man's point of view, the first importance naturally attaches to the question whether or not the veins and other gold-bearing deposits of the district will be found to persist to great depth, and if so whether they will continue to carry about the same amounts of gold as near the surface.

In regard to physical persistence, the conclusions may be drawn that these deposits are of deep-seated origin, that the present topographic surface is a chance surface due to erosion, without significant relation to the ore deposits, and that on the whole the deposits must be as abundant at any depth that might be chosen for consideration as they are at the existing surface. Although these general conclusions are fully warranted by the geologic features of the district, they should not be taken as a guaranty that all the veins of the district will be found to be continuous to indefinite depths. It is probable that the lodes showing long outcrops, like the Carissa and Miners Delight, persist to great depths, whereas it would not be surprising if lodes that can be traced at the surface for very short distances are found to pinch out at correspondingly moderate depths. On the whole the writer is inclined to believe that in this district strike veins, if well defined, are likely to prove more persistent than cross veins.

As to the downward continuance of gold content, though it is likely that there has been some enrichment through solution and redeposition in the oxidized portions of the lodes, it is not believed that any really large proportion of the gold in the upper parts of the veins has been secondarily precipitated from surface solutions; and no hesitation is felt in stating the conclusion that the occurrence of valuable ores is not limited to a shallow zone. It may be expected that here, as is the rule in other districts, different parts of the same lode will be found to carry varying amounts of gold, or, in other words, that in any vein the best ore will be found in the form of shoots.

The foregoing conclusions and suggestions indicate the writer's belief that the district is worthy of further development.

COPPER-GOLD VEINS

Thin gold-bearing quartz-calcite veins, also containing chalcopyrite, occur in shear zones related to the major faults. The faults displace the gold-quartz veins described above, and therefore the copper-gold veins in the fault zones represent a separate and later epoch of mineralization. The veins are commonly only a few inches thick. They have been extensively prospected by test pitting, but nothing has been produced from them. Assayed samples from three test pits show traces of gold, and spectrographic analyses show up to 5 percent copper. The copper is in chalcopyrite and malachite. Limonite stains most exposures, and most chalcopyrite seen is partly altered to limonite. The wallrocks adjacent to this set of veins, mostly sheared and brecciated sericite-altered graywacke, are rather soft and bleached and found in zones as much as 100 feet wide along certain of the major east-trending faults.

FUTURE OF GOLD MINING

It is difficult to find any sound basis for evaluating the future of gold mining in this district. The record is incomplete and unimpressive, in comparison with other mining districts. What is known about the cost of mining and, in exceptional instances, the cost of construction of mills and other paraphernalia (and there were a great many mills) leads one to suspect that the total expenditure may have exceeded the value of the total gold production.

The recent geologic mapping indicates that most of the exposed lodes have been tested and that the possibility of finding new ones is remote. Also, on a district-wide basis, most exposed veins are too lean to be of economic interest. However, the available production records suggest that the major vein systems, that is, the Carissa, Caribou-Diana, and Miners Delight, were very rich in gold. Each of these systems is 0.25–0.5 mile long, and although each may be expected to extend to great depth, none has been mined below 360 feet. Necessarily then, any future gold mining in the district must be based on the recovery of the partly oxidized and the sulfide ores from the deeper parts of these vein systems and possibly on the extraction of other ore that seems less promising. Below about 200 feet, the district is still in its virginal state. Whether the deep ore will warrant mining remains to be learned. Exploration by drilling seems the most practical and direct way to the answer, but as yet (1970) it has not been tried.

IRON

IRON-FORMATION OF THE GOLDMAN MEADOWS FORMATION

The iron-formation members of the Goldman Meadows Formation are the only source of iron ore in the district. These iron-formations, so-called taconites, are metasedimentary rocks, rather precisely fixed stratigraphically, that reacted in characteristic ways to deformation and metamorphism.

The distribution of iron-formation shown on plate 1 is shown in more detail in figure 24, and in even greater detail on a previously published map at scale of 1:6,000 (1 inch = 500 feet) (Bayley, 1963, pl. 1).

The iron-formation, a hard, dense, dark rock, commonly gray and black, consists of alternate iron-rich (dark) and quartz-rich (light) layers, each generally less than 1 cm thick. (See figs. 25 and 26.) Quartz and magnetite make up 90 percent of the rock, and amphibole (grunerite or actinolite), chlorite, and garnet the remainder. The rock is very fine grained, the microtexture granular or hornfelsic. Individual quartz crystals, averaging about 0.2 mm across, are about twice the size of the magnetite crystals, which average about 0.12 mm. The average iron content, as indicated by 150 analyses, is 33.5 percent; the average silica content, about 50 percent. Minor elements, such as Ti, P, and S, which affect the quality of the ore, average 0.025, 0.0046, and 0.011 percent, respectively. The average specific gravity of 10 representative samples is 3.4. A chemical analysis of a sample chipped from resistant layers across 200 feet of outcrop on Iron Mountain appears in table 2, which, for comparison, also shows weighted averages of 12 analyses of banded magnetite iron-formation from the Precambrian Biwabik Iron-formation, Mesabi district, Minn.

The rocks represented by the analyses in table 1 are approximately equivalent to each other in quantity of iron and are probably equivalent iron-formation facies (magnetite-banded iron-formation of James, 1954, p. 261), but the Mesabi analyses indicate that the magnetite-banded rocks of the Biwabik probably contain both more iron silicates and some primary carbonate. The high Fe_2O_3 in the Wyoming sample is caused by minor outcrop surface oxidation.

ORIGIN OF IRON ORE

The iron-formation is apparently a product of chemical sedimentation. The primary or diagenetic mineralogy, closely controlled by the sea-bottom chemical environment (Huber, 1958) at the time of sedimentation, determines what minerals will form if the rocks are subjected to thermal metamorphism (Yoder, 1957). Actually, an infinite variety of starting mixtures of chert, magnetite, hematite, iron silicate, and iron carbonate could, upon metamorphism, form banded magnetite iron-formation; but the great preponderance of quartz and magnetite in this iron-formation and the lack of any granular or oolitic structures suggest strongly that the original starting material consisted almost entirely of chert and diagenetic magnetite. Metamorphism has merely coarsened these constituents and formed new silicates (amphibole, chlorite, garnet) from an original silicate (possibly chamosite) and probably from some original iron carbonate mineral, perhaps siderite.

STRUCTURE OF THE IRON MOUNTAIN ORE BODY

The structural feature at Iron Mountain and vicinity, despite its large size, is basically a steeply pitching dragfold, the anticlinal part of which was torn in half by faulting (fig. 24). The limbs of the fold, as defined by the key iron-formation member, are nearly vertical and even slightly overturned locally. The iron-formation member is intensely plicated internally. The plications and larger fold elements plunge 70°–90° SW., and the limbs have been greatly stretched in the plunge direction, as indicated by mineral lineations, elongated basalt pillows, and boudinage structures. The syncline was compressed and shortened, in the longitudinal sense, probably after it had attained its form and the limbs were nearly vertical. There are several indicators of the shortening: (1) East to northeast crossfolds have affected opposite limbs in parallel and thus have caused parallel sinuosities in the axial plane of the syncline. The structure at Iron Mountain is dominated by folds of the above class that have parallel counterparts in the limb opposite (fig. 24). All such folds on the west limb of the main syncline are turned in a sense opposite to that expected if genetically related to the formation of the original syncline; consequently, the plunging crests and troughs are upside down. (2) Imbrication and telescoping of limbs along what appear to be lateral and reverse faults have caused shortening of the

FIGURE 24.—Geologic map and cross sections of Precambrian iron deposits near Atlantic City. Tertiary and Quaternary deposits omitted. Cross sections spaced arbitrarily along reference line *R*. Note, in the explanation, that the metasedimentary rocks are not separated into formations. The upper schist includes some rocks of the Goldman Meadows and Roundtop Mountain Formations. The granite includes mainly granodiorite as well as some granite of the Louis Lake Batholith (Bayley, 1963).

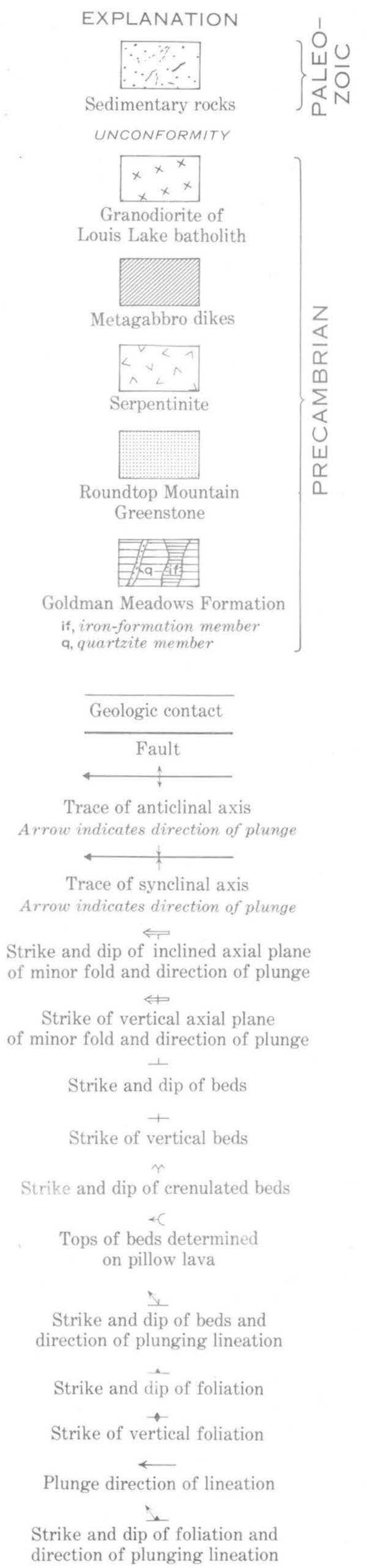


FIGURE 25.—Typical laminated magnetite-chert iron-formation with boudinage structures.

FIGURE 26.—Contorted magnetite-chert iron-formation from the crest of a minor dragfold.

limbs of the syncline at a number of places. Nearly all these fault zones were invaded by basaltic magma, probably while movement was taking place. (3) The iron-formation member has been shortened and thickened by internal folding and plication at many places but especially at Iron Mountain. The plications are systematic, generally southwest plunging, and they indicate that the iron-formation responded to the stresses that produced the drag folding at most places by faulting.

The enormous concentration of iron-formation at Iron Mountain, which makes up the U.S. Steel Corporation's iron ore body, is not due to any stratigraphic thickening. Where the iron-formation enters and emerges from Iron Mountain structure it is of average thickness, about 150 feet (fig. 24). Between the points of entry and egress, crossfolds are superposed on the original syncline. Compaction and thickening of the iron-formation in this fold zone took place in several ways: First, and no doubt most important, was the movement, probably in response to high compressive forces, of iron-formation into the crestal area of the anticlinal part of the fold couplet. Inasmuch as the crest of the anticline was already occupied by iron-formation, the movement took place by internal accordion-type folding that, in effect, shortened the strike length of the iron-formation and increased the thickness about fourfold. The second way in which the iron-formation was compacted and thickened was second in sequence as well. Axial-plane cleavage developed across the already-folded iron-formation. The iron-formation appears to have been repeated by upward and southwestward movement along some cleavage planes, particularly in the northern and southern parts of the Iron Mountain structure. Cross sections *A*, *B*, and *I* (fig. 24) indicate how effectively the reverse faults on cleavage planes have amassed iron-formation at the present surface. Nearly equal-spaced cleavage planes were invaded by basaltic magma, now metagabbro, probably at the time of movement. The magma rose through the breached trough of the original syncline, where it formed massive dikes in the upper schist member of the Goldman Meadows Formation and the greenstones of the Roundtop Mountain Greenstone. The dikes are 200–400 feet thick in the schist and greenstone, but only 10–25 feet thick where they cross the somewhat more competent iron-formation; a few flare out and thicken again in the schist on the footwall side of the iron-formation.

Reverse faults, much younger than the cleavage faults just described, but similar in strike and dip, provide the third way in which the thickness of the iron-formation was increased at Iron Mountain. Large blocks of iron-formation appear to have moved up on these faults, particularly in the southern part of the ore body; however, it has not been possible to determine whether this faulting actually resulted in a net increase in the amount of iron-formation near the surface. The vast difference in age of the early and late faults at Iron Mountain is indicated by the fact that the younger faults cut granitic rocks west of Iron Mountain that were not intruded until after the basic Iron Mountain structural features had formed.

ORE BODIES

The main ore body of the district lies along the north trend of Iron Mountain, which crests about 500 feet above the valley of Rock Creek and is eminently well situated topographically for open-pit mining. (See figs. 27 and 28.) The structure of the body has been described in the preceding paragraphs. The body is depicted in three dimensions in figure 24. Three separate and structurally different parts can be distinguished: (1) an arcuate northern ore body (in sections *E* to *I*, fig. 24), which, though faulted, seems to have maintained its structural continuity and therefore may extend to great depth; (2) a small faulted-in ore body at shallow depth (east half of cross section *G*, fig. 24); and (3) a southern ore body, separated from the others by faults and a belt of schist, faulted internally, and of great width but limited depth (cross sections *A* to *D*, fig. 24). Because the several ore bodies are ribbed by metagabbro dikes, as indicated in figure 24 and because many minor schist bodies are sliced in by faults and infolded with the iron-formation close to its upper and lower contacts, the ore-gangue mixture necessitates close, daily supervision at the mining face to maintain a uniform mill feed.

FIGURE 27.—U.S. Steel Corp. iron ore mill viewed from the south. Iron Mountain in background on the right.

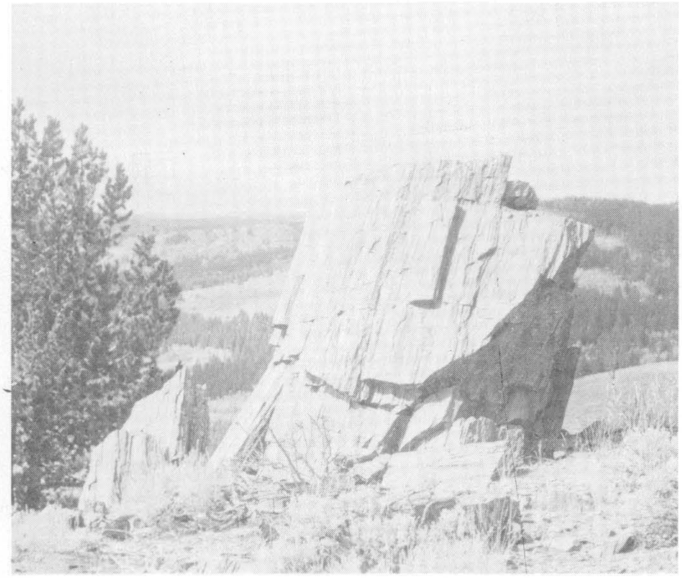


FIGURE 28.—Typical outcrop of plunging iron-formation on Iron Mountain.

Published tonnage and grade figures for this mine are as follows (Mining World, 1960):

121 million tons (25 to 32 percent Fe) proved reserves,

300 million tons (22 to 35 percent Fe) indicated ore.

A more recent report (Engineering and Mining Jour., 1965, p. 84) listed the proved reserves as 111 million tons (30 percent Fe).

Because of their small bulk, bodies of iron-formation in several areas northeast of Iron Mountain (fig. 24) would not have been considered as ore before the development at Iron Mountain, but these may now be classed as ore because of that development. These potential mine areas are believed to be owned by the U.S. Steel Corporation. The longer haul from these deposits to the existing mill south of Rock Creek would be the only added cost. The larger deposits crop out on hills and therefore are very suitable for open-pit mining. Together the potential mine areas will yield only millions of tons of iron-formation in contrast to the tens of millions of tons the mine is expected to yield at Iron Mountain, but properly utilized they will extend open-pit mining in this district by at least 3–5 years, assuming 3 million tons per year volume, and longer at a reduced rate.

IRON MINING

It is not known when or by whom the iron deposits were first discovered, but their location and extent have been a matter of public record since 1916 (Spencer, 1916). Because they are composed of low-grade magnetic iron-formation (taconite), their exploitation had to await the development of modern taconite technology and a favorable economy. In August 1962, the shipping of the first iron-ore pellets to Provo, Utah, from the U.S. Steel Corporation's Atlantic City project, marked the successful conclusion of nearly 8 years of exploration and development begun in 1954.

The iron-formation at Iron Mountain is mined from an open pit benched each 75 feet to maintain an overall 1:1 slope. Electric drills are used for blast holes, and electric 6-yard shovels load 45-ton diesel trucks, which haul the ore about 4,000 feet to the primary crusher plant. Cone crushers, rod mills, and ball mills reduce the ore until about 90 percent is smaller than 270 mesh. A straight magnetic separation is made in two stages over barrel-type magnetic cobbers with permanent magnets. The magnetic concentrate, about 65 percent iron and 9 to 12 percent silica, is pelletized and roasted. (See Engineering and Mining Jour. (1965) for mill details.)

The amounts of iron-formation (taconite) mined from the U.S. Steel Corporation's open-pit mine at Iron Mountain are as follows:

	Gross tons
1962	1,043,111
1963	3,782,488
1964	3,656,062

These figures indicate that the mine operated at about its reported intended capacity in 1963 and 1964 (Eng. and Mining Jour., 1965, p. 84); they indicate also that the mill operated at close to intended capacity for the same period and manufactured about 1.3 million gross tons of iron ore pellets per year (iron-formation to pellet ratio about 2.64).

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