Precambrian Petrochemistry of the Northern Park Range, Colorado, and Its Implications for Studies of Crustal Derivation

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U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1343

U.S. DEPARTMENT OF THE INTERIOR

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By GEORGE L. SNYDER, ELAINE L. BRANDT, *and* VERTIE C. SMITH

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Studies of sillimanite-grade Proterozoic rocks, particularly mafic and ultramafic intrusive bodies; local and statewide volume-weighted chemistry; and comparison of local crust-mantle chemical models with Earth crust-mantle chemical models

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PRECAMBRIAN PETROCHEMISTRY OF THE NORTHERN PARK RANGE, COLORADO, AND ITS IMPLICATIONS FOR STUDIES OF CRUSTAL DERIVATION

By GEORGE L. SNYDER, ELAINE L. BRANDT, *and* VERTIE C. SMITH

ABSTRACT

This report summarizes the geology, concentrating on the Proterozoic rocks, of a 1,280-square-mile (3,300-square-kilometer) area comprising the northern Park Range of northernmost Colorado. Techniques are developed that are applicable to crystalline rocks of many kinds in other areas. The summary is supported by study of more than 2,300 thin sections collected during some 20 man-seasons of field work between 1965 and 1976, by 66 new rock and 10 new mineral chemical analyses, and by 36 other published analyses of Park Range rocks.

The Precambrian rocks are about half sillimanite-grade, 1.8-billion-year (b.y.) -old metavolcanic and metasedimentary layered rocks, and half former magmatic rocks that intruded the layered rocks between 1.8 and 1.4 b.y. ago. The old layered rocks consist of 44 percent amphibolites, 37 percent felsic gneisses (both considered to be either volcanic rocks or sediments derived from a nearby volcanic source), 13 percent sediments (mainly metashales) from a chemical or distant clastic source, and 6 percent other or uncertain. In the last category are siliceous pod rocks containing 2–25 percent quartz-sillimanite-muscovite pods set in a matrix of quartz, oligoclase, microcline, biotite, and muscovite. Some of the pods are late metamorphic differentiates but others may be recrystallized relict primary structures of various types.

Metamorphism of the old layered rocks proceeded in three stages:

1. Progressive regional dynamothermal metamorphism (1.8–1.7 b.y.);
2. Static, purely thermal regional metamorphism (1.7–1.4(?) b.y.), during which many mineral species formed poikiloblastic crystals of great fragility;
3. Geographically localized dynamic metamorphism (1.4(?)–1.2 b.y.).

Thermal peak (550°-700°C, 1.7 b.y.) metamorphic mineral assemblages in metashales that have excess alumina are regionally arranged in increasing grade from one small area of a sillimanite-staurolite-muscovite assemblage, through successive broad areas of sillimanite-muscovite and sillimanite-muscovite-potassium feldspar assemblages, to three small maxima of a sillimanite-potassium feldspar assemblage. One tiny portion of the lowest grade area contains all three aluminum silicate polymorphs in equilibrium with staurolite and muscovite. Two areas of chloritoid schists outside of the lowest grade staurolite-containing zone are believed to be compositionally controlled. Wherever aluminous metashales of sillimanite grade occur, clinopyroxene, garnet, and scapolite are found in intercalated mafic or calc-silicate rocks. Rocks of a rare third composition (high Mg, low Ca) contain anthophyllite and gedrite. Cordierite occurs in some representatives of both aluminous metashales and anthophyllite-gedrite rocks, giving the area some aspects of both Barrovian- and Abukuma-type facies series (but no exact match for either). The regional pattern of isograds bears no simple relation to the areas or contacts of preorogenic or synorogenic gabbroic, quartz monzonitic, and quartz dioritic intrusive bodies.

Tables summarize 190 theoretically possible contact relations between each of 20 recognized types of Precambrian intrusives. Most of these separate intrusive types are grouped in three main rock series:

1. 1.8-b.y. gabbro of Elkhorn Mountain in the northwest part of the area, originally intruded in separate but contiguous inhomogeneous batches and now consisting of:
   a. Peridotite rafts(?) in olivine gabbro containing coronas around olivine (6 percent);
   b. Gabbros (60 percent; normatively containing olivine but modally free of olivine) to diorite (33 percent);
   c. Late, volumetrically minor basalt dikes.
2. 1.7-b.y. quartz monzonite of Seven Lakes in the northern half of the area; 1.7-b.y. quartz monzonite of Buffalo Pass in the southern half of the area (these first two occurring in about equal proportions); and undated, volumetrically minor quartz diorite of Gilpin Lake, locally gradational with quartz monzonite of Seven Lakes but possessing chemical affinities (possibly due to assimilation) with gabbro of Elkhorn Mountain. (Details of plagioclase distribution in different quartz diorite bodies suggest some unique sequential intrusive history.)
3. 1.4-b.y. quartz monzonite porphyry of Rocky Peak, quartz monzonite of Roxy Ann Lake, and other phases of the Mount Ethel pluton in the middle of the northern Park Range.

All the intrusive rocks except this last series, which is believed to be younger than the thermal-peak assemblage described above, show visible mineral modification due to metamorphism.

Volumetrically minor pegmatites, miscellaneous mafic intrusives, and small, isolated peridotite bodies resist organization in the above categories, but metamorphic remobilization and recrystallization have affected many of these rocks too.

Corona minerals, developed by reaction between olivine and plagioclase in olivine gabbro and peridotite, generally occur in parallel layers or shells in the following order:

1. Olivine
2. Comb orthopyroxene (perpendicular to olivine contact)
3. Clinopyroxene
4. Light-colored clinoamphibole
5. Clinoamphibole-spinel symplectite (symplectite bodies perpendicular to plagioclase contact)
6. Plagioclase

For example, electron-probe analysis of one small websterite body showed the following succession:

1. Hyalosiderite
2. Bronzite
3. Fassaite
4. Pargasite
5. Pargasite-pleonaste symplectite
6. Bytownite

A detailed survey of 1:48,000 Park Range maps and of unmapped traverse observations and the assignment of relevant rock analyses to four major times of crustal increment have greatly improved our understanding of the changes in weighted Park Range chemistry in the 1.8- to 1.4-b.y. time period. The average composition of Park Range rocks has never strayed far from a low-silica granodiorite (60–64 percent SiO_2; normative plagioclase An_{41-50}), despite some inputs much different from this. When Park Range analyses are applied to a detailed statewide survey of exposed rocks of similar age (excepting the Uncompahgre Formation), a similar result is obtained. Average Colorado rocks have been slightly more silicic and slightly less mafic than average Park Range rocks at comparable times in their history, and alumina and alkali contents of these two rock types have been roughly comparable. Like the Park Range analyses, the statewide values cluster near a composition of low silica granodiorite (SiO_2 62–66 percent; normative plagioclase An_{35-48}). If the Precambrian crust of either the Park Range or Colorado as a whole were melted completely, and stirred thoroughly, it would supply a rhyodacitic or quartz latitic magma.

Average Park Range Precambrian and average Colorado Precambrian compositions are compared with worldwide averages for Precambrian shield, continental crust, and lithosphere compiled from the literature. As might be expected, both the Park Range and Colorado averages are most comparable with the shield average. Similarly, the average composition of Park Range peridotite (46 percent SiO_2, 26 percent MgO) is close to the average of 11 separate estimates of upper mantle composition (45 percent SiO_2, 38 percent MgO) compiled from the literature. From the above data, seven chemical models are constructed to test the chemical constraints necessitated by derivation of various average crusts of known thickness from various average mantles. It is shown that, given the K_2O values of the respective models and after correction for the Earth's sphericity, the minimum thicknesses of the model mantles required to derive the specified thicknesses of the model crusts after an average partial melt of about 3 percent range from 376 to 1,580 kilometers. These estimates assume that the mantle could be completely purged of K_2O in the crust-forming process. Similar limiting conditions are imposed successively by Na_2O, Al_2O_3, and other compounds (assuming that earlier limiting conditions have been met in some way), and calculations are made and a graph is provided to facilitate similar calculations with any model. For all the models chosen, unrealistic mineralogy limits partial melts to a maximum near 25 percent, and the course of differentiation of the progressively depleted mantle residuum is toward normative olivine and away from normative plagioclase and pyroxene (especially away from normative orthopyroxene). Similar results would be expected for any other reasonable crust-mantle chemical models, thus casting doubt on models that require an increase in orthopyroxene in depleted mantle residua.

INTRODUCTION

This report, based on field studies completed between 1965 and 1976, examines the implications of petrographic and chemical descriptions of Park Range Precambrian rocks not dealt with in several previous reports by the senior author. It builds on these preceding reports and should be used in conjunction with them to fully understand the petrochemical nature and problems of the area. Detailed geologic maps and cross sections of the area have been published (Snyder, 1980a, 1980b, 1980c). Adjoining areas of Precambrian rocks have been mapped by Steven (1954), Houston and others (1968), and Karlstrom (1977) to the northeast, and by Divis (1976), Houston and Ebbett (1977), Houston, Karlstrom, and Graff (1979), and Graff (1978) to the north. The Colorado geologic setting is shown on the summary maps of Ogden Tweto (1976a and b, 1978, 1979). The intrusive rocks in the central third of the area of this report, particularly the 1.4-b.y. Mount Ethel pluton, are discussed in detail in Snyder (1978) and are therefore touched only briefly in the present report. The general and economic geology of the northern two-thirds of the area is discussed in Snyder and others (in press). Northern Park Range radiometric geochronology by Carl E. Hedge and Charles W. Naeser is described in Segerstrom and Young (1972) and in Snyder (1978; 1980a, b, and c). Additional geochronology in nearby areas is summarized by Bickford and others (1982), Bowring and Condie (1982), Condie (1982), Divis, (1976, 1977), Edwards (1981), Hills and Armstrong (1974), Hills and others (1968), Hills and Houston (1979), Peterman and Hildreth (1978), and Premo and Van Schmus (1982).

Geographic localities of rock samples mentioned in the text are shown on figure 1. The geology and the distribution of key metamorphic minerals are summarized on plate 1. A final appendix of this report describes both petrochemical procedures and nomenclature, and also lists, in seventeen appendix tables, petrographic and chemical analyses of rocks and minerals from the Park Range and some pertinent comparative analyses from the literature. Spectrographic data are summarized in table 4 of Snyder and others (in press). Mount Zirkel, possibly the best known topographic feature in the area, from which the Mount Zirkel Wilderness is named, is shown in figure 2. (See also Snyder and others, in press, figs. 2, 13, and 16.) Typical, almost "signature" poikilitic textures in metamorphic rocks are shown on plate 2. Classification and nomenclature of typical mafic and ultramafic rocks are shown in figure 3, and of quartzofeldspathic rocks in figure 27. (Although more nomenclatural discussion is presented in the appendix, the reader should note here that the Streckeisen (1973, 1976) phaneritic classification is used throughout, except for the undifferentiated plagioclase-rich half of the granite field, for which the traditional U.S. term "quartz monzonite" is preferred. This term is synonymous with "adamellite," which is used in other English-speaking countries and the U.S.S.R.)

The senior author's petrographic studies of Precambrian rocks of the Park Range have involved the repeated examination of some 2,000 thin sections of samples collected over a period of more than a decade. Paul Graff kindly made available the thin sections he had used in his thesis study of the West Fork Lake 7 1/2-minute quadrangle (Graff, 1973) and also provided his petrographic observations. Also available were 149 thin sections of specimens collected by John Hill in the Big Agnes Mountain area (Hill, 1969) and 195 thin sections of specimens collected by Kenneth Segerstrom and Edward J. Young in the Hahns Peak and Farwell Mountain 7 1/2-minute quadrangles (Segerstrom and Young, 1972; Young and Segerstrom, 1973). The textural observations and mineral identifications for all these thin sections (plate 1*B*, for example) are by Snyder. Peter A. Drobeck performed point counts for some of the petrographic analyses, as credited in tables B2, B6, B8, B10 and B12. The late Louise S. Hedricks provided the photomicrographic illustrations in this report.

Co-authors Brandt and Smith are responsible for the high quality rock (and some mineral) analyses listed in tables B1–B12. Snyder probed the mineral compositions for one peridotite (table B17) and is also responsible for all mathematical calculations involving these and other analyses, as well as for the conclusions based on these calculations.

GEOLOGY AND PETROCHEMISTRY

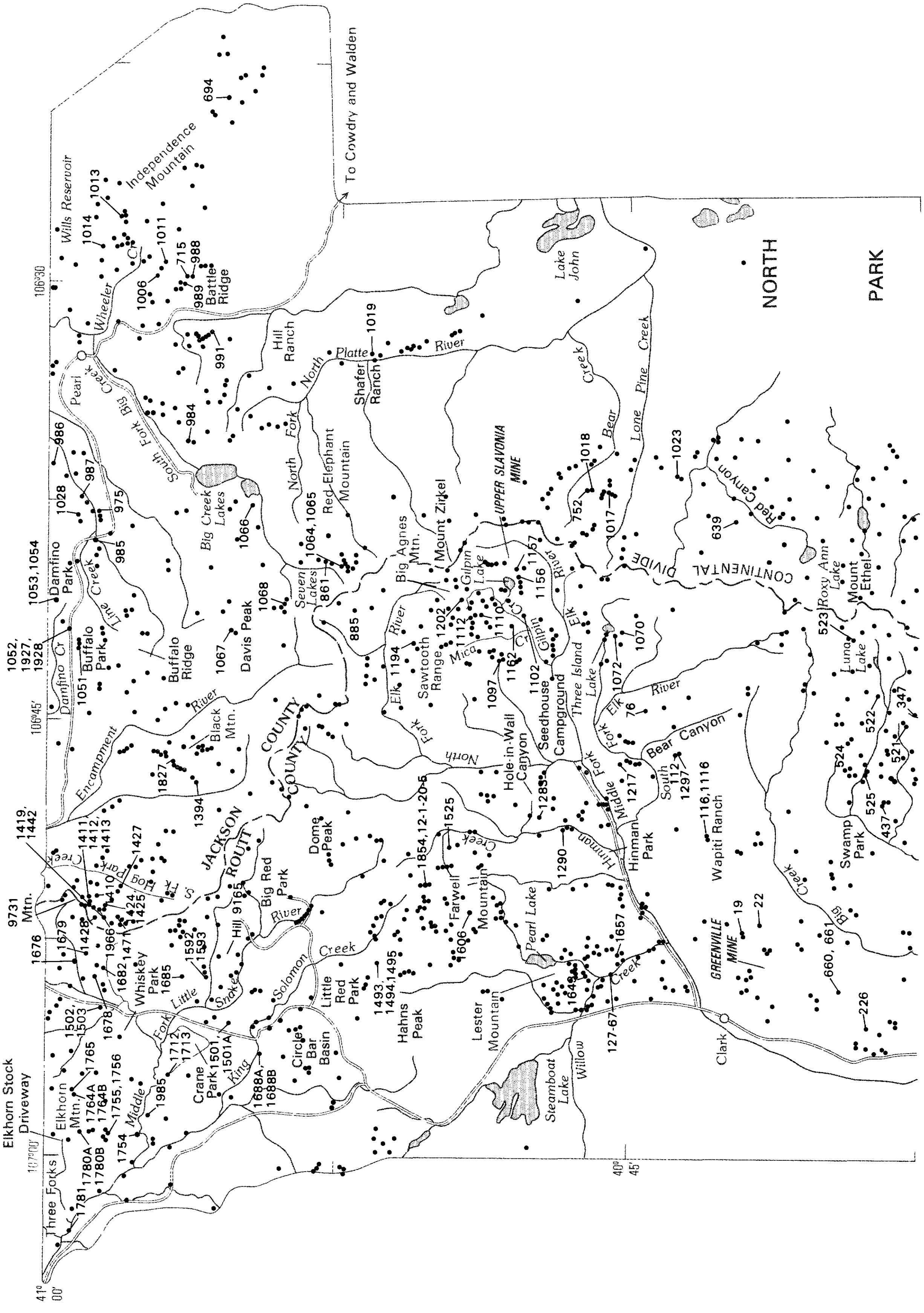
The oldest Precambrian rocks of the Park Range originally consisted of water-deposited and massive (subaerial?) volcanic rocks and water-deposited sedimentary rocks of conventional composition, and these were intensely metamorphosed and intruded by other rocks during a long, complex subsequent history. Because the metamorphism involved recrystallization at a high grade, most primary features have been masked or obliterated. However, both the mineralogy and chemistry of these layered metamorphic rocks give clues to their origins, and enough primary features have been recognized in these high-grade rocks to be sure of at least some progenitors. Previously recognized primary features include intrusive igneous textures (figs. 15, 18, 19, 29, and 31; and Snyder 1978, figs. 6 and 7) and contacts (figs. 21 and 25; Snyder, 1978, figs. 5, 6, 8, 10, and 11; and Snyder and others, in press, figs. 6, 7, 10, and 11); pillows (in an area of many mines south of Pearl (William Gunter, American Selco, Inc., oral commun., Feb. 28, 1980) and along the Whiskey Park–Hog Park road); conglomerate (Segerstrom and Young, 1972, p. 9, 12) and agglomerate structures on Farwell Mountain; crossbedding in the quartzite of Willow Creek (fig. 5; and Segerstrom and Young, 1972, p. 14); compositional layering some of which probably reflects original sedimentary layers (figs. 5 and 8; and Snyder and others, in press, fig. 5); and some highly enigmatic pod or pisolite rocks, which may owe their origin to concretionary processes of mixed sedimentary and metamorphic origin (figs. 5 through 12; and Snyder and others, in press, fig. 6). The mineral symbols used in all the photomicrographs that follow are defined in table 1.

METAVOLCANIC AND METASEDIMENTARY ROCKS

The oldest rocks in the northern Park Range are part of a sequence of metavolcanic and metasedimentary rocks that were accreted onto the southern margin of an ancestral Archean North American continent 1.8 b.y. ago (Condie, 1982, fig. 1, p. 38). These Proterozoic layered metamorphic rocks, almost exactly half of the Precambrian rocks exposed, consist of mainly metabasaltic amphibolites to metadacitic hornblende gneisses, and subordinate aluminous, calcareous, and siliceous metasedimentary rocks (originally shales, limestones, and quartzites respectively) (figs. 4, 5, and 6). Intercalated felsic gneisses, locally prominent, are compositionally similar to either arkoses or rhyolitic tuffs, but so far no diagnostic primary features have been discovered. The antecedents of rare high-magnesium, low-calcium rocks

TABLE 1.— *Mineral symbols used on all photomicrographs in this report*

Symbol	Mineral name	Symbol	Mineral name
Al	Allanite.	OA	Orthoamphibole.
An	Anorthite.	Ol	Olivine.
AnCA	Anorthite-clinoamphibole symplectite.	OP	Orthopyroxene.
Ap	Apatite.	Pa	Pargasite.
B	Biotite or any dark mica.	Pi	Pinite (sericite after sillimanite).
Ca	Carbonate.	Pl	Plagioclase.
CA	Clinoamphibole.	Q	Quartz.
Ch	Chlorite.	Se	Sericite (after plagioclase).
ChCA	Chlorite-clinoamphibole intergrowth.	Serp	Serpentine (after olivine).
Chr	Chromite.	Si	Sillimanite.
CP	Clinopyroxene.	Sph	Sphene.
D	Diopside.	Spi	Spinel.
E	Epidote.	Sy	Symplectite of pargasite and spinel.
FH	Ferrohastingsite.	V	Vesuvianite.
Fr	Fluorite.	W	Wollastonite(?).
G	Garnet.	WCA	Wollastonite(?)-clinoamphibole intergrowth.
He	Hematite (after sulfide).	Z	Zircon.
Hole	Hole in thin section.		
K	Potassium feldspar.		
La	Labradorite.		
MI	Magnetite-ilmenite.		
Mu	Muscovite.		


To Cowdry and Walden
NORTH PARK
Independence Mountain
Wills Reservoir
Wheeler Cr
Battle Ridge
Lake John
Hill Ranch
North Platte River
Shafer Ranch
Pearl
South Fork Big Creek
North Fork
Red Elephant Mountain
Big Creek Lakes
Seven Lakes
Bear Creek
Lone Pine Creek
UPPER SLAVONIA MINE
Big Agnes Mtn.
Mount Zirkel
Gilpin Lake
Gilpin Cr
Mica Cr
Red Canyon
CONTINENTAL DIVIDE
Roxy Ann Lake
Mount Ethel
Luna Lake
Damfino Park
Damfino Cr
Buffalo Park
Line Creek
Buffalo Ridge
Davis Peak
Encampment River
Black Mtn.
JACKSON COUNTY
ROUTT COUNTY
Sawtooth Range
Elk River
North Fork Elk River
Seedhouse Campground
Three Island Lake
Hole-in-Wall Canyon
Middle Fork
South Fork Elk River
Bear Canyon
Hinman Park
Hinman Creek
Wapiti Ranch
Swamp Park
Big Creek
Dome Peak
Big Red Park
Hog Park Creek
S. Fk Hog Park Creek
9731 Mtn.
Whiskey Park
Hill 9165
Little Snake River
Solomon Creek
Little Red Park
Farwell Mountain
Pearl Lake
GREENVILLE MINE
Hahns Peak
Lester Mountain
Crane Park
Circle Bar Basin
King Creek
Middle Fork Little Snake
Elkhorn Mtn.
Elkhorn Stock Driveway
Three Forks
Steamboat Lake
Willow Creek
Clark
106°30′
106°45′
107°00′
41° 00′
40° 45′
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1014
1011
715
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1780B
1781

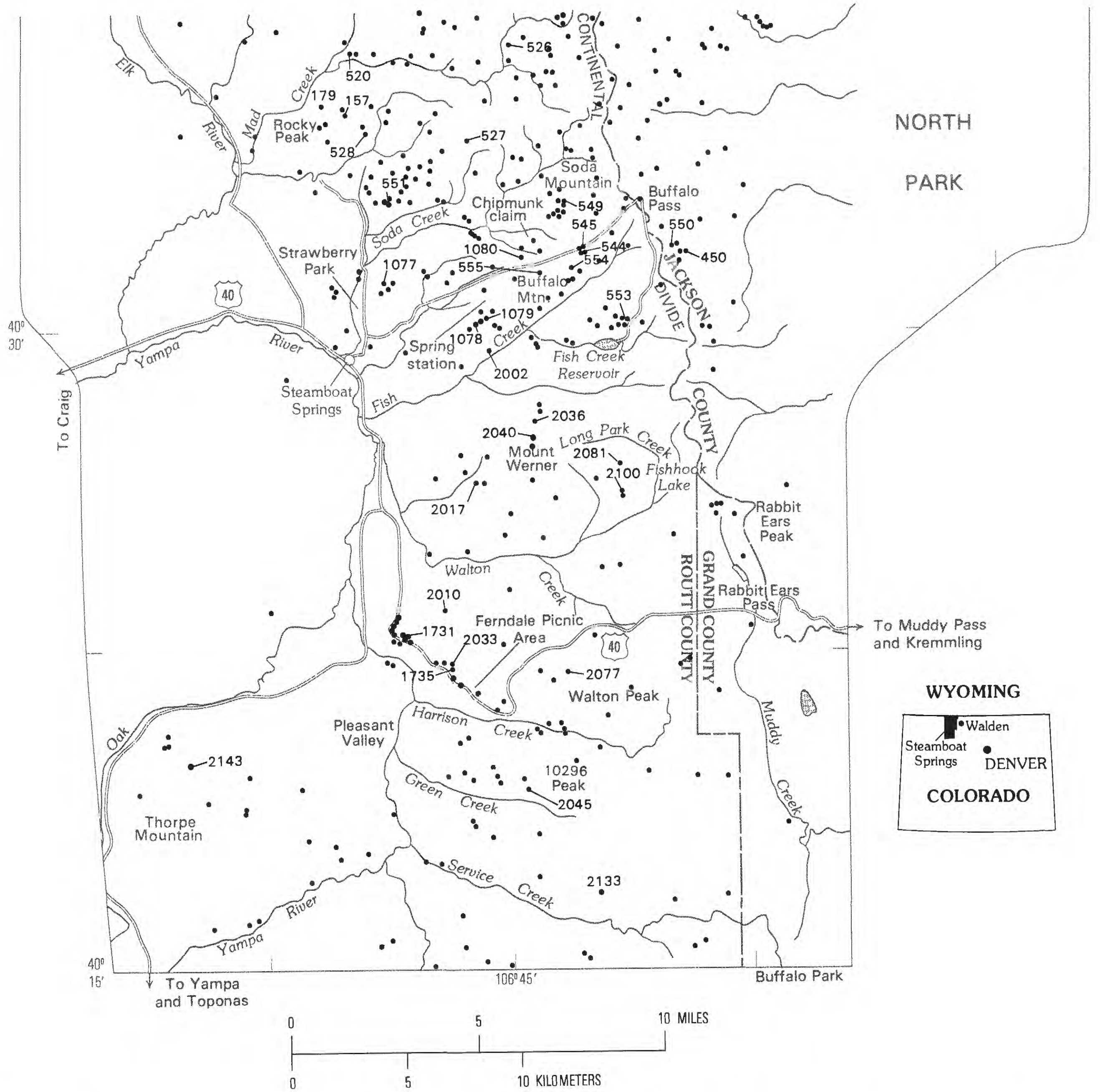


FIGURE 1.—Index map of the northern Park Range showing location of studied area, geographic names, and rock-sample localities (dots). Sample numbers are shown for rock samples mentioned in text.

FIGURE 2.—Mount Zirkel as viewed from the west from the lower slopes of Big Agnes Mountain. The mountain consists of interlayered metavolcanic and metasedimentary rocks intruded by quartz monzonite of Seven Lakes.

occurring mainly in the northern half of the area (plate 1*E*) are totally unknown. All of these rocks have been described in other reports: Snyder (1978, 1980a, b, and c), and Snyder and others (in press); typical petrography is summarized in Snyder (1978, table 4, p. 19), and detailed petrographic data on many representative samples are available in the appendix tables and under the descriptions of individual minerals in the section to follow on metamorphism. The compositional field of these layered rocks spans almost the entire quartzofeldspathic diagram (fig. 27), and many of them contain more quartz than most observed intrusive igneous rocks. Most metasedimentary or metavolcanic Park Range rocks have chemistry bracketed by the following extremes: 52–79 percent SiO_2, 12–20 percent Al_2O_3, 1–19 percent mafic oxides (much higher for amphibolites and calc-silicate rocks), and 2–8 percent alkalies (tables B5, B9, and B11). Most critical metamorphic mineral assemblages occur in the rocks that have excessive alumina, calcium, or magnesia.

CHARACTERISTICS AND ORIGIN OF SILICEOUS POD ROCKS

One metavolcanic or metasedimentary rock type of striking appearance will be discussed in more detail here: the siliceous pod rock (figs. 7–12, tables B11, and B12; Snyder and others, in press, fig. 6C). These rocks crop out in a belt trending southwest from Independence Mountain, through Big Agnes Mountain and the eastern part of Hole-in-Wall Canyon, to Lester Mountain and the canyon of Willow Creek, but most of the outstanding examples occur in the northeastern part of the belt within 6 miles (10 km) of Pearl (Snyder, 1980b). Similar rocks are located in a 2-mile (3 km) -wide belt along the northwest margin of a quartz monzonite batholith from Pleasant Valley to Walton Creek (Snyder, 1980c). More is presently known about the composition of these rocks than about their origin, although it is thought that similar-appearing structures have developed in several ways.

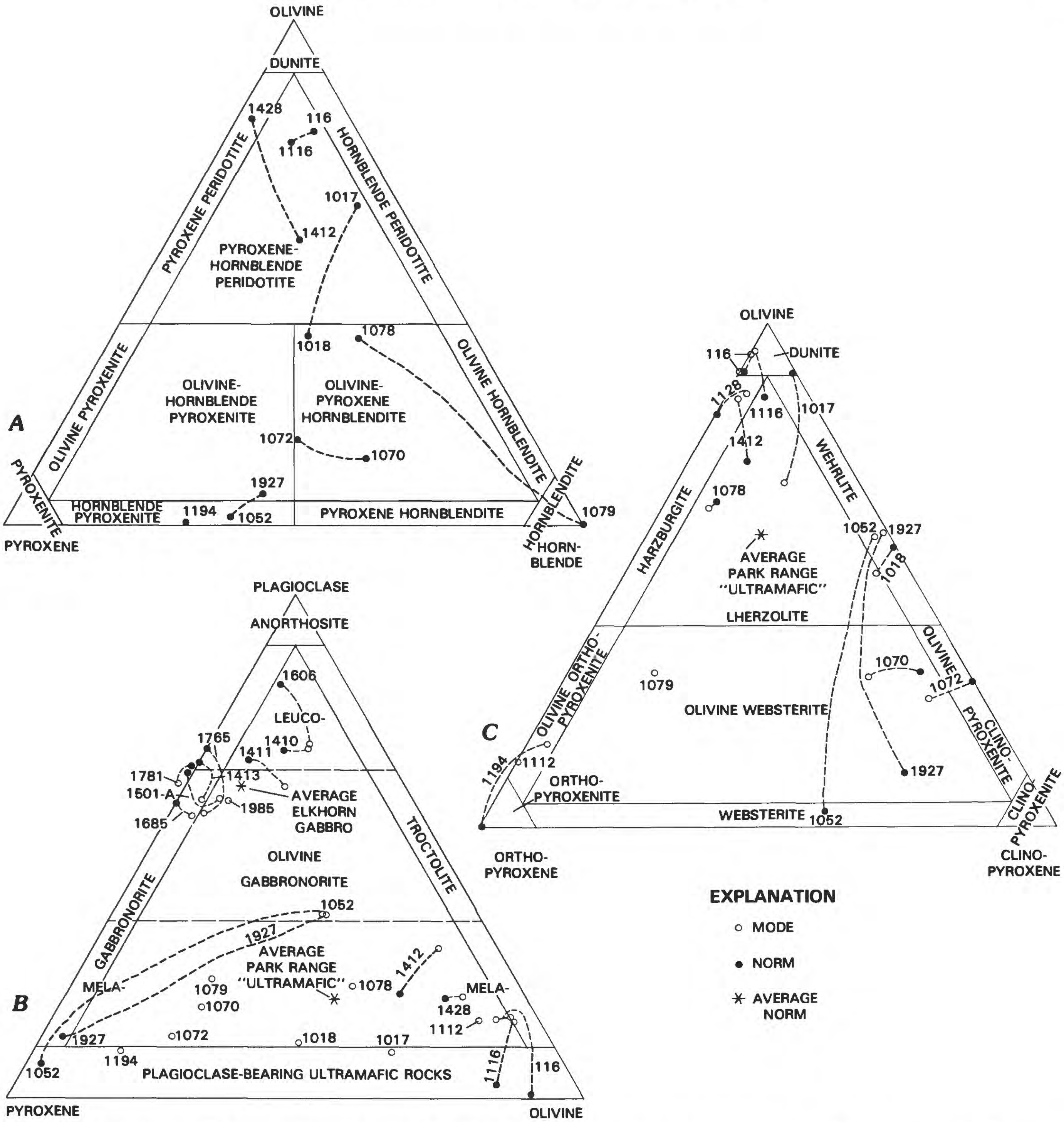


FIGURE 3.—Classification and nomenclature of analyzed mafic and ultramafic rocks of the northernmost Park Range, Colorado, as recommended by the IUGS Subcommission on the Systematics of Igneous Rocks (Streckeisen, 1973, 1976, figs. 2a, 2b, 3a). Note that all rocks containing the Al_2O_3 in amphibole(s) are less mafic normatively than modally, thus complicating the classification procedure. The averages plotted are those computed in the twelfth columns of tables B1 and B3. Note that the average amphibole-containing ultramafic rock in the Park Range is normatively an olivine melanorite near lherzolite.

A, Classification of amphibole-containing ultramafic or near-ultramfic rocks. Tie lines connect rocks from related exposures. All amphiboles here lumped as "hornblende."

B, Classification of mafic rocks. Tie lines connect modal and normative plots of the same rock where it is possible to plot each. Note the two populations of rocks as exemplified by the plotted averages.

C, Classification of ultramafic or near-ultramafic rocks. Tie lines connect modal and normative plots of the same rock where it is possible to plot each.

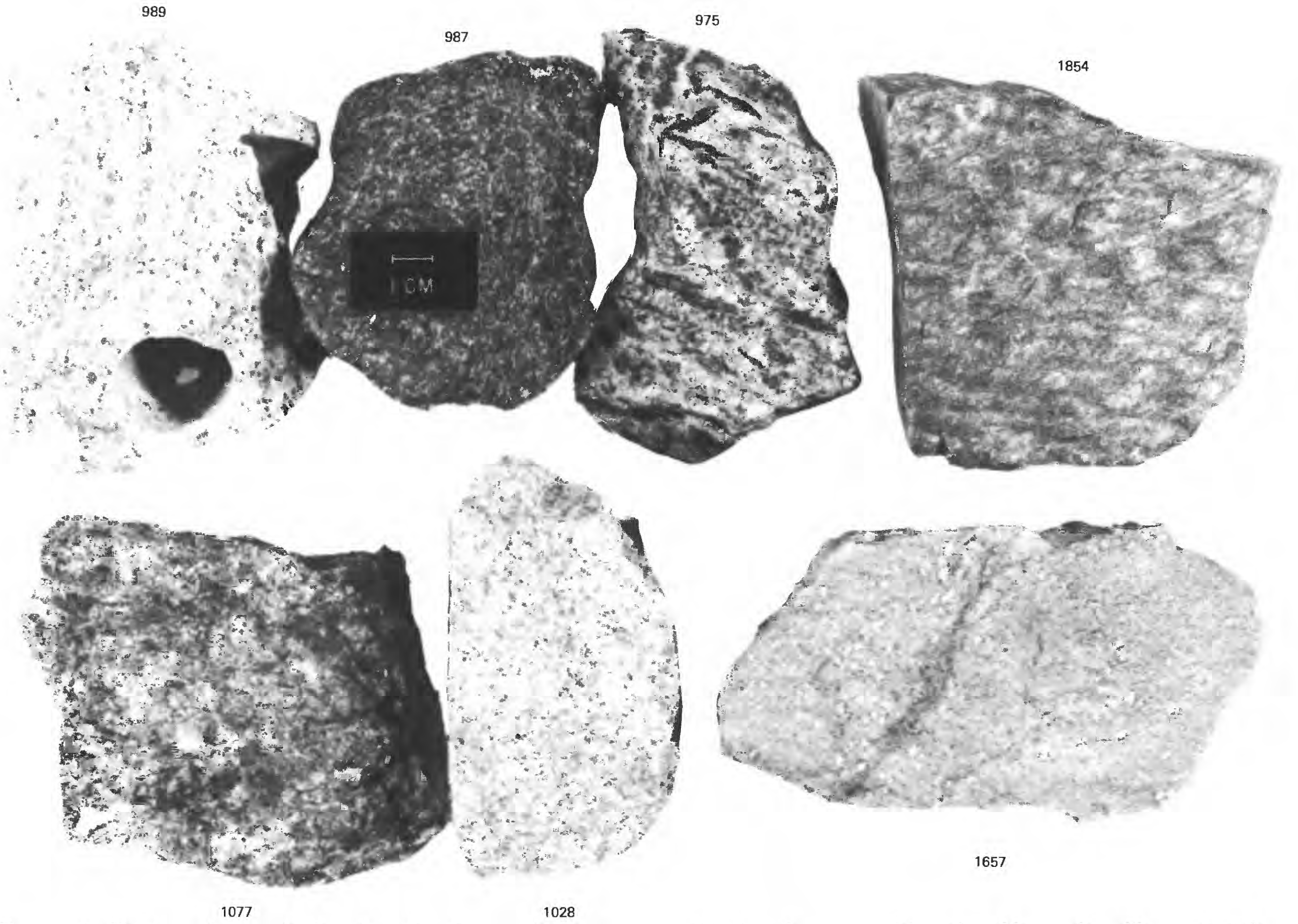


FIGURE 4.—Hand specimens of selected analyzed metasedimentary-metavolcanic rocks, arranged in order of increasing silica content from top left to bottom right (24.81 to 77.33 percent SiO_2). Photo by Louise S. Hedricks.

SAMPLE DESCRIPTIONS

989, Calc-silicate marble from Independence Mountain (tables B9, B10).

987, Amphibolite from Line Creek (tables B5, B6). See figure 6*A* for thin section.

975, Gedrite rock from Line Creek (tables B5, B6). See figure 6*C* for thin section.

1854, Pisolite rock from Farwell Mountain (tables B9, B10). See figure 6*D* for thin section.

1077, Pelitic schist of Soda Mountain from Strawberry Park (tables B9, B10).

1028, Layered, fluorite-containing metamorphosed alkali rhyolite from north of Line Creek (tables B5, B6). See figure 6*H* for thin section.

1657, Pod rock from Farwell Mountain (tables B9, B10).

The siliceous pod rocks generally have dark, felsic, biotitic matrices and swarms of discrete lighter colored pods that range in maximum dimension from less than 1 mm (.04 in) to about 16 cm (6.3 in), averaging about 5 cm (2 in). Typically the matrix contains (in decreasing order) quartz, oligoclase, microcline, biotite, and muscovite; small amounts of garnet, sillimanite, and magnetite; and rare staurolite, gahnite, and pyrite. The average pod contains quartz, sillimanite, and muscovite; some have only the first two of these; others contain additional oligoclase, microcline, garnet, biotite or magnetite; and some have accessory zircon. Any one exposure is generally quite uniform in character of matrix (unlayered or faintly layered) and in spacing, size, shape, and composition of pods, but there is much variation between different localities. Pods make up a few percent to as much as 25 percent of the rock; they generally are not in contact with one another. Contacts with the matrix may be either smooth or irregular and generally appear sharp in outcrop, but in thin section the margins are seen to

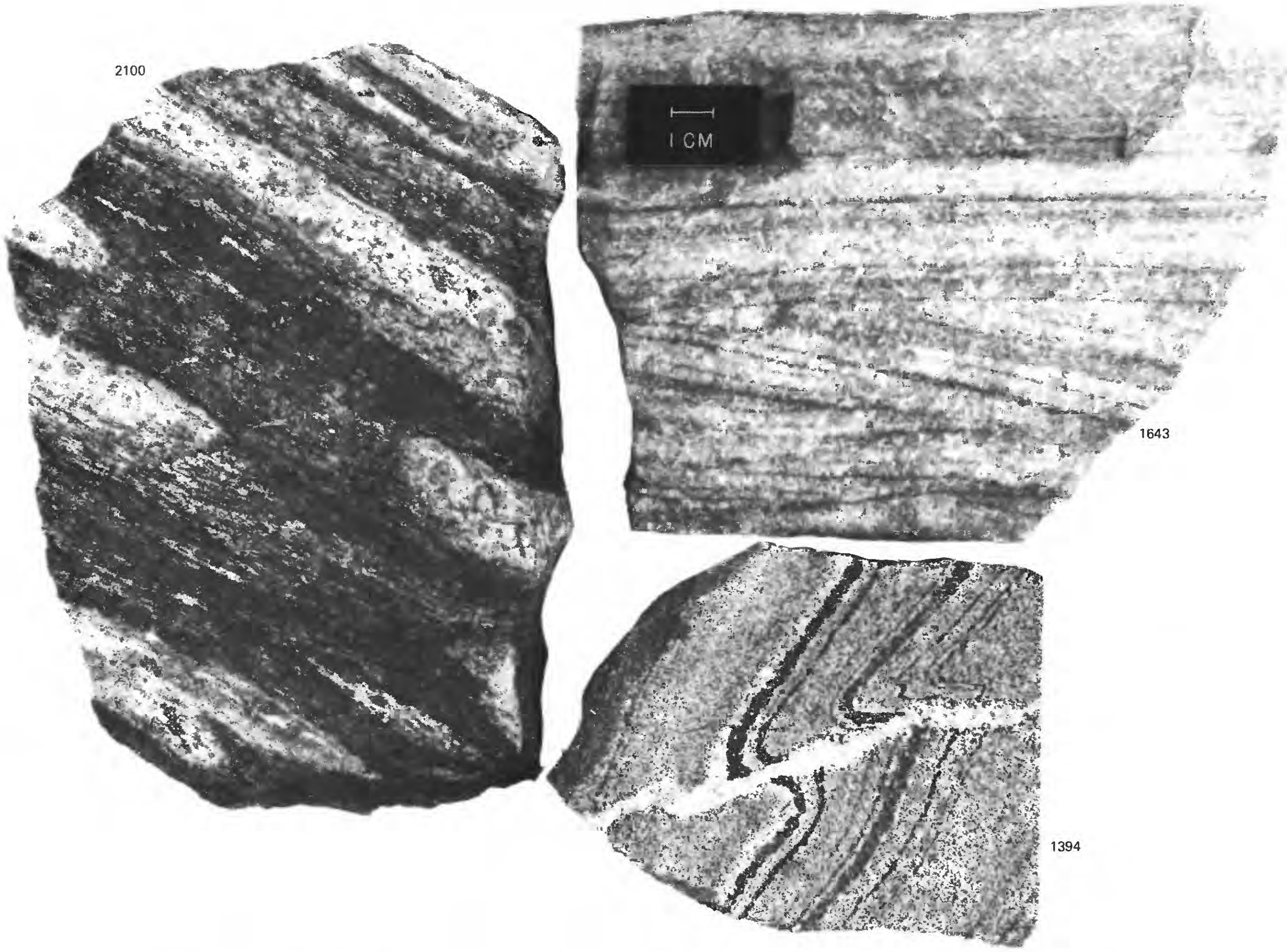


FIGURE 5.—Hand specimens of typical layered metasedimentary rocks. Photo by Louise S. Hedricks.

SAMPLE DESCRIPTIONS

2100, Pod rock consisting of calc-silicate pods in an amphibolite matrix from 4.4 miles (7.0 km) west-northwest of Rabbit Ears Peak. Rock may represent metamorphosed limestone concretions in a water-deposited basaltic ash.

1643, Crossbedded quartzite of Willow Creek (tables B9, B10).

1394, Folded layered felsic amphibolite cut by small pegmatite from west slope of Black Mountain. Rock may represent metamorphosed andesitic or dacitic water-deposited ash.

be gradational over a millimeter or so. Shapes are highly variable, as figure 7 and table 2 illustrate.

Most pods are internally structureless but all of the following internal structures have been observed in some pods:

1. Sillimanite swarms that have a preferred orientation across muscovite grains and grain boundaries within pods, across entire pods, or across both pods and matrix.
2. Sillimanite, muscovite, or biotite arranged in concentric rings within or at margins of pods or in matrix at pod margins.
3. Sillimanite prisms radiating from the centers of pods.
4. Internal muscovite in the form of a single poikilitic crystal, usually containing sillimanite swarms (this is common on Independence Mountain), the sillimanite swarms being oriented preferentially or randomly within the pods.
5. Garnets in some pods but not in others nearby.
6. Garnets that have halos or atolls of light-colored minerals around them.

Externally, pods may be elongated parallel to lineation, foliation, or faint layering in the matrix, or they may be at an angle, even perpendicular, to these features,

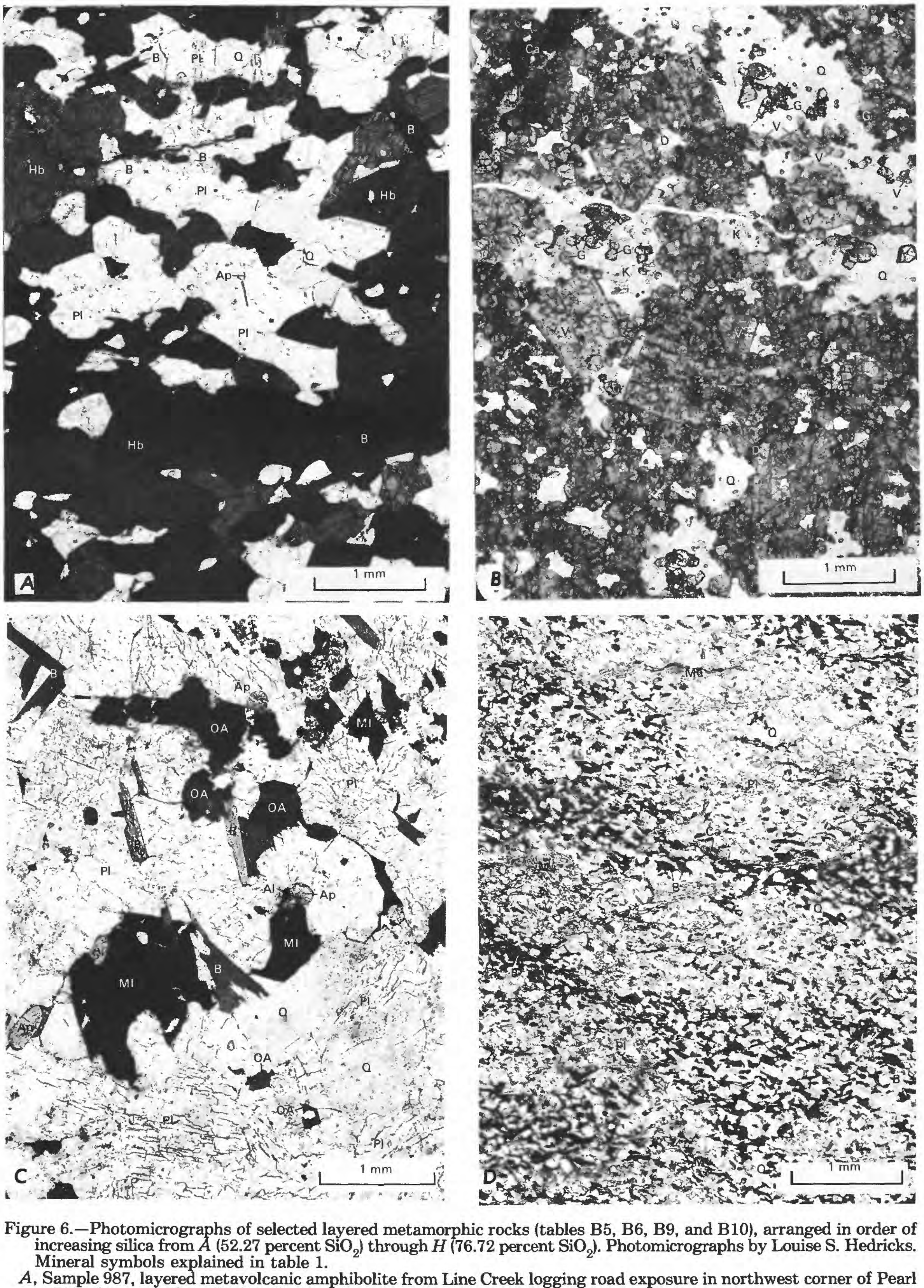


Figure 6.—Photomicrographs of selected layered metamorphic rocks (tables B5, B6, B9, and B10), arranged in order of increasing silica from *A* (52.27 percent SiO_2) through *H* (76.72 percent SiO_2). Photomicrographs by Louise S. Hedricks. Mineral symbols explained in table 1.

A, Sample 987, layered metavolcanic amphibolite from Line Creek logging road exposure in northwest corner of Pearl 7½-minute quadrangle. See figure 4 for hand specimen.

B, Sample 1065, vesuvianite marble from west side of Red Elephant Mountain. Areas labeled as garnet (G) also contain many tiny diopside crystals.

C, Sample 975, gedrite gneiss from Line Creek road cut. See figure 4 for hand specimen.

D, Sample 1854, pisolite rock from northeast of summit of Farwell Mountain. Note preferential segregation of muscovites within and biotites on margins of pisolitic structures. For hand specimen see figure 4.

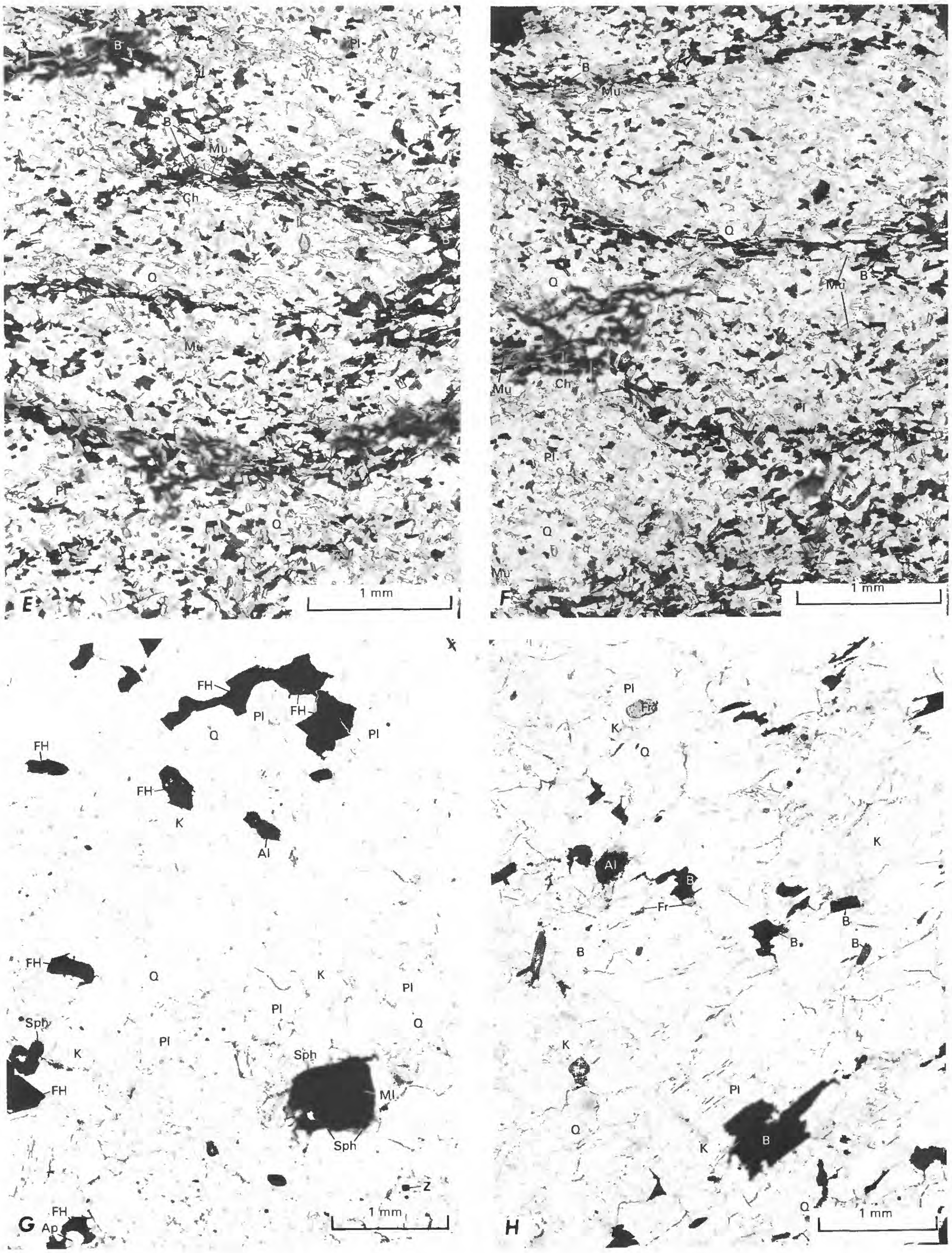


FIGURE 6.—Continued.

E, F, Two views of sample 12-1-20-5, pisolite rock from near sample 1854. Pisolites can be nearly equant or quite flattened in same rock. In this rock both micas are concentrated along pisolite margins.

G, Sample 1297, ferrohastingsite gneiss from south of junction of South Fork Elk River and Bear Creek. Chemical analysis of ferrohastingsite separate from this rock contained in last column of table B5. Optical data in text, in the "Metamorphic Minerals" section.

H, Sample 1028, layered biotite-fluorite gneiss from road cut between Line Creek and Buffalo Park. For photo of hand specimen see figure 4.

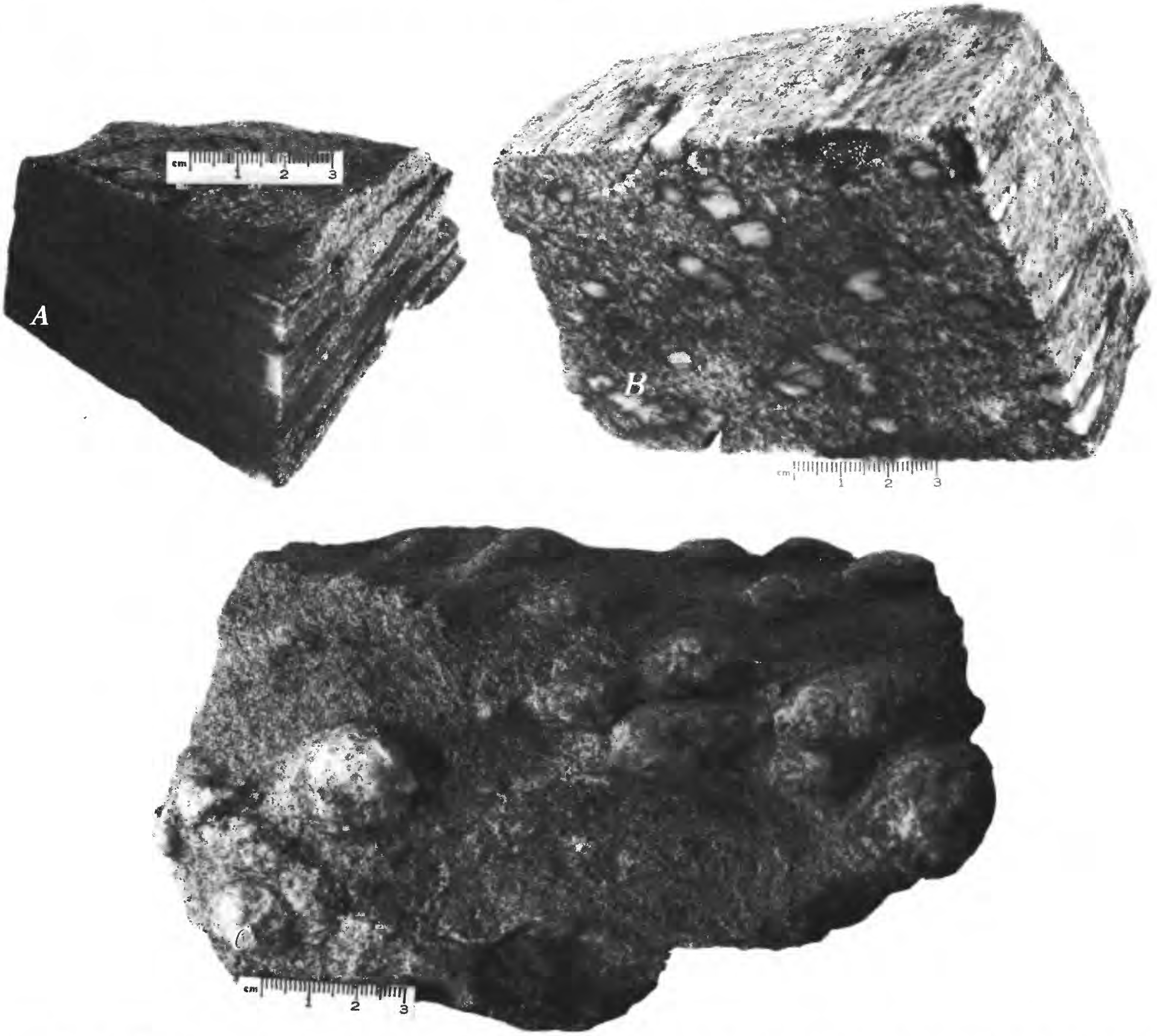


FIGURE 7.—Park Range siliceous pod rocks containing: *A*, Flat, discoid-shaped pods; *B*, Elongate, cigar-shaped pods; *C*, Football-shaped pods. Photographs by Louise S. Hedricks.

TABLE 2.—*Shapes of siliceous pods in analyzed rocks from the northern Park Range, Colorado*

Sample No.	Fig. Nos.	Percent pods	Average dimensions (centimeters)			Description
			Height	Width	Length	
715	9,10	23.3	2.5	3.5	>7	Small squashed footballs.
988	11--	3.2	1.5	1.5	10.5	Cigars.
1006	None	24.8	.5	1.5	4	Flat lozenges.
1014	9,12	2.7	2	5	>7	Large, elongate egg yolks.
1657	None	7.1	.1	.2	1	Sunflower seeds.

(for example, fig. 8). Several swarms of pods have been observed elongated parallel to fold axes, or flattened parallel to fold axial planes. Some pod swarms occur within pegmatites or crossing pegmatite boundaries. Some appear to have been pulled apart to form boudins.

Distinctive pisolitic rocks, possibly gradational with the pod rocks, were observed near the summit of Farwell Mountain (part of map unit Xca on Snyder, 1980b). The pea-sized segregations of the pisolitic rocks appear similar to the smaller pods of the pod rocks (compare samples 1854 and 1657 on fig. 4), but they contain more

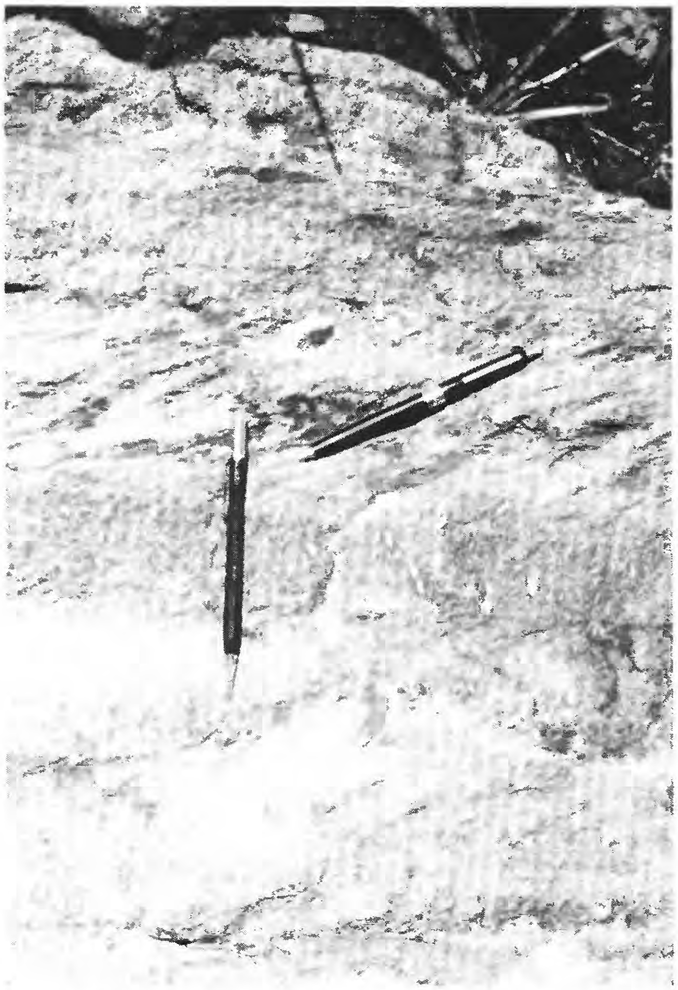


FIGURE 8.—Outcrop near north contact of quartzite of Willow Creek showing alternating metasedimentary layers that are more quartzitic (more resistant) or micaceous (less resistant). These metasedimentary layers are cut by micaceous cleavage that is refracted differently in different layers. It is perpendicular to the contacts (parallel to the pencil) in the quartzitic layers and at an acute angle to the contacts (parallel to the pen) in the micaceous layers. Note that white siliceous sillimanitic pods are elongate parallel to the pencil throughout all layers demonstrating that these pods grew in a thermal metamorphic environment after the completion of the dynamothermal metamorphism that formed the cleavages.

plagioclase than the pods and they lack sillimanite. The pisolitic structures have a greater content of granular minerals than the biotitic matrixes, and some have more muscovite (fig. 6). A pisolitic origin as volcanic mudballs is consistent both with these observations and with the further recognition of volcanic agglomerate structures in the same area.

Chemically, pisolitic rocks and pod rocks seem to be distinguishable in several important ways. (Compare data on tables B9 and B11.) Pod rocks contain 73 to 79 percent SiO_2, whereas pisolitic rocks contain 63 percent SiO_2. Pod rocks contain 12 to 13.5 percent Al_2O_3 versus 17.5 percent for pisolitic rocks. Pod rocks contain 1 to 6 percent mafic oxides versus 9 percent for pisolite rocks. Pisolitic rocks average 7.2 percent alkalies, which is near the upper limit of alkali content in pod rocks (3.5 to 7.6 percent). Park Range pisolitic rocks may be at lower metamorphic grade than that of most pod rocks, but this chemical evidence argues that pisolitic rocks are not identical with low-metamorphic-grade pod rocks.

Siliceous pod rocks of the types described are common at many places in the world. They have been reported in Russia by Gimmel'farb and others (1969), in Norway by Macaudière and Touret (1969), and in Rhode Island and eastern Connecticut by Feininger (1965) and Goldsmith (1967). Losert (1968) gives an excellent summary of nodular sillimanitic rocks; he cites localities in the Canadian, Baltic, African, and Siberian shields, the United States, and six areas of Europe. He quotes 15 different schemes of origin that have been espoused by more than 30 different authors. Losert claims the following generalities apply to nodular (pod) sillimanitic rocks (the starred items apply to the northern Park Range; the others, as far as is known, do not):

*1. Nodules form less than 25 volume percent of the nodular rock.
2. Nodules are irregularly distributed throughout the nodular rock.
*3. Nodular rocks, in many cases, are interbedded with nodule-free rocks.
*4. Matrix of nodular rocks consists of feldspars, quartz, and micas.
5. Matrix of nodular rocks may contain kyanite or andalusite.
6. No dispersed sillimanite occurs in matrix of nodular rocks.
*7. Transitional forms between ellipsoidal nodules, cigar-shaped rods, veinlets, and layers occur in many nodular rocks, all of them being similar in composition.
*8. Nodules consist dominantly of quartz and subordinate sillimanite, with or without muscovite.
*9. If present in pods, muscovite forms coarse poikiloblastic flakes or irregular aggregates.
10. Feldspars are lacking in the nodules. [They are generally lacking in Park Range nodules, but there are important exceptions.]
*11. Quartz, biotite, or muscovite form concentric nodule zones.
*12. In a given nodular rock the nodules are nearly constant in composition and similar in shape.
*13. Nodules may be elongated parallel or at an angle to primary or tectonic layering or to fold axes.
14. Biotite foliation of the matrix may enter the nodules and continue across them.

15. Potassium and sodium contents of nodules are much lower than those of matrix. [This is true for Na_2O in all analyzed Park Range samples and for K_2O in sample 1014, but it is definitely not true for the K_2O of samples 715 or 988.]

On Losert's graph of normative or + ab in matrix versus weight percent Al_2O_3 in nodules (Losert, 1968, fig. 7, p. 120) the Park Range rocks plot medially for or + ab and low for Al_2O_3, compared with the four dozen other examples Losert plotted. Losert concludes that "the formation of quartz-sillimanite nodules in metamorphic rocks is a special type of late metamorphic differentiation" (p. 121) and that "growth of nodules is post kinematic after the main tectonic movements and metamorphic crystallization has ceased" (p. 116).

It seems true that *some* Park Range nodules (such as those in fig. 8) are late metamorphic segregations. It is probable that nodules that display zoning or radial structures, that cross the layering, or that parallel the fold axes or axial planes are likewise late metamorphic segregations. But many nodules display no critical criteria. Could some be metamorphic alterations of granitic pebbles in oligomictic arkosic paraconglomerates or altered lithophysae in rhyolites? Both of these origins seem possible in the Independence Mountain area. Pods from samples 715 and 1014 resemble a muscovitic quartzite in composition, and pods from sample 988 resemble rhyolite or granite (fig. 27). Some nodules might even be derived from shale inclusions in intrusive or anatectic quartz monzonite; textures and geographic proximity make this seem probable in the area from Pleasant Valley to Walton Creek. All four of these suggested mechanisms may exist in the Park Range. It seems that several explanations are probable for similar-appearing representatives of this strange family of Park Range rocks.

METAMORPHISM

Metamorphism of the Precambrian rocks exposed in the northern Park Range proceeded in three probably continuous phases: First, a progressive regional dynamothermal metamorphism, during which tectonism and temperature both increased; second, static, purely thermal metamorphism throughout the area; third, localized shearing and cataclasis. During the first dynamothermal metamorphic phase the rocks were intruded first by mafic batholiths and later by quartz monzonite batholiths and smaller plutons, and were folded, sheared, deformed, and recrystallized at amphibolite grade. Isoclinal folds were extensively developed, and these involved not only the layered rocks but also many bodies of granite and quartz monzonite. Heat was supplied in a variety of ways: by exothermic reactions, radioactive decay, internal friction, and introduced magma bodies. Enough heat was available to raise the regional temperature to 550°-700°C and to begin the recrystallization of all rocks involved. That the process was a long and complex one seems clear from the evidence of remobilization of intrusive rocks of

FIGURE 9.—Siliceous pod rocks from Independence Mountain. Photomicrographs (*B–E*, facing) by Louise S. Hedricks. Mineral symbols explained in table 1. For analyses, see tables B11 and B12.

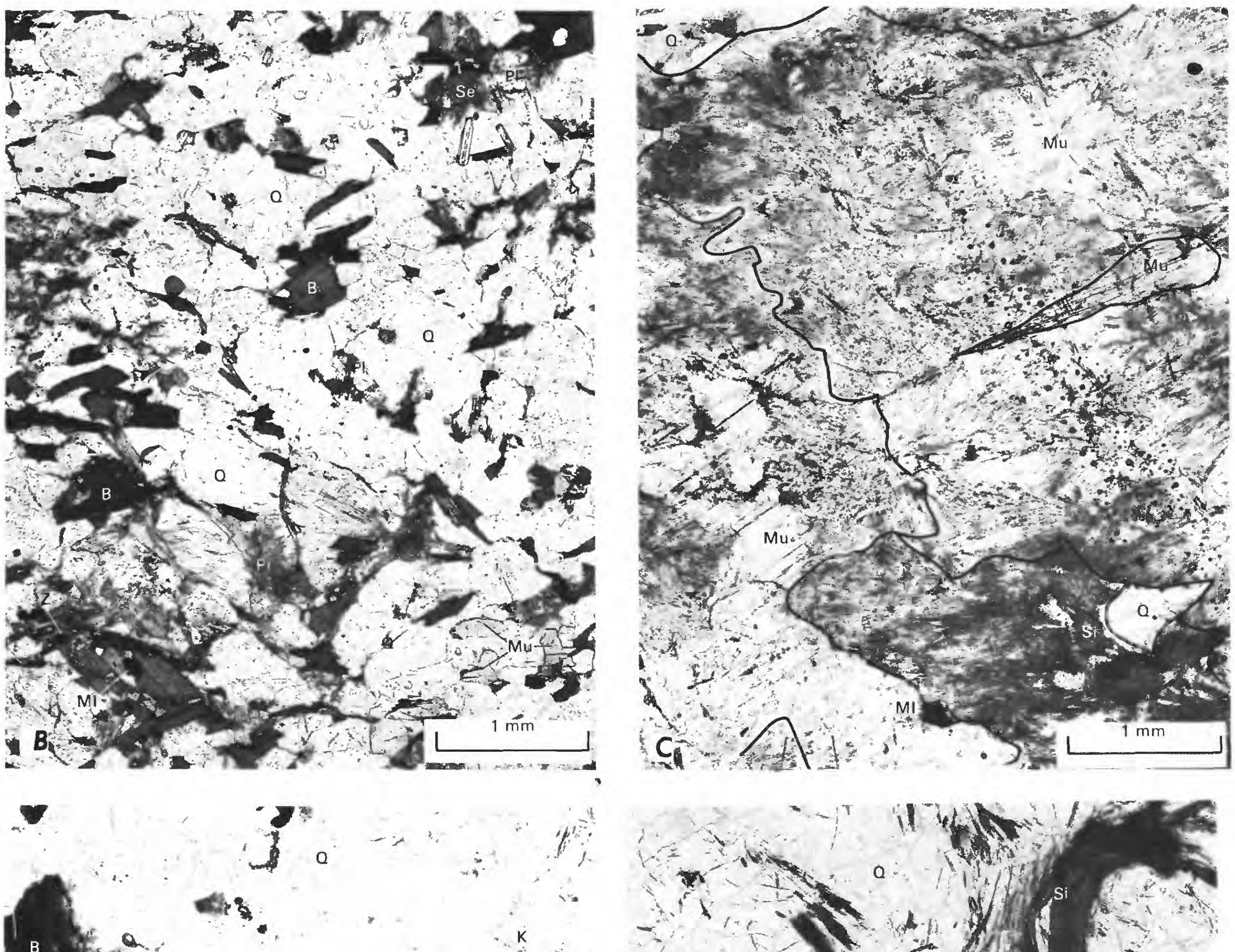
A, Typical field exposure of siliceous pods in felsic matrix on point 1¼ miles (2 km) S. 10° E. of junction of South Fork of Big Creek and Wheeler Creek southeast of Pearl.

B, Sample 715, matrix of siliceous pod rock, from Independence Mountain placer-ditch exposure east of Battle Ridge.

C, Sample 715, pod. Lines enclose individual giant muscovite crystals having different orientations. Muscovites contain swarms of tiny sillimanite needles, most too small to label.

D, Sample 1014, matrix of siliceous pod rock (fig. 12) from top of Independence Mountain 1.1 mile (1.8 km) S. 30° W. from Wills Reservoir.

E, Sample 1014, pod F (fig. 12), dominantly tiny quartz grains and sillimanite sheaves without feldspars or micas.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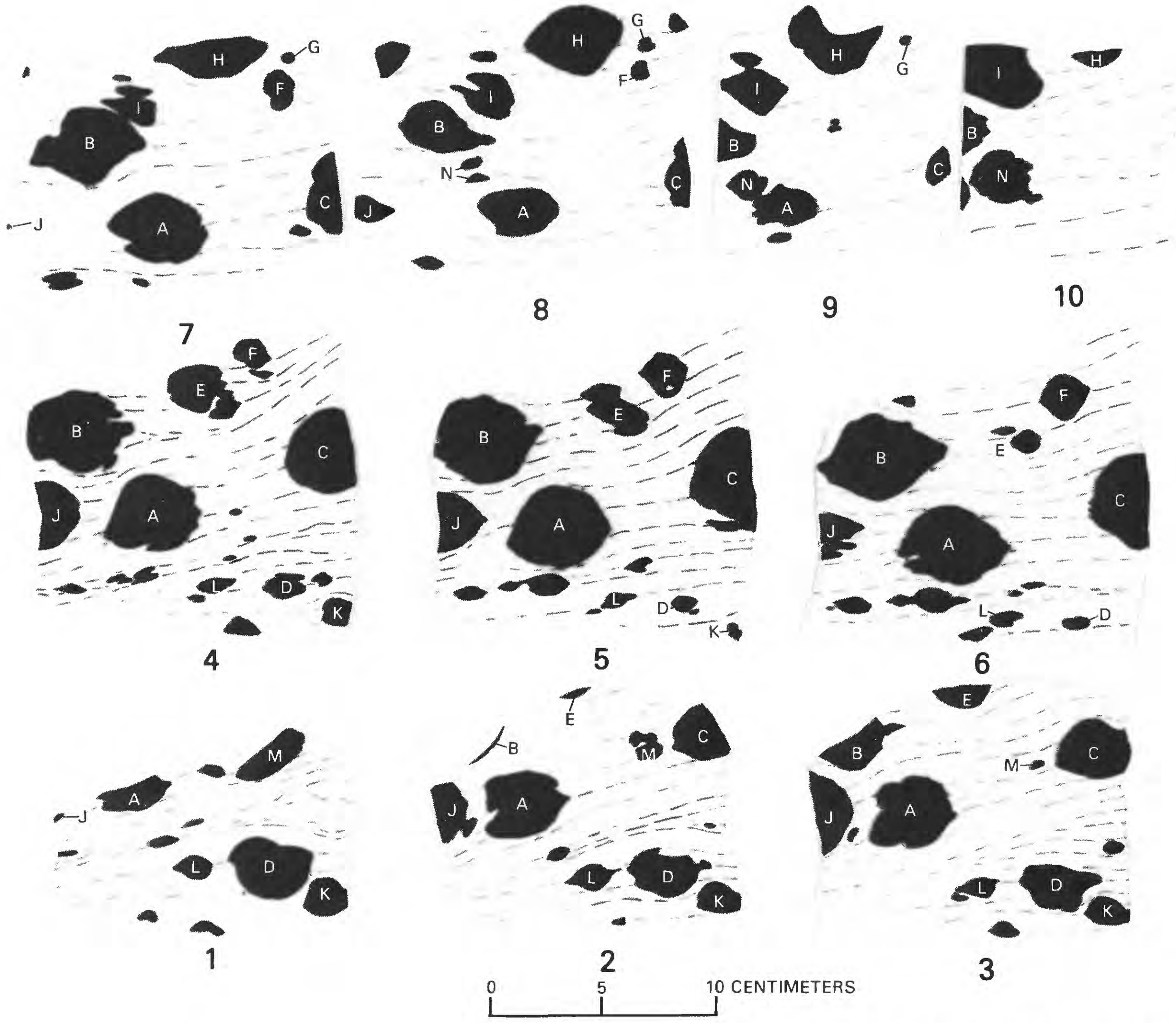

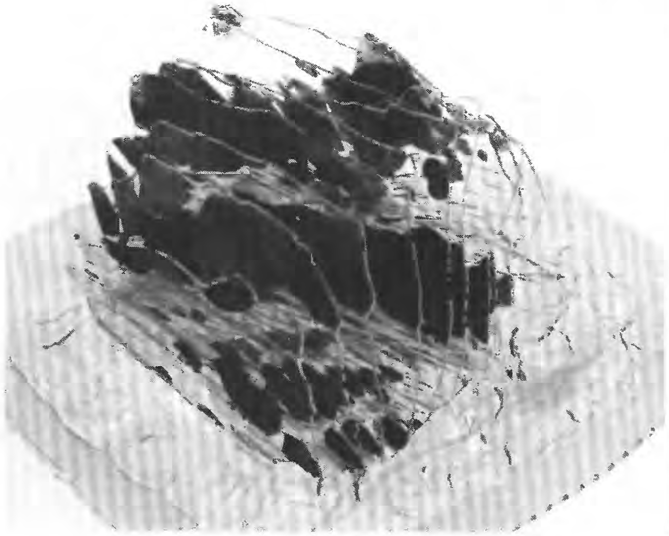

FIGURE 10.—Diagrammatic sections through Independence Mountain siliceous pod rock 715 (tables B11 and B12). Rock was sawed at ½-inch (1.3-cm) intervals and the slabs were sketched on rigid plastic sheets numbered sequentially from front to back in the model shown reassembled in the photograph at left. Letter labels added to facilitate tracing of particular pods through the rock. Analyses of pods A, B, and C given in tables B11 and B12. Pods C, D, K, and L easily traceable in front part of model in photograph. Average pod cross section is 2.5 x 3.5 cm (1 x 1.3 in.). Photographs by Louise S. Hedricks.

several compositions (fig. 25). It appears that 100 million years, the period from 1,800 (dated gabbro) to 1,700 m.y. (dated quartz monzonite), may have been available for this first dynamic heat-raising phase of metamorphism. (See also Edwards, 1981.)

There is little evidence preserved to indicate the balance between mechanical breakdown of mineral grains and nucleation and recrystallization during this

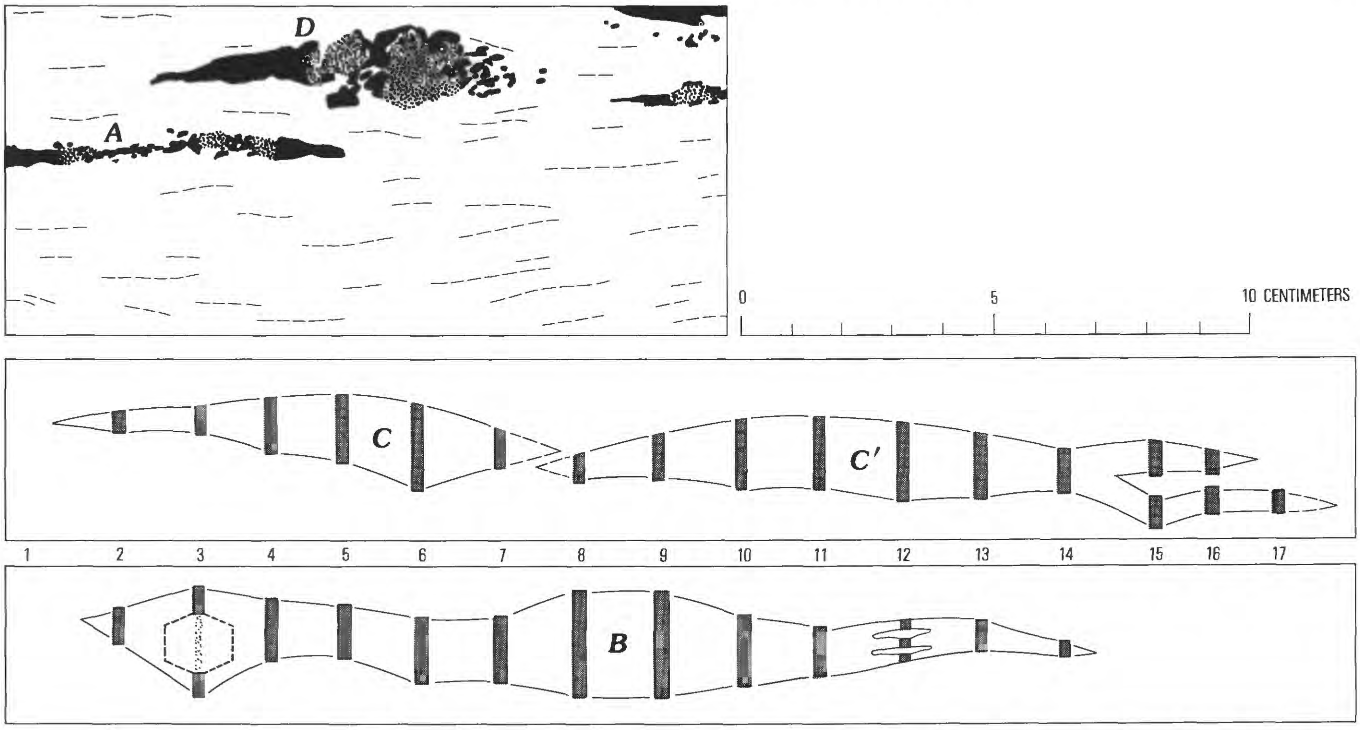

FIGURE 11.—Structure of siliceous pods in analyzed rock 988 (tables B11 and B12). Garnets shown dotted, other pod minerals solid. Top drawing is a tracing of saw cut 1, which is perpendicular to the two lower drawings of pods B, C, and C′, assembled from sawed slabs 2 through 17 (saw cuts shown by heavy lines). Note erratic location of garnet.

first phase. There *is* evidence to indicate that, prior to the peak of the regional metamorphism, tectonic movements essentially ceased and the second phase ensued—a long period of metamorphic mineral crystallization during which poikilitic crystals of great fragility were formed. These are preserved only because the rocks in which they occur were never again sheared significantly. The poikilitic crystals commonly grew across or replaced older igneous structures (for example, olivine-plagioclase contacts, figs. 18 and 19) or older metamorphic structures formed in the earlier dynamothermal phase (for example, the sillimanite pods in fig. 8, the muscovite poikiloblasts in fig. 13*A*, and the amphibole poikiloblasts on plate 2*C* and *F*). Sillimanite pods cross bedding or parallel fold axial planes at several localities on Independence Mountain, near Big Agnes Mountain, and near the quartzite of Willow Creek (fig. 8). Large muscovite crystals growing across foliation are common in metapelites. Examples include the area southeast of Buffalo Pass (plate 2*A*), the area southeast of Big Agnes Mountain (sample 1110), and the area north of the Ferndale Picnic Area and west of Rabbit Ears Pass (sample 2010). Large, crosscutting muscovite crystals are also found in many siliceous pod rocks on Independence Mountain (for example, fig. 9*C*).

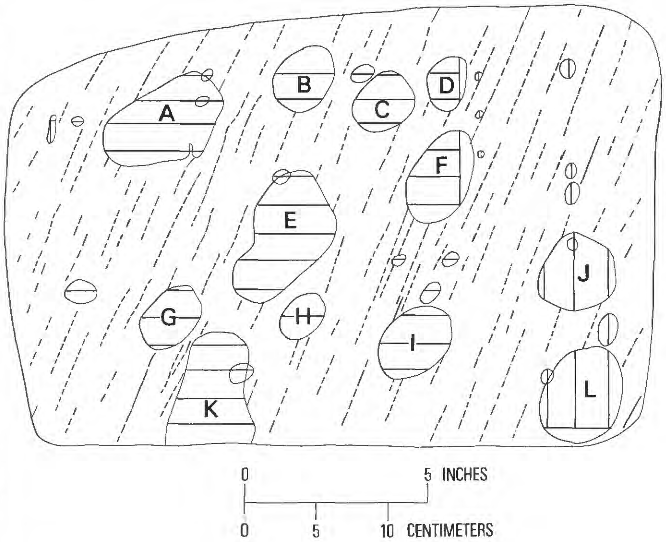

FIGURE 12.—Projection to a horizontal plane of all siliceous pods in a 4-inch (10-cm) thickness of vertically sawed analyzed rock 1014 (tables B11 and B12) from Independence Mountain. Faint rock lineation shown by dashes; saw cuts shown as solid black lines within pods. Some pods lettered for convenience. Analyses of pods A and E and a composite analysis of I and J are shown in tables B11 and B12.

A complete list of minerals that formed delicate, poikiloblastic crystals might include every metamorphic mineral in the range, but especially those in the following (alphabetic) list: andalusite, anthophyllite, biotite, chloritoid, cordierite, diopside, epidote, gahnite, garnet, hornblende, kyanite, muscovite, pargasite, plagioclase, potassium feldspar, quartz, scapolite, staurolite, sillimanite, tourmaline, and vesuvianite. Certainly tens and possibly hundreds of millions of years were available for the growth of such high-grade poikiloblastic and other more granular crystals and for the gradual decrease of metamorphic temperatures. The region may still have been at relatively high temperature when the Mount Ethel pluton was emplaced 1,400 million years ago. The lack of visible metamorphic effects of this pluton on its wall rocks suggests that the wall rocks may still have been relatively warm. (Peterman and Hildreth (1978) suggest that a large crustal block in central Wyoming was uplifted and cooled below 300°C perhaps as late as 1,400 m.y. ago. This block may have extended as far south as the northern Park Range.) As the heat dissipated and the regional temperature dropped, mild retrogressive effects were widespread in the Park Range and some rocks were severely affected. Biotite and garnet were partly chloritized, and sillimanite and plagioclase were partly sericitized.

Lastly, shearing and mylonitization took place in restricted zones 1 inch (2.5 cm) to 30 feet (9 m) wide in a few areas, chiefly between Soda Creek and the North Fork of Fish Creek, and on the northwest side of Farwell Mountain. In these thin zones, mechanical reduction of grain size was dominant over recrystallization. These thin mylonitic zones mark faults along which there has been left-lateral separation of at least 12 miles (19 km) (Snyder, 1978, p. 2). It is possible that this localized shearing began prior to 1,400 m.y. ago but not at high grade, since no new high-grade minerals have been found in any recognizable mylonite. It seems likely that most mylonites formed by transcurrent movements after 1,400 m.y. ago, perhaps 1,200 m.y. ago, as suggested for a similar shear zone to the east (Abbott, 1972). Similar shear zones in Colorado and southern Wyoming that have extensions to the northeast and southwest have been grouped together as "The Colorado Lineament" by Warner (1978). (See also discussions by Dutch, 1979, Hickman, 1979, and Warner, 1979a, b.) Shearing concentrated at the southeast margin of the Archean continent north of this area has been referred to variously as the "Mullen Creek–Nash Fork Shear Zone" (Houston and others, 1968), the "Cheyenne Belt" (Houston, Karlstrom, Hills, and Smithson, 1979; Mueller, 1982), the "Cheyenne Shear Zone" (K. E. Karlstrom, A. J. Flurkey, and R. S. Houston, written commun., 1982), and the "Wyoming Shear Zone" (Condie, 1982).

During the first, dynamothermal phase and continuing during the second, thermal metamorphic phase, most primary features were masked or obliterated. This change occurred without significant change in overall rock chemistry except for some chemical and mineralogic redistribution over a span of several millimeters or centimeters (as much as 16 cm) (for example, fig. 8 and plate 2*A*). Stanton (1976) and Stanton and Williams (1978) have shown that metamorphism at Broken Hill, New South Wales, took place in closed systems on the scale of a few millimeters and that sedimentary rocks were not significantly changed chemically during metamorphism. Similarly, La Roche's work (1974) with metamorphic rocks from Norway to Madagascar has indicated to him that the chemical changes instituted by regional metamorphism are small by comparison with the original sedimentary and magmatic effects on rock composition.

THERMAL-PEAK ISOGRADS

Most metamorphic rocks of the northern Park Range are sillimanite grade or amphibolite facies; presumably they crystallized at temperatures of between 550° and 700°C (Garlick and Epstein, 1967). This thermal history is evident not only from the abundance of sillimanite in many metashales throughout the area, but also from the presence of diopside, garnet, and (or) scapolite in many metamorphosed mafic or calc-silicate rocks (plate 1*D*). The isogradal surfaces are gently curved planes that show no simple relationship to the complex quartz monzonite contacts (plate 1*A* and *B*). The distribution of metamorphic minerals in these rocks (plate 1) indicates a progressive sequence of mineral assemblages. These assemblages date from the thermal peak (metamorphic phase two above), and are generally intermediate between Barrovian-type almandine amphibolite facies and Abukuma-type cordierite amphibolite facies (Winkler, 1965), even though there are several Park Range mineral assemblages that are inconsistent with either of these facies.

The isograds shown on plate 1*B* are only approximate, owing in part to the limited distribution of rocks of appropriate composition and in part to insufficient sampling. Their general shapes are probably correct, but future studies will lead to refinements in many areas. For example, no attempt has been made to depict offsets of isograds on post-metamorphic faults, although such offsets must occur. Future workers concerned with refining the isograds shown here should be cognizant of the following decisions or potential problems:

(1) The mineral assemblages on which the isograds were based are only found in pelitic schists (metashales) that have *excess alumina.* Generally, these are feldspar-quartz-mica schists that contain sillimanite or its

sericite pseudomorphs. Numerous plagioclase-quartz-biotite-muscovite schists, plagioclase-quartz-microcline-biotite schists, and plagioclase-quartz-microcline-muscovite schists occur in all metamorphic zones, but their compositions are not appropriate to produce the critical mineral assemblages. A few sillimanite schists contain neither muscovite nor potassium feldspar and are thus nondiagnostic.

(2) Only minerals that grew during progressive regional metamorphism are pertinent. Such minerals are as coarse or coarser than the other minerals of the rock and intergrown with them in textures indicative of simultaneous growth. Care must be taken to distinguish primary muscovite from aggregates of fine-grained retrogressive muscovite, sericite, or pinite that are present in many rocks as pseudomorphs after sillimanite. Potassium feldspar produced during retrogressive metamorphism occurs as tiny lenses or pods dilating biotite cleavages, accompanied by prehnite in a similar habit. This type of potassium feldspar is believed to be produced when nearby biotite alters to chlorite during retrogressive metamorphism. Fortunately the texture is distinctive and there is little danger of mistaking it for primary potassium feldspar.

(3) The areas on figure 3 shown as containing primary potassium feldspar are minimal. Future work will probably indicate that primary potassium feldspar occurs over somewhat larger areas. During the sericitization of sillimanite, potassium feldspar is consumed. Large quantities of primary potassium feldspar are thus preserved only in rocks that have minimal retrogressive effects.

(4) Isogradal boundaries in the Park Range are more gradational than in some other areas that have rocks of similar grade. In Connecticut, Snyder (1961, 1964) has shown that staurolite has commonly disappeared before sillimanite is stable. Not only are staurolite and sillimanite stable with each other in the Park Range (plates 1*B* and 2*B*), but they locally occur together with both kyanite and andalusite (plate 2*B*). This pattern is consistent with experimental results that show staurolite breakdown reactions on either side of the aluminum silicate triple point (Grew and Day, 1972, fig. 3, p. D155), indicating that fortuitous compositions and metamorphic conditions could permit the local stable existence of all four minerals. In many other areas there is a sharp transition from sillimanite muscovite rocks to sillimanite potassium feldspar rocks. In the Park Range there is apparently a wide zone between sillimanite-muscovite schist and sillimanite-potassium feldspar schists in which both muscovite and potassium feldspar are stable with sillimanite. This circumstance may be explained by one or more of the following factors:

a. Isogradal surfaces may be near horizontal rather than near vertical where transitions are rapid. However, isogradal surfaces do not correspond closely with topography in the Park Range.

b. Pressure, temperature, time, or other conditions of metamorphism may vary from area to area, causing a variation in the peak mineral suite or suites preserved.

c. Rock compositions vary through a wide spectrum, and the compositional controls here may differ from those elsewhere.

This latter explanation is preferred.

METAMORPHIC MINERALS

Besides the major minerals reported in plate 1*B* and many ubiquitous but volumetrically minor accessory minerals, these rocks contain a host of other minerals related to metamorphism. Many of these, as well as those from figure 3*B*, are discussed briefly in the alphabetical list below, and some specific localities are mentioned there or shown on figure 1 and plate 1*C*, *D*, and *E*.

Amphiboles.—Many varieties of this complex group of chain silicates exist in the northern Park Range. Common hornblende is the most abundant amphibole, especially in amphibolites. These rocks grade from pure hornblendite to felsic hornblende gneiss, but most contain nearly equal proportions of hornblende and plagioclase. Hornblende grades continuously into many other forms of clinoamphibole, including actinolite and (or) tremolite, ferrohastingsite (see fig. 6*G* for a photomicrograph, table B5 for a chemical analysis of one, and the next paragraph for some optical data on it), fluotaramite, edenite, tschermakite (see discussion in appendix A), and pargasite (see table B17 for analyses). Tiny amounts of tremolite and (or) cummingtonite are found locally in sharp contact with hornblende grains in amphibolites, but in coaxial position on the tips of these grains. Pargasite is most common in mafic and ultramafic rocks and is discussed in more detail in the sections on those rock types; some pargasite may be an igneous mineral[1], but much is certainly metamorphic. The orthoamphiboles—anthophyllite and its more aluminous solid-solution partner, gedrite—occur sparsely, but are more common in the northern half of the area (Snyder, 1980b; this report, plate 1*E*). Anthophyllite and gedrites range in color from green to a distinctive clove brown or gray, and they generally form distinctive splayed aggregates resembling turkey tracks in outcrop. In some schists and the rarer metamarbles

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[1] Some pargasites may be stable under upper-mantle conditions (Semet and Ernst, 1981, p. 74).

they are generally the only amphibole species (see the typical analyzed rock sample 975 in table B6 and fig. 6*C*) but in some altered peridotites they coexist with another clinoamphibole, usually tremolite (see analyzed sample 1112 in table B4). Anthophyllite-gedrite schist and common-hornblende amphibolite are interlayered along the dirt road above the mouth of Mad Creek; in this area the former rock is punky and nonresistant to weathering, and the latter is a resistant ledge maker.

Ferrohastingsite was separated from samples 112 and 1297, which were both from the same locality south of the South Fork of the Elk River. The ferrohastingsite from sample 1297 was analyzed (table B5; fig. 6*G*), and optical data were determined for ferrohastingsite from sample 112. With help from R. E. Wilcox and G. A. Izett, three different ferrohastingsite crystals were separated from sample 112 and mounted on a spindle stage, and indices of refraction were determined at 25 °C, as follows:

$X\wedge a=10°-12°$; $n_x=1.709-1.710$, light brown
$Y\wedge c=0°-18°$; $n_y=1.730-1.731$, deep green to blue green
$Z\|b$, $n_z=1.730-1.732$, deep olive green
Dispersion $\rho<<\nu$, very strong

$-2V_{(\alpha)}=5°-10°$ (estimated on one nearly uniaxial grain); 15° (estimated, maximum opening ¼ of microscope field on second grain); 29° (direct measurement on third grain).

Note that n_y (or β) is nearly to exactly parallel to *c* (not n_z (or γ) as in normal hornblende).

Andalusite.—This aluminum silicate is rare, being positively identified from only a half dozen localities (plate 1*C*); it is everywhere associated with muscovite, generally with sillimanite, and once with potassium feldspar. It also occurs in an equilibrium assemblage with sillimanite, kyanite, and staurolite (plate 2*B*). A typical schist containing andalusite (sample 639 from the west wall of Red Canyon) consists of (in order of decreasing abundance) quartz, brown biotite, garnet (much altered to green biotite), muscovite, plagioclase, cordierite(?) (all altered to sericite and a colorless isotropic mineral), sillimanite, andalusite (faint pleochroism from pink to colorless), zircon, and monazite(?). Andalusite occurs with potassium feldspar in a schist inclusion in quartz monzonite south of Walton Peak and 2 miles (3.2 km) southeast of the nearby 10,296-foot (3,138.2-m) peak (sample 2133); the schist consists of plagioclase, quartz, biotite, sillimanite, muscovite, orthoclase, andalusite, and magnetite and contains rare, completely altered cordierite(?) and accessory zircon.

Biotite.—Biotite is common in nearly all schists; there are many iron-rich varieties that range in pleochroic colors from brown to greenish brown (red titanium-rich varieties are very rare). These grade into lighter colored, more magnesium-rich phlogopites, especially in marbles and some ultramafic rocks.

Chlorite.—Most common as a product of retrogressive alteration, especially of biotite, garnet, olivine, or cordierite. It is not common as a primary progressive mineral, but primary chlorite occurs in some pelitic schists east and northeast of Strawberry Park, a few quartzite lenses north of Buffalo Pass, some amphibolites northeast of Pearl Lake (shown as "Lester Creek Reservoir" on some maps), some orthoamphibole rocks, and some metamorphosed peridotites (plate 2*E*). Nowhere is this primary chlorite an indication of greenschist facies. It is stable locally at sillimanite grade generally because of an unusually high magnesium rock composition.

Chloritoid.—This iron-aluminum silicate was observed in only two exposures, a ridge in the extreme northwestern part of the Farwell Mountain massif, and eastern Independence Mountain (plate 1*C*). Chloritoid is generally considered to be an indicator of low metamorphic grade. If so, the lowest isograd of plate 1*B* should perhaps be redrawn to include these exposures. The isograds have not been modified because sillimanite was observed near each chloritoid occurrence, suggesting that some subtle compositional variation controls the chloritoid. The assemblage near Farwell Mountain is quartz-muscovite-chloritoid-biotite-chlorite schist without feldspar (samples 1493 to 1495); that at Independence Mountain is plagioclase-quartz-muscovite-chloritoid-chlorite schist without biotite (sample 694).

Cordierite.—This magnesium-aluminum silicate occurs in two types of Park Range rocks, aluminous metapelites and magnesian anthophyllite-gedrite rocks, from medium to highest grade (plate 1*C* and *E*). It was previously recognized near Pearl (Read, 1903, p. 495, 496), but in the present study it was recognized in the field in only a single outcrop, where it had the diagnostic blue-violet ("grape juice") color. In thin section it displays polysynthetic twinning and has indices of refraction and birefringence similar to plagioclase, but can be distinguished from plagioclase in three ways: (1) It shows a greater tendency to alter retrogressively than plagioclase, and the alteration is of a distinctive type. Plagioclase generally becomes sericitized from the inside out, whereas cordierite preferentially alters from the margins inward to a mixture of sericite and either chlorite or an unknown nonmicaceous, isotropic mineral. (2) Yellow pleochroic halos form around tiny radioactive inclusions in some cordierite samples. These halos are unlike any others (and therefore diagnostic) where they occur, but they are rare or nonexistent in the cordierite in some rocks. (3) Polysynthetic twin lamellae in cordierite commonly are highly lenticular, and some sets of polysynthetic twins can abut at 30° angles.

Three typical pelitic assemblages are plagioclase-quartz-microcline-biotite-garnet-cordierite-sillimanite schist (sample 179 from west of Rocky Peak); quartz-biotite-cordierite-microcline-sillimanite-chlorite-muscovite schist with accessory magnetite, zircon, and monazite (samples 660 and 661 southeast of Clark); and quartz-cordierite-oligoclase-biotite-sillimanite (unusually coarse)-garnet-magnetite-clinozoisite-muscovite schist (sample 2017, 2 miles (3 km) southwest of Mount Werner). Anthophyllite-gedrite assemblages that contain cordierite are known from two places. Quartz-albite-anthophyllite-gedrite-staurolite-chlorite-biotite-garnet-magnetite granofels containing accessory zircon and apatite was collected from the 11,060-foot (3,371-m) elevation 2 miles (3 km) south of Seven Lakes; this rock contains more than 50 percent poikilitic twinned cordierite with pleochroic halos (sample 885). Cordierite also occurs in garnet-anthophyllite-gedrite-plagioclase-quartz-biotite-cordierite-magnetite schist (sample 1156) along the horse trail on the pass south of Gilpin Lake. This rock contains accessory rutile and apatite and rare spinel, which occurs as inclusions in garnet. The rock also contains late dilational potassium feldspar veins.

Epidote.—This common calcium-iron-aluminum silicate is widespread in most prograde or retrograde mineral assemblages in the northern Park Range. Clinozoisite or colorless aluminous epidote is most common in impure marble, whereas yellow-green ferriferous epidote (pistacite or piemontite) is found most commonly as an accessory in amphibolites and some quartz monzonites. There is no indication that epidote series minerals are indicators of metamorphic grade in these rocks.

Garnet.—This common pink to red to orange isotropic mineral is found in all but the most mafic rocks. It ranges from sharply euhedral to totally anhedral and poikiloblastic. Commonly it is helicitic. Aluminous rocks contain aluminous garnets, chiefly pyralspite (Winchell and Winchell, 1959, p. 486), and calc-silicate rocks contain the calcium garnets or ugrandite (Winchell and Winchell, 1959, p. 489), which commonly tends toward the orange end of the color spectrum. One analyzed garnet from siliceous pod rock 988 (table B11) calculates out as dominantly almandine containing small amounts of pyrope and spessartite and traces of andradite and grossularite. One coarse diopside marble (sample 2077, 1¼ miles (2 km) northwest of Walton Peak) contains small quantities of an unusual yellow-green garnet, possibly uvarovite.

Kyanite.—Despite an assiduous search, this aluminum silicate polymorph was found only in one small area of the canyon of Willow Creek. There it is associated with quartz, plagioclase, biotite, sillimanite, staurolite, muscovite, andalusite, allanite, and zircon (all shown in plate 2*B*) and with garnet, an unknown isotropic mineral, tourmaline, a sulfide mineral, aluminous epidote, sphene, magnetite, and dilational veins of potassium feldspar or a zeolite (not shown). The unknown isotropic mineral is clear to slightly yellow in thin section, is poikilitic, and is estimated from comparison with nearby thin-section minerals to have an index of refraction between 1.60 and 1.65; so far this description fits the sodium-calcium-zirconium silicate mesodialite, an intermediate species in the mineral series eudialite-eucolite, but more work is needed before this tentative identification is accepted. In addition, pyrophyllite has been reported in this vicinity (Segerstrom and Young, 1972, p. 13).

Muscovite.—This common potassium-aluminum silicate is present in many schists and pod rocks and in the more siliceous metamorphosed intrusive rocks. It occurs either interleaved with biotite or cutting across biotite books (for example, sample 2143 on the north side of Thorpe Mountain; also see plate 2*A*). It is apparently stable in all but the highest grade areas of plate 1*B*.

Plagioclase.—All members of the solid solution series from albite (part of the anthophyllite-gedrite assemblage in sample 885; see "Cordierite" section, above) to anorthite (Figs. 20*G* and *H*) are found. Plagioclase composition is controlled by rock composition and is apparently not related to grade of metamorphism. Much of the plagioclase in the metamorphic rocks is zoned; plagioclase zoning is clearly not a criterion for distinguishing metamorphic from igneous rocks.

Potassium feldspar.—Potassium feldspar is generally microcline but is locally orthoclase. It is anhedral or subhedral, commonly poikiloblastic, locally helicitic. Exsolution perthites are as common as uniform grains.

Pyrophyllite.—See comment under "Kyanite," above.

Pyroxene.—Several varieties of these chain silicates occur. The commonest is diopside, which is a key to sillimanite grade in mafic and calc-silicate rocks (plate 1*D*). In hand specimen, diopside rocks appear lighter green than hornblende rocks; in thin section, diopside ranges from clear and colorless to bright green, presumably according to its iron content. Clinopyroxene is also a rare constituent of corona shells in altered peridotites (figs. 19*A*, *B*, and *C*; analyses in table B17). The pure calcium clinopyroxene, wollastonite, occurs in equant grains associated with diopside and other calc silicate minerals in rare marbles northwest of Seedhouse Campground (Segerstrom and Young, 1972, p. 16) and on the west side of Red Elephant Mountain (sample 86, plate 1*D*); confirmed by X-ray analysis). Wollastonite(?) also occurs in curious clinoamphibole symplectites in altered gabbros between the South Fork of Hog Park Creek and Whiskey Park (figs. 20*C* through *F*, and plate 1*D*). Nonpleochroic orthopyroxene is common in corona reaction zones between olivine and plagioclase of olivine gabbros and peridotites (figs. 18 and 19; table B17). An analysis of an igneous enstatite and its metamorphic alteration products (plate 2*E*; table B4) is given in table B3, column 11.

Scapolite.—Scapolite is a key metamorphic mineral in sillimanite grade mafic and calc silicate rocks (plate 1*D*); scapolite in the Park Range is undoubtedly near meionite in composition because it always occurs associated with other calc-silicate minerals and calcite. Scapolite resembles white plagioclase and is seldom recognizable in hand specimen except in small veins in amphibolite where the scapolite crystals grow parallel to the vein contacts.

Sillimanite.—This most critical of metamorphic aluminum silicates is present either as sheaf-like bundles of fibers (fibrolite) or as coarse single prisms that have a single cross cleavage. It is commonly pseudomorphically altered to a white mica, here referred to either as sericite or pinite. Swarms of sillimanite needles or prisms may occur in quartz, feldspar, muscovite, garnet, biotite, or other minerals, apparently in equilibrium. Sillimanite is most common in aluminous rocks, here called metapelites or metashales, that range from highly micaceous rocks to mica-poor granular schists and granofelses. It is also very abundant locally in the siliceous pod rocks, as on Independence Mountain, south of Pearl, near Big Agnes Mountain, and between Willow Creek canyon and Pearl Lake (Snyder, 1980b). In these rocks, sillimanite, quartz, and muscovite form discrete pods of various shapes as much as 6 inches (16 cm) in diameter scattered randomly through a matrix of quartz, plagioclase, microcline and biotite; locally (as in sample 1157 from the ridge southeast of Gilpin Lake), microcline is concentrated in pods and sillimanite and muscovite are concentrated in the matrix. In either case, sillimanite and microcline are in contact near the margins of the pods, demonstrating equilibrium.

Spinel.—Two types of the spinel mineral series occur in rocks of the Park Range. Deep-green hercynite, pleonaste, or spinel (the mineral) occurs preferentially in symplectite intergrown with pargasite or clinopyroxene in corona shells in mafic and ultramafic rocks that lack quartz (figs. 18 and 19; see table B17 for a chemical analysis of pleonaste); it also occurs in quartz-rich schists in protective microenvironments (such as sample 1156, described under "Cordierite," above). The apple-green zinc aluminate spinel, gahnite, is rare (plate 1*C*) but always occurs with quartz, apparently in equilibrium with it and other associated metamorphic minerals. Only euhedral green octahedrons are conclusively identifiable in hand specimen; in thin section, gahnite grains commonly resemble anhedral garnet in shape, shagreen surface texture, and general refringence, but differ in color. Gahnite occurs in felsic gneisses and schists (three observations in the matrix of siliceous pod rocks) mainly along a linear zone east and south of Pearl (plate 1*C*), where it has been known for 80 years (Read, 1903). Gahnite has recently been found near the Greenville Mine (Johnson, 1979). Gahnite separated from garnet amphibole rock at the upper Greenville Mine averages 4.8 percent Fe, 15.4 percent Zn, 0.6 percent Mn, and 6.6 percent Mg, according to the average of 24 electron-probe observations by G. A. Desborough (D. M. Sheridan, written commun., 1980). Four rocks rich in gahnite or zincian[2] spinel from various localities on Independence Mountain contain from 1 to 7 percent Zn according to semiquantitative spectrographic analyses by L. A. Bradley (D. M. Sheridan, written commun., 1980). A new association of gahnite with andalusite, sillimanite, muscovite, and garnet is known from sample 2002 in Fish Creek (plate 1*C*). Sheridan and Raymond (1977) have recommended gahnite as a guide to zinc sulfide ores in Colorado. If their theory holds true in the northern Park Range, the ore must have been emplaced prior to or during the thermal peak of metamorphism, since gahnite is a metamorphic mineral. This timetable is consistent with the 1.7-b.y. "best-fit" lead isotope age on the Greenville ore (Antweiler and others, 1972, p. 310).

Staurolite.—This yellow-pleochroic iron-alumimum silicate is found in only two mineral assemblages in the northern Park Range. The first, aluminous schist, is present only in a linear zone from the canyon of Willow Creek to west of Hinman Park. In this zone, staurolite is stable with sillimanite and muscovite, and locally with kyanite and andalusite as well (plate 2*B*). It also occurs with cordierite and anthophyllite in an unusually high-magnesium, low-calcium rock (as represented by sample 885 from south of Seven Lakes, described under "Cordierite," above). Apparently there are at least two rock compositions that permit the retention of staurolite into the lowest sillimanite zone.

Talc.—This hydrous magnesium silicate is sparsely distributed in the northern Park Range, mainly in a few altered peridotites. (For example, see sample 1112 in table B4.)

Vesuvianite.—This unique calcium-aluminum silicate is known from only one marble in the northern Park Range, where it is associated with wollastonite and other calc-silicate minerals (tables B9 and B10, fig. 6*B*, and plate 1*D*).

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[2] For this usage of "zincian" see Palache and others (1946, p. 691, 692) and Raymond and others (1980, p. 13).

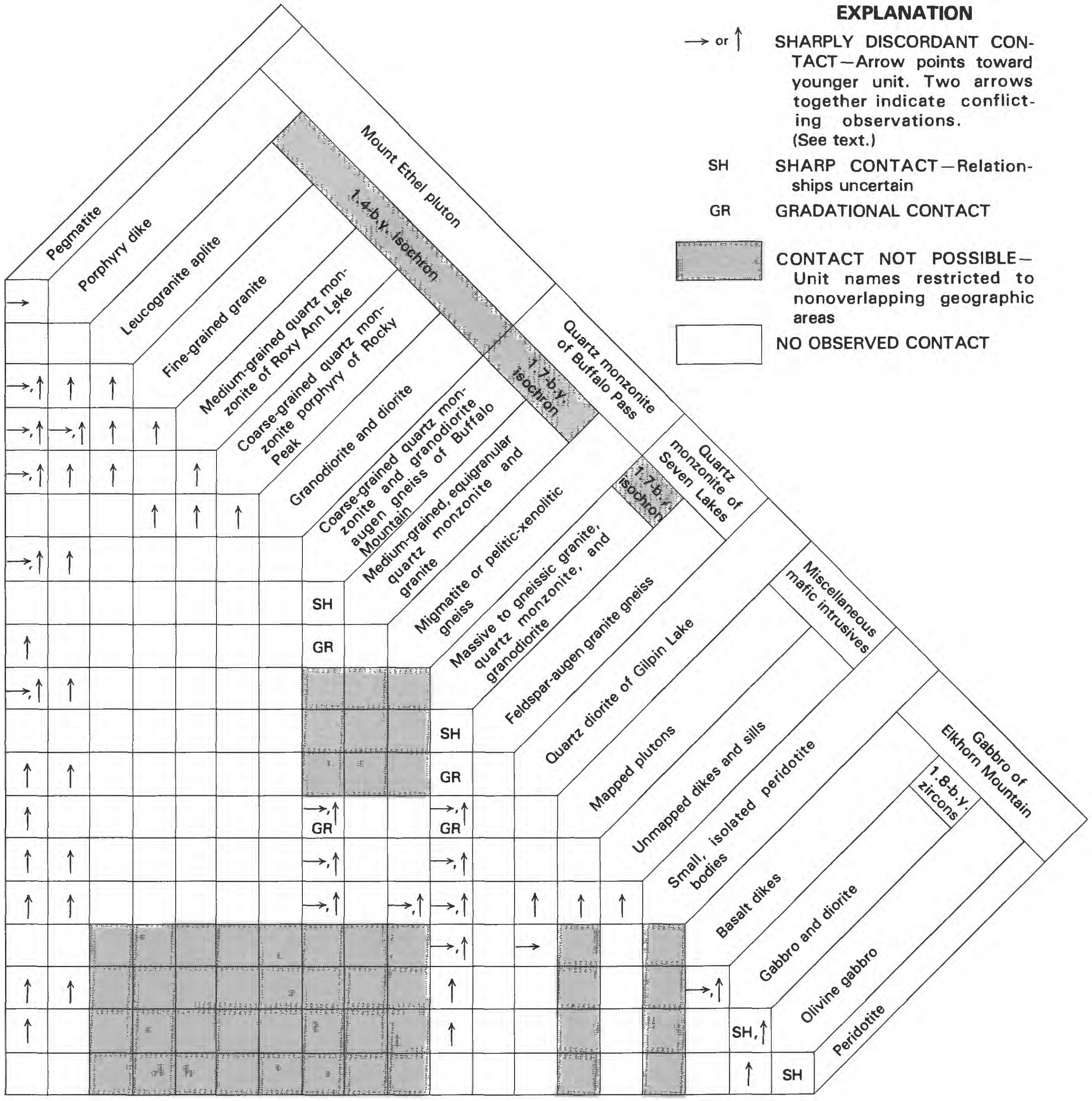


FIGURE 13.—Contact relationships between Park Range Precambrian intrusive rocks.

INTRUSIVE ROCKS

CONTACT RELATIONSHIPS

A summary of the contact relations of 20 different types of Park Range Precambrian intrusive rocks is presented in figure 13, which also shows available radiometric ages for these units (Snyder, 1978, 1980b; Segerstrom and Young, 1972). The Rb-Sr isochrons noted in this figure were obtained from samples representing the units spanned in the table. Of the 190 theoretically possible contacts between units, 49 are ruled out because the unit names are restricted to nonoverlapping geographic areas, observed contact relations of various types are compiled for 53 others, and none of the remaining 88 have been observed. All of the intrusive rock types (except unmapped mafic dikes and sills) are shown on published geologic maps (Snyder, 1980a, b, and c).

Figure 13 shows several cases in which one intrusive rock type both cuts and is cut by another. Most of these represent conflicting relations observed in separate outcrops, but in a few cases, these apparently incompatible relationships were observed in the *same* outcrop. (For example, see fig. 25.) This apparent contradiction might come about in any or all of several ways:

(1) Either or both of two intrusive magma types are emplaced continuously over a finite period of time, and thus an older member of series A might be older than B, even though a younger member is younger than B. This explanation apparently applies to some pegmatites, porphyry dikes, miscellaneous mafic intrusives, and small, isolated peridotite bodies.

(2) Either or both of two simultaneously emplaced intrusive magma types can have different thixotropic or rheomorphic (liquid-solid) properties in different areas, possibly owing to different tectonic stresses, different cooling histories, preferential loss of volatiles, or other properties affecting melt viscosities, which may give rise to different contact relations. Such a circumstance may explain some of the observed relations between different Mount Ethel plutonic phases (Snyder, 1978, figs. 9 and 10) and between different Elkhorn Mountain gabbroic phases (Snyder, 1980b, cross section *A–A'*).

(3) Intrusive contact relationships can be reversed in detail by remelting or remobilization of the older rock by later metamorphic events. (For example, see fig. 25.) This phenomenon apparently is relatively common between 1.7-b.y. quartz monzonites and mafic dikes and sills, and remobilization is not restricted to the felsic member of the pair.

(4) Either or both of two intrusive types may be misidentified or misgrouped or their contact relations misread. This explanation should be suspected if exposures are poor or few or if conditions of observation are marginal, as, for example, between basalt dikes and the quartz diorite of Gilpin Lake. It is unlikely where many good observations have been made on many outcrops and on many scales by many qualified observers, as, for example, between the Roxy Ann Lake and Rocky Peak phases of the Mount Ethel pluton.

Although figure 13 summarizes a great deal of interesting data, it is not the sum total of observable relative age criteria. For example, most of the posttectonic Mount Ethel plutonic phases occur in a single batholith that has a generally simple curviplanar outer contact; this batholith is quite different from (and predictably younger than) the smaller, complexly folded bodies of the 1.7-b.y. syntectonic quartz monzonites. Furthermore, the 1.4-b.y. Mount Ethel rocks apparently cut 1.7-b.y. isograds (plate 1*B*). Likewise, the observation that the quartz monzonite of Buffalo Mountain is offset more than porphyry dikes (Snyder, 1978, p. 2) along the same Precambrian mylonite zone confirms the older age of the quartz monzonite. Some mineral distributions and textures are related to a regional metamorphic episode that may place an upper age limit on an otherwise undated intrusive suite. Sheared rocks such as augen or flaser gneisses are not represented in granitic suites younger than 1.7 b.y. Premetamorphic mafic and ultramafic rocks were very susceptible to metamorphic amphibolization (plate 2*C–F*). However, some mineral distributions seem anomalous; for example, the persistence of readily alterable olivine in the oldest intrusive suite must be at least partly attributable to the armoring effect of coronas or later poikilitic minerals around the metastable olivine cores.

1.8-B.Y. MAFIC AND ULTRAMAFIC INTRUSIVES

GABBROS AND DIORITES OF ELKHORN MOUNTAIN

Typical gabbros and diorites are dark rocks having a diabasic texture (figs. 14 and 15), but some are also porphyritic and some are poikilitic. The most amphibolized rocks have granular metamorphic textures, but most rocks retain some remnant of diabasic, porphyritic, or poikilitic textures. Among 79 determinable gabbro and diorite samples studied, the average total-mafic-mineral content is 48 percent or less (range 7–80 percent). The most mafic rocks are most amphibolized: of 13 gabbro and diorite samples that have total mafic content of 65 percent or more, 12 are completely amphibolized. Studied gabbros outnumber studied diorites by a ratio of 3/2, and this ratio compares with the 2/1 ratio representative of the actual field proportions (table B13, fig. 23*B*). Although the average plagioclase in these rocks is labradorite, they contain substantial quantities of andesine. Bytownite and oligoclase are uncommon. Most rocks are dark gray and medium grained; several grain sizes may be present in a single outcrop (fig. 15*B*, *C*). Studied gabbros include 37 gabbros and 9 norites or noritic gabbros, and studied diorites include 25 diorites, 4 tonalites, 1 granodiorite, and 1 hypersthene granite. ("Red rock" granitic or granophyric differentiates have not been observed as part of this pluton.) The major primary minerals are plagioclase, clinopyroxene, green hornblende, clear pargasite or orthopyroxene, and biotite in that order of abundance in nearly all rocks, and magnetite, quartz, potassium feldspar, apatite, tremolite, and ilmenite in some rocks. Accessories include pyrite, sphene, allanite, epidote, zircon, carbonate, and pyrrhotite. Amphibolized rocks (about a third of those studied) generally contain green hornblende, plagioclase, chlorite or biotite, and epidote in about that order of abundance. Some of these rocks contain major amounts

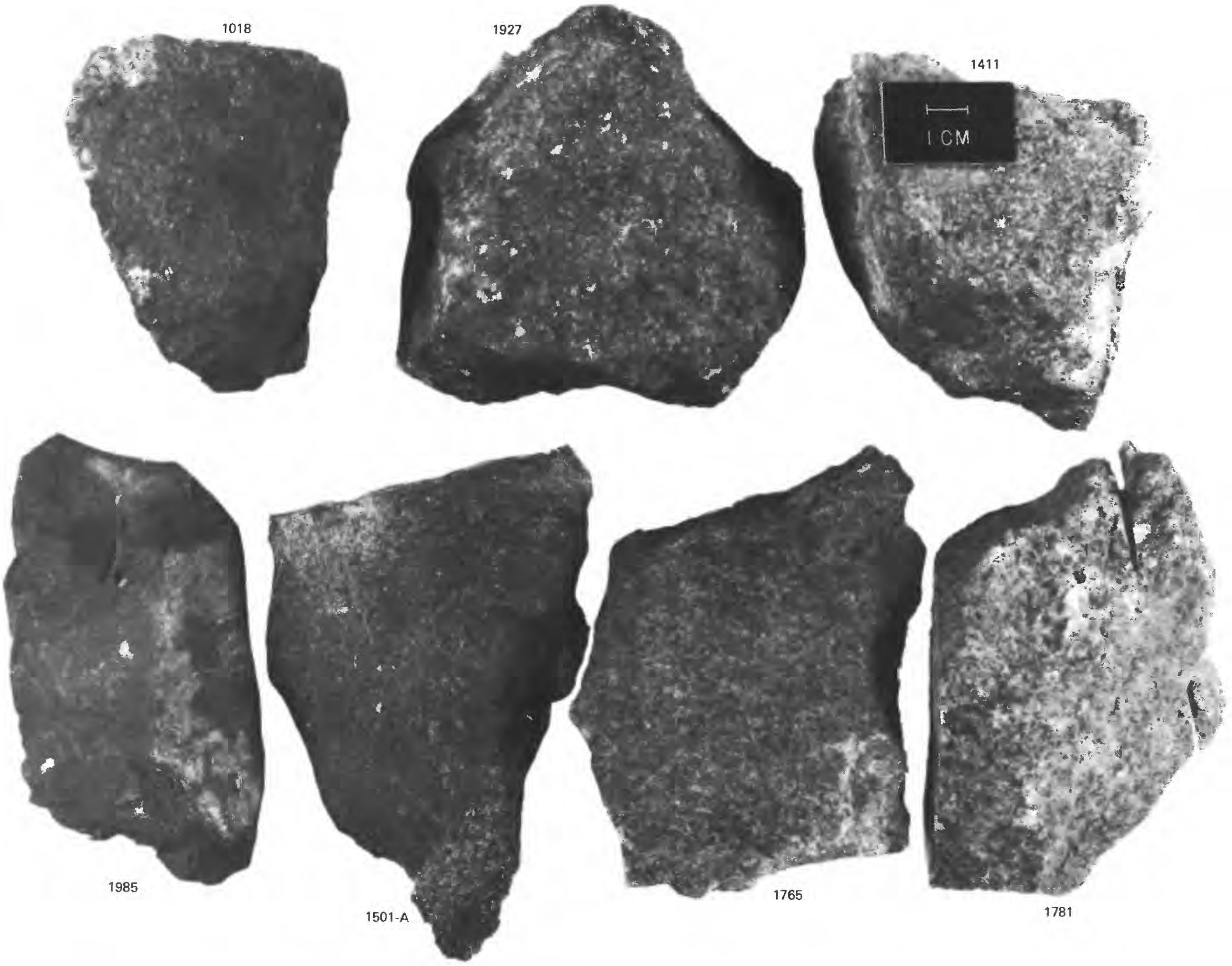


FIGURE 14.—Hand specimens of selected analyzed 1.8-b.y. mafic and ultramafic rocks of Elkhorn Mountain, arranged in order of increasing silica content from upper left (44.22 percent SiO_2) across top then bottom row to lower right (53.06 percent SiO_2). Photographs by Louise S. Hedricks.

SAMPLE DESCRIPTIONS

1018, Bear Creek amphibole wehrlite (tables B3, B4). For thin section see figure 19*G*.

1927, Damfino Creek spinel-pargasite-olivine websterite (tables B3, B4). For thin section see figure 19*J*.

1411, Continental Divide pargasite-olivine leuconorite (mapped olivine gabbro) (tables B1, B2). For thin section see figure 18*D*.

1985, Dark basalt porphyry dike south-southwest of Elkhorn Mountain (tables B1, B2). For thin section see figure 15*A*.

1501-A, Hornblende-biotite norite (mapped gabbro) from east of Crane Park (tables B1, B2). For thin section see figure 15*C*.

1765, Hornblende-biotite leucogabbro (mapped gabbro) from summit of Elkhorn Mountain (tables B1, B2). For thin section see figure 15*G*.

1781, Three Forks biotite diorite (mapped gabbro) (tables B1, B2). Zircons separated by Robert Sperandio from this rock have a highly concordant U-Pb age (C. E. Hedge, written commun., Nov. 23, 1976; analyst Margarita Gallego); the Pb^{207}/Pb^{206} age, usually the best approximation to the true age, is reported as 1,781 m.y. (Snyder, 1980b). For thin section see figure 15*H*.

of magnetite, remnant pyroxene, ilmenite, sphene, pyrite, quartz, tremolite, apatite, or wollastonite(?). Most rocks in which the main mafic mineral is green hornblende have been largely amphibolized, but it is clear that some green hornblende (as well as minor biotite) is primary (fig. 15, sample 1754) and that primary and metamorphic hornblende cannot normally be distinguished. Some pargasite replaces clinopyroxene and orthopyroxene, but other pargasite has a primary appearance. Some andesine may be metamorphic (note small andesine bumps on the plagioclase distribution curves in figs. 16*B* and *C*), but most primary plagioclase has distinctive twinning, zoning, crystal shape, and texture that suggest it survived metamorphic recrystallization. Plagioclase in the

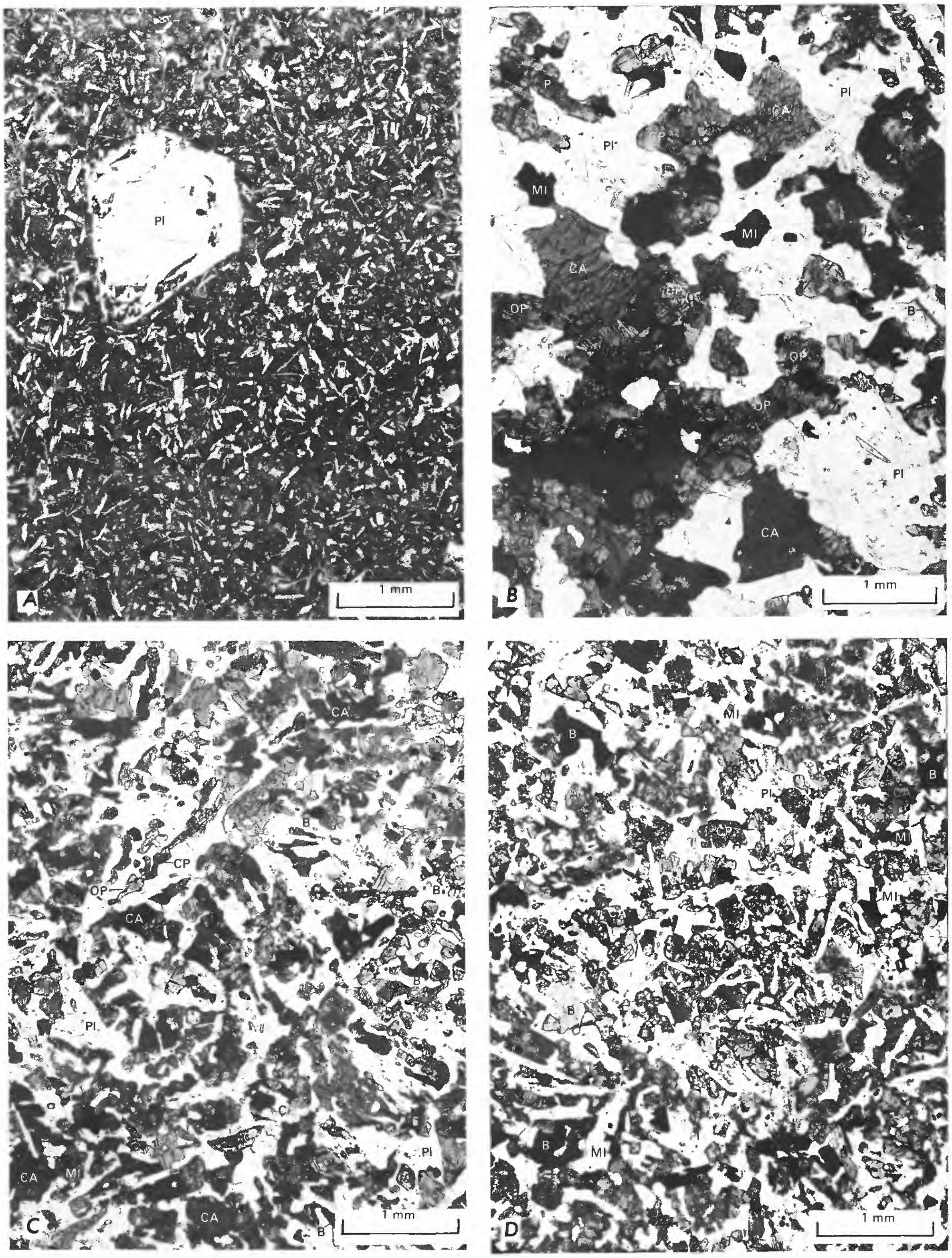


FIGURE 15.—Photomicrographs of normal hornblendic, noritic, diabasic gabbro of Elkhorn Mountain and a basalt dike cutting it (analyses in tables B1 and B2 for all samples but 1501 and 1754), arranged in general order of increasing SiO_2 content (48.52 to 53.06 percent). Mineral symbols explained in table 1. Photomicrographs by Louise S. Hedricks.

A, Sample 1985, basalt porphyry dike, showing zoned plagioclase phenocryst in mesostasis of anhedral pyroxene, anhedral amphibole, lathe-like plagioclase, and minor biotite and magnetite-ilmenite. For hand specimen see figure 14.

B, Sample 1501, norite textural phase gradational over 5 feet (1.5 m) in same outcrop to sample 1501-A (fig. C). Amphibole is common green hornblende.

C, Sample 1501-A, norite from road cut east of Crane Park. For hand specimen see figure 14.

D, Sample 1685, gabbro from side of logging road east-northeast of Crane Park.

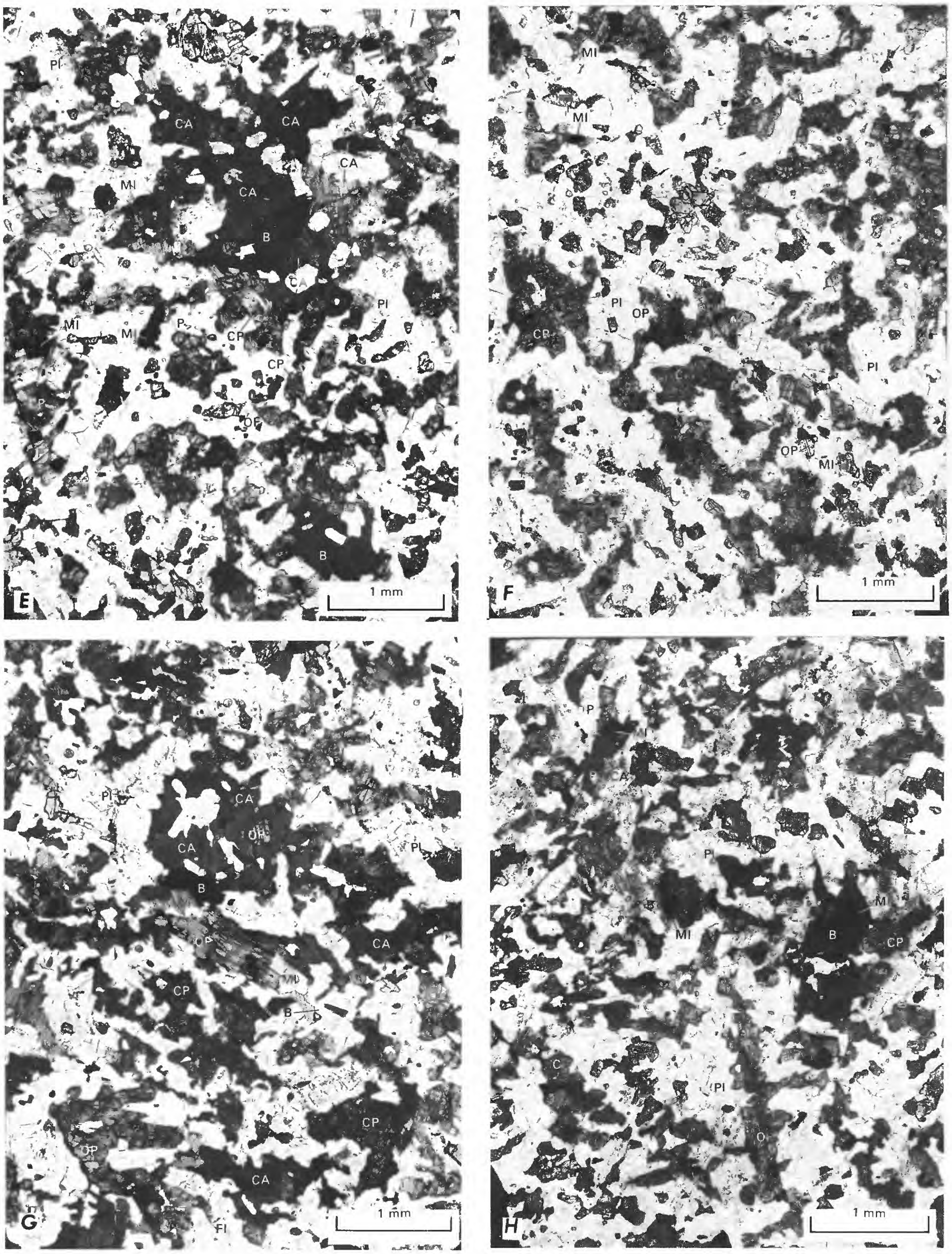


FIGURE 15.—Continued.

E, Sample 1754, gabbro (near diorite) containing large primary hornblendes and biotites associated with smaller, unaltered groundmass pyroxenes, from east of junction of King Solomon Creek and Middle Fork Little Snake River.

F, Sample 1413, from norite dike cutting olivine gabbro along Continental Divide.

G, Sample 1765, leucogabbro (almost noritic diorite) from summit of Elkhorn Mountain. For hand specimen see figure 14.

H, Sample 1781, dated biotite diorite from Three Forks road cut. For hand specimen see figure 14.

amphibolized rocks tends to be somewhat more sodic (fig. 16*A*). The rocks of the Farwell Mountain pluton tend to be more amphibolized than those of the Elkhorn Mountain pluton, and this observation may help to explain the higher diorite to gabbro ratio (fig. 23*B*) in the Farwell Mountain pluton.

Most rocks of the gabbro diorite suite appear similar in hand specimen and grade smoothly and evenly from one composition to another over short to broad distances in the field (figs. 15*B* and *C*). However, there are some abrupt local compositional changes in single outcrops where knife-blade-sharp contacts are traceable over several meters. Four documented instances (fig. 17) of these few sharp internal contacts are as follows:

(1) A road cut on the north edge of Whiskey Park shows a sharp contact between a light (25 percent total mafic content) flow(?)-layered diorite containing andesine, clinopyroxene, opaque iron oxide, quartz, and orthopyroxene (sample 1502) and a dark (63 percent total mafic content) gabbro containing labradorite, hornblende, clinopyroxene, biotite, magnetite, and orthopyroxene (sample 1503).

(2) A stream bank exposure 3/4 mile (1.2 km) west northwest of the 9,165-foot (2,793.5-m) hill northwest of Big Red Park shows fine-grained gabbro and medium-grained diorite porphyry in sharp contact in irregular layers. The gabbro (sample 1592) contains labradorite, clinopyroxene, brown hornblende, biotite, magnetite, and orthopyroxene, and the diorite (sample 1593) contains calcic andesine, clinopyroxene, biotite (in large phenocrysts), orthopyroxene, magnetite, and hornblende.

(3) A hillside outcrop 1¾ mi (2.8 km) west of the intersection of King Solomon Creek with the Crane Park-Whiskey Park road exposes a 10×50-yard (9×45-m) inclusion of slightly darker (45 percent mafic content) gabbro (sample 1712) in a slightly lighter (35 percent mafic content) but otherwise mineralogically similar gabbro (sample 1713).

(4) The summit of Elkhorn Mountain exposes a sharp contact between a leucocratic (15 percent mafic content) tonalite and a finer grained much darker (55 percent mafic content) diorite. The tonalite (sample 1764A) contains sodic andesine, quartz, hypersthene, magnetite, potassium feldspar, biotite, and clinopyroxene while the diorite (sample 1764B) contains calcic andesine, hornblende, clinopyroxene, biotite, orthopyroxene, and magnetite.

Chemically the gabbros and diorites of Elkhorn Mountain can be distinguished from each other with difficulty (table B1). Gabbros contain 49–50 percent SiO_2, compared to 50–53 percent for diorites, and Al_2O_3 content is comparable for the two. Gabbros contain 28.5–29 percent mafic oxides, compared to 25–28.5 percent for diorites. The alkali contents of gabbros and diorites overlap: 2.5–3.5 percent for the former and 3.2–4.3 percent for the latter.

OLIVINE GABBROS AND PERIDOTITES OF ELKHORN MOUNTAIN

Nineteen samples of rocks classed as olivine gabbros and eleven samples of dunites or related ultramafic rocks were examined. These two groups are distinguished by their total content of mafic minerals: olivine gabbros average 40 and range from 20 to 65 percent; dunites or related rocks average 83 and range from 75 to 100 percent. The average plagioclase is calcic labradorite or bytownite in both groups. Rocks of these groups are cut by rare dikes of normal gabbro. Typical olivine gabbro consists of plagioclase, pargasite or orthopyroxene, olivine, and clinopyroxene in that order. Some rocks contain abundant green to brown hornblende, biotite, magnetite, ilmenite, spinel, and apatite. A few of the more altered ones contain abundant serpentine, chlorite, actinolite, epidote, or wollastonite(?) (figs. 14 and 18). The average dunite or related rock is predominantly olivine and also contains plagioclase, orthopyroxene, clinopyroxene, and pargasite in that order of abundance. Some also contain significant amounts of hornblende, magnetite, or chromite (fig. 19). Orthopyroxene, clinopyroxene, pargasite, or, locally, plagioclase may form large poikilitic crystals, commonly studded with irregularly distributed, unoriented smaller crystals of the other minerals. On the weathered outcrop, one dunite (sample 1417) appeared to exhibit a plagioclase "flow structure" formed by parallel elongate lathes of plagioclase; in thin section these "lathes" are seen to be part of a single giant poikilitic crystal, and their

FIGURE 16 (facing page).—Histograms of plagioclase compositions in several classes of samples from the gabbro and diorite of Elkhorn Mountain. All histograms except *C* compile data derived from many different single plagioclase crystals; *C* compiles data derived from the average plagioclases of different rock samples. Histograms show anorthite contents of the following:

A, 177 individual plagioclase crystals in gabbros, diorites, or olivine gabbros in which all or nearly all original pyroxene has been altered to hornblende.

B, 1,488 individual plagioclase crystals from 122 rock samples from the gabbroic plutons of Elkhorn Mountain and Farwell Mountain. Of these, 1,045 are from normal gabbros or diorites, 400 are from olivine gabbros or dunites, 40 are from dark, fine-grained basalt dikes, and 3 (in the range from An_4 to An_{10}) are from a single unusual cleavelandite pegmatite cutting olivine gabbro on the 9,731-foot (2,966-m) mountain along the Continental Divide. Most of the data in this histogram are regrouped in histograms *D*, *E*, and *F*.

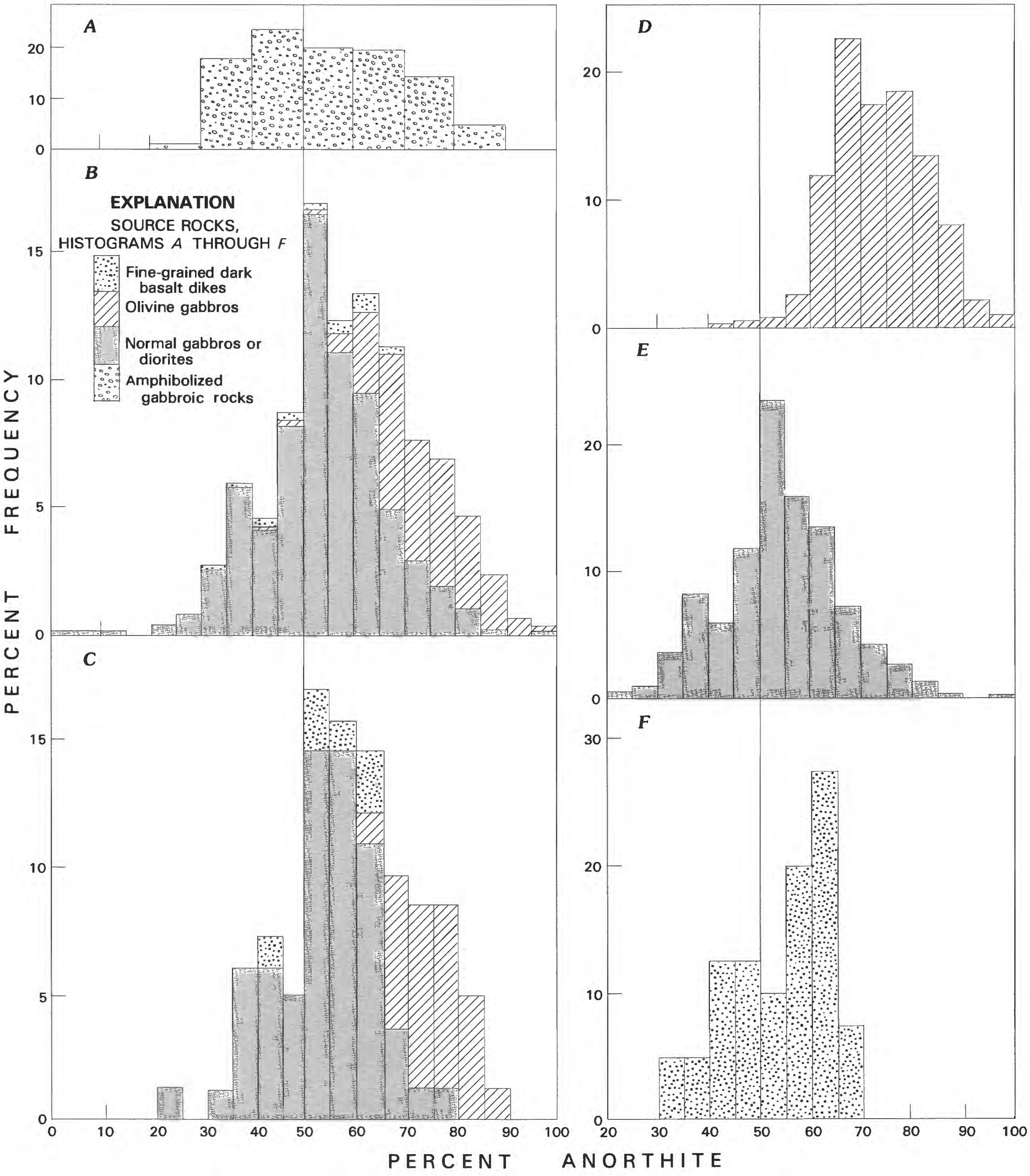
C, Average (mean) plagioclase in 83 gabbroic rock samples, including 54 normal gabbros and diorites, 23 olivine gabbros, and 6 basalt dikes. Each average is based on measurements of five or more individual plagioclase crystals.

D, 400 individual plagioclase crystals from 29 olivine gabbros to dunites.

E, 1,045 individual plagioclase crystals from 80 normal gabbros or diorites.

F, 40 individual plagioclase crystals from 13 basalt dikes.

common optical orientation is derived from growth, not flowage. Several ultramafic rocks have been completely altered to hornblendites, probably during the regional dynamothermal metamorphism 1.7 b.y. ago. In addition, in many the olivine is pseudomorphically replaced by a mixture of serpentine or chlorite and magnetite, and this alteration could be either metamorphic or hydrothermal.



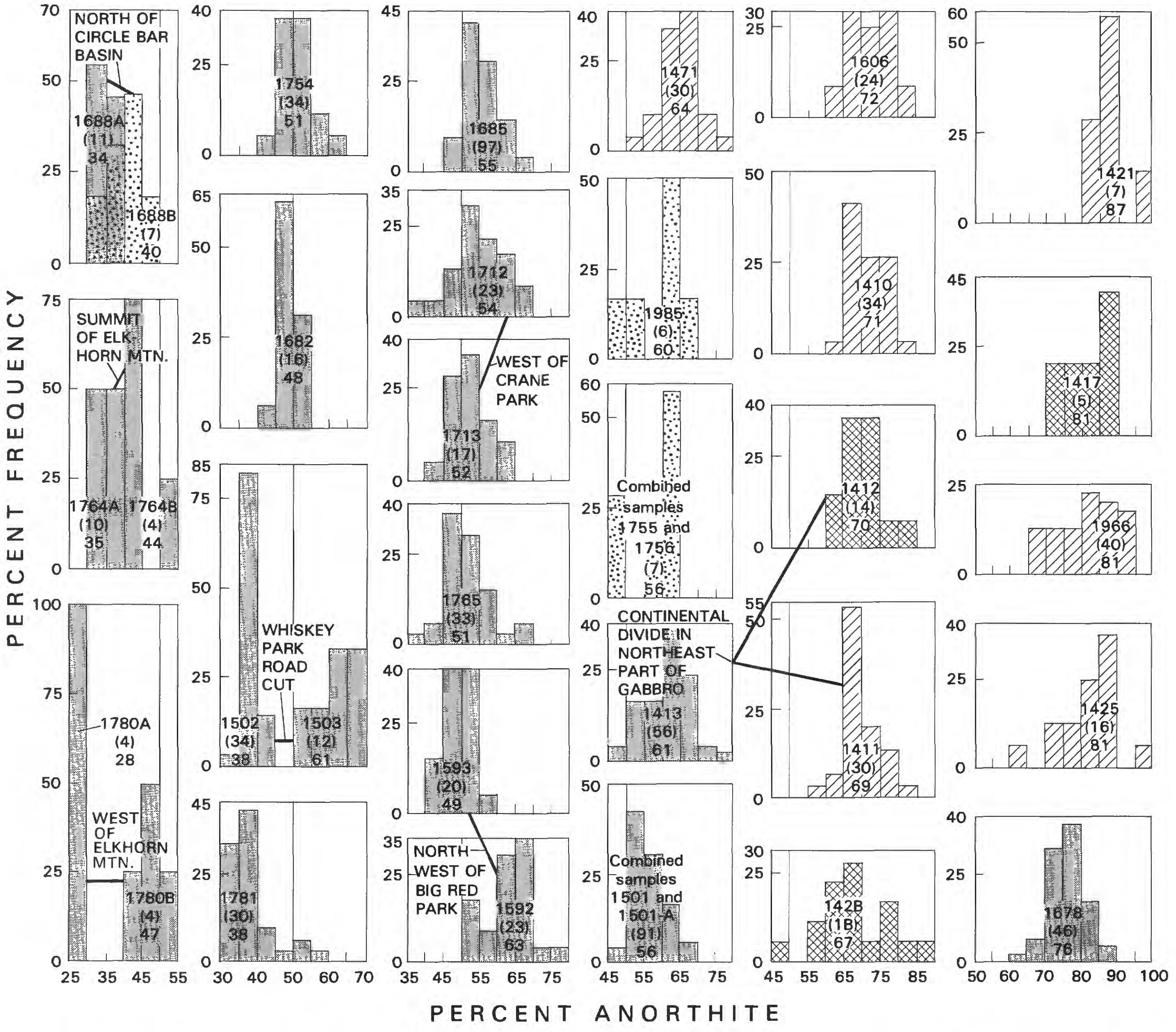


FIGURE 17.—Histograms of plagioclase compositions in 32 individual rocks from the gabbro of Elkhorn Mountain. Heavy lines join rocks observed in sharp contact. Patterns indicate source rocks as follows: shaded, normal gabbros and diorites; diagonal lines, olivine gabbros; cross hatches, dunites and other near-ultramafic rocks; dots, fine grained dark basalt dikes. Numbers indicate following data: sample number(s) at top, number of different plagioclase crystals determined in parentheses in middle, and average (mean) anorthite content of each rock's plagioclase at bottom. For comparing different columns, note An_{50} line in each column.

SAMPLE DESCRIPTIONS AND LOCALITIES

[Minerals listed in order of decreasing abundance]

1780A: Coarse-grained leucocratic stringers of potassium feldspar-plagioclase-quartz-hypersthene-magnetite granite (with accessory apatite and biotite) cutting 1780B diorite at 9,030-foot (2,752-m) elevation on nose southwest of 9,192-foot (2,801.7-m) hill on Elkhorn Stock Driveway 1 mile (1.6 km) west of the summit of Elkhorn Mountain.

1780B: Fine-grained diabasic clinopyroxene-plagioclase-hornblende-biotite-orthopyroxene-magnetite diorite cut by sample 1780A stringers, same location.

1764A: Coarse-grained plagioclase-quartz-hypersthene-magnetite-potassium feldspar-biotite-clinopyroxene tonalite in sharp contact with diorite (sample 1764B) on summit of Elkhorn Mountain.

1764B: Fine-grained plagioclase-hornblende-clinopyroxene-biotite-orthopyroxene-magnetite diorite in sharp contact with tonalite (sample 1764A) on summit of Elkhorn Mountain.

1688A: Coarse-grained plagioclase (with microcline perthite)-clinopyroxene-biotite-quartz-orthopyroxene-magnetite tonalite cut by dike (sample 1688B) on south side of King Solomon Creek north of Circle Bar Basin.

1688B: Fine-grained plagioclase-clinopyroxene-biotite-hornblende-magnetite diorite (with rare orthopyroxene) in dike cutting tonalite (sample 1688A), same location.

1781: Plagioclase-clinopyroxene-biotite-magnetite-orthoclase-orthopyroxene diorite (with accessory hornblende, quartz, and zircon) from Three Forks road cut just east of the Middle Fork of the Little Snake River. Contains coarse knots of hornblende biotite tonalite.

1502: Light plagioclase-clinopyroxene-magnetite-ilmenite-quartz(?)- orthopyroxene diorite (with accessory biotite and potassium feldspar) in sharp contact with gabbro (sample 1503), in road cut on the north edge of Whiskey Park.

1503: Dark plagioclase-hornblende-clinopyroxene-biotite-magnetite-orthopyroxene gabbro (with accessory apatite) in sharp contact with diorite (sample 1502), same location.

1682: Plagioclase-hornblende-clinopyroxene-biotite-magnetite-orthopyroxene diorite (with accessory apatite, potassium feldspar perthite, quartz) from 8,960 feet (2,731 m) elevation on the nose northeast of Whiskey Park, 1/3 mile (0.6 km) southeast of calcic gabbro (sample 1678).

1754: Porphyritic (biotite and hornblende), diabasic plagioclase-clinopyroxene-hypersthene-biotite-hornblende-magnetite-apatite gabbro from 1.1 mile (1.7 km) east of the junction of the Middle Fork of the Little Snake River and King Solomon Creek.

1593: Porphyritic (biotite), diabasic plagioclase-clinopyroxene-biotite-hypersthene-magnetite-hornblende diorite (with accessory apatite and potassium feldspar perthite) in sharp contact with gabbro (sample 1592), 3/4 mile (1.2 km) west-northwest of 9,165-foot (2,793.5-m) hill northwest of Big Red Park.

1592: Diabasic plagioclase-clinopyroxene-hornblende-biotite-orthopyroxene gabbro (with accessory apatite) in sharp contact with diorite (sample 1593), same location.

1765: Diabasic plagioclase-hornblende-clinopyroxene-orthopyroxene-biotite-magnetite gabbro (with accessory apatite) from summit of Elkhorn Mountain just north of locality of samples 1764A and 1764B.

1713: Diabasic plagioclase-clinopyroxene-hornblende-biotite-orthopyroxene-magnetite gabbro matrix for gabbro inclusion (sample 1712), from 1 3/4 mile (2.8 km) west of the intersection of King Solomon Creek with the Crane Park–Whiskey Park road.

1712: Diabasic plagioclase-clinopyroxene-hornblende-biotite-orthopyroxene-magnetite gabbro inclusion (30x150 ft, 9x46 m) in gabbro (sample 1713), same location.

1685: Diabasic plagioclase-clinopyroxene-biotite-hornblende-orthopyroxene-magnetite gabbro (with accessory apatite and microcline perthite) from lumber road cut at 9,020 feet (2,749 m) elevation about 1 1/2 miles (2.4 km) east of the north end of Crane Park.

1501 and 1501-A: Diabasic plagioclase-hornblende-clinopyroxene-orthopyroxene-magnetite-biotite gabbro (with accessory apatite, quartz, pyrrhotite, carbonate and potassium feldspar perthite) from road cut southeast of Crane Park.

1755 and 1756: Fine-grained, porphyritic (giant plagioclase) hornblende-plagioclase-magnetite-biotite basalt dike cutting gabbro 1.3 mile (2 km) northeast of the junction of King Solomon Creek and the Middle Fork of the Little Snake River.

1985: Porphyritic (plagioclase and clinopyroxene), amphibolized hornblende-plagioclase-clinopyroxene-magnetite-chloritized biotite basalt dike in swarm cutting diorite on east side of 8,444-foot (2,573.7-m) hill between the Middle Fork of the Little Snake River and King Solomon Creek.

1413: Diabasic plagioclase-orthopyroxene-hornblende-clinopyroxene-magnetite norite (with accessory biotite and carbonate) from 10-foot (3-m) dike cutting olivine gabbro (sample 1411), at 9,620 feet (2,932 m) elevation east of 9,731-foot (2,966-m) mountain on the Continental Divide.

1471: Diabasic plagioclase-clinopyroxene-orthopyroxene-magnetite-ilmenite-hornblende-biotite-olivine-sulfide-spinel gabbro (with rare apatite, pargasite, and carbonate) from 9,300 feet (2,835 m) elevation on nose in southwest part of mapped olivine gabbro.

1428: Olivine-orthopyroxene-plagioclase-pargasite dunite (with accessory brown hornblende, magnetite, ilmenite, chromite, and very rare biotite) from 9,380 feet (2,859 m) elevation slumped crop in stream southwest of the 9,731-foot mountain mentioned above. Unusual in its rarity of coronas, sample has only simple pargasite rims or no rims between olivine and plagioclase.

1411: Coronitic plagioclase-clinopyroxene-orthopyroxene-pargasite-olivine-magnetite-spinel gabbro with rare carbonate and biotite, from 9,620 feet (2,932 m) elevation east of the 9,731-foot mountain. Cut by norite dike (sample 1413) and contains peridotite pods (sample 1412).

1412: Coronitic olivine-pargasite-plagioclase-orthopyroxene-clinopyroxene-magnetite-chromite-spinel lherzolite containing accessory carbonate, biotite, and pyrite; 10-foot (3-m) pod in olivine gabbro (sample 1411) from 9,610 feet (2,929 m) elevation east of the 9,731-foot mountain.

1410: Coronitic plagioclase-olivine-orthopyroxene-clinopyroxene-pargasite-spinel-magnetite gabbro from 9,370 feet (2,856 m) elevation east of the 9,731-foot mountain.

1606: Coronitic plagioclase-olivine-pargasite-orthopyroxene-clinopyroxene-biotite-spinel-aluminous epidote(?) gabbro containing accessory apatite, sulfide, and carbonate from 10,000 feet (3,048 m) elevation on southwest shoulder of Farwell Mountain.

1678: Plagioclase-hornblende-clinopyroxene-magnetite calcic gabbro containing rare carbonate from 8,940 feet (2,725 m) elevation on ridge northeast of Whiskey Park, 1/3 mile (0.6 km) northwest of diorite (sample 1682).

1425: Poikilitic (clinopyroxene and orthopyroxene), coronitic plagioclase-olivine-clinopyroxene-orthopyroxene-pargasite-hornblende-magnetite-pyrrhotite-spinel-apatite gabbro at 9,480 feet (2,890 m) elevation south of the 9,731-foot mountain, 0.15 mile (0.2 km) south of olivine norite (sample 1966).

1966: Coronitic pargasite-orthopyroxene-olivine-spinel norite containing rare carbonate from the 9,560-foot (2,914-m) knob on ridge south of the 9,731-foot mountain, 0.15 mile (0.2 km) north of olivine gabbro (sample 1425).

1417: Coronitic olivine-plagioclase (poikilitic)-pargasite-orthopyroxene dunite containing accessory spinel and magnetite from atop the 9,731-foot mountain on the Continental Divide.

1421: Coronitic plagioclase-clinopyroxene (poikilitic)-olivine-orthopyroxene-brown hornblende-spinel gabbro from 8,870 feet (2,704 m) elevation on west side of the South Fork of Hog Park Creek southeast of the 9,731-foot mountain.

FIGURE 18 (on following pages).—Photomicrographs of olivine gabbros that have various proportions of corona minerals. Sample in *A* and *B* is from Farwell Mountain, samples in *C–H* are from gabbro of Elkhorn Mountain along the Continental Divide. Mineral symbols explained in table 1. Photomicrographs by Louise S. Hedricks.

A, Sample 1606 (analyses in tables B1 and B2). Inset is outline of figure *B*.

B, Closeup of olivine-plagioclase reaction coronas in sample 1606. Since primary crystallization, olivine has altered to orthopyroxene, and plagioclase has altered to symplectite of spinel and pargasite, along grain boundaries. The symplectite is locally more pargasite rich nearer the orthopyroxene. Biotite grains are primary and are apparently trapped at original olivine-plagioclase contact within the spinel symplectite, an observation in agreement with some theoretical models (for instance, Joesten, 1978). Black areas in olivine are thin films of hematite.

C, Sample 1410 (analyses in tables B1 and B2), showing olivine-plagioclase reaction to intermediate coronas of orthopyroxene or pargasite and pargasite-spinel symplectite. Pargasite is colorless near olivine and light brown near magnetite-ilmenite.

D, Sample 1411 (analyses in tables Bl and B2), showing olivine-reaction coronas and large schillerized poikilitic clinopyroxene-orthopyroxene grain. Inset is outline of figure *G*.

E, Sample 1424, showing olivine-plagioclase reaction corona containing intermediate orthopyroxene, pargasite, and pargasite-spinel symplectite; and orthopyroxene-plagioclase reaction coronas containing pargasite and (locally) pargasite-spinel symplectite.

F, Sample 1966, anorthositic layer in olivine gabbro, showing wide corona rims around olivine except where olivine is armored by poikilitic orthopyroxenes. Inset is outline of figure *H*, rotated 90°.

G, Closeup of olivine-plagioclase reaction coronas in sample 1411, showing orthopyroxene corona next to olivine, pargasite-spinel symplectite corona next to plagioclase, and clear greenish pargasite between. Latest alteration has changed some olivine to serpentine.

H, Closeup of corona reaction rims on olivine in sample 1966, consisting of a wide rim of orthopyroxene, a local narrow rim of pargasite, and a wide rim of pargasite-spinel symplectite.

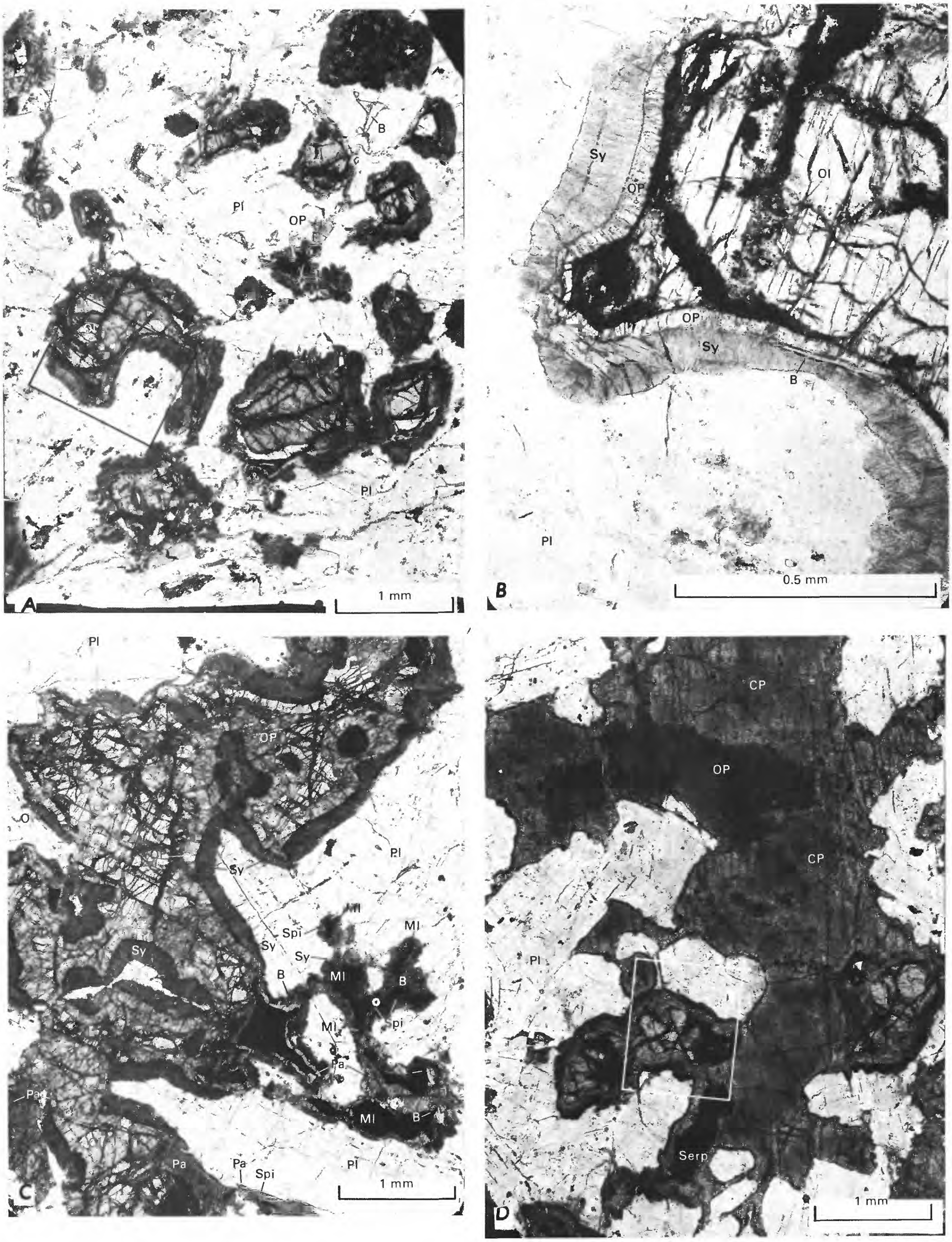

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FIGURE 18.

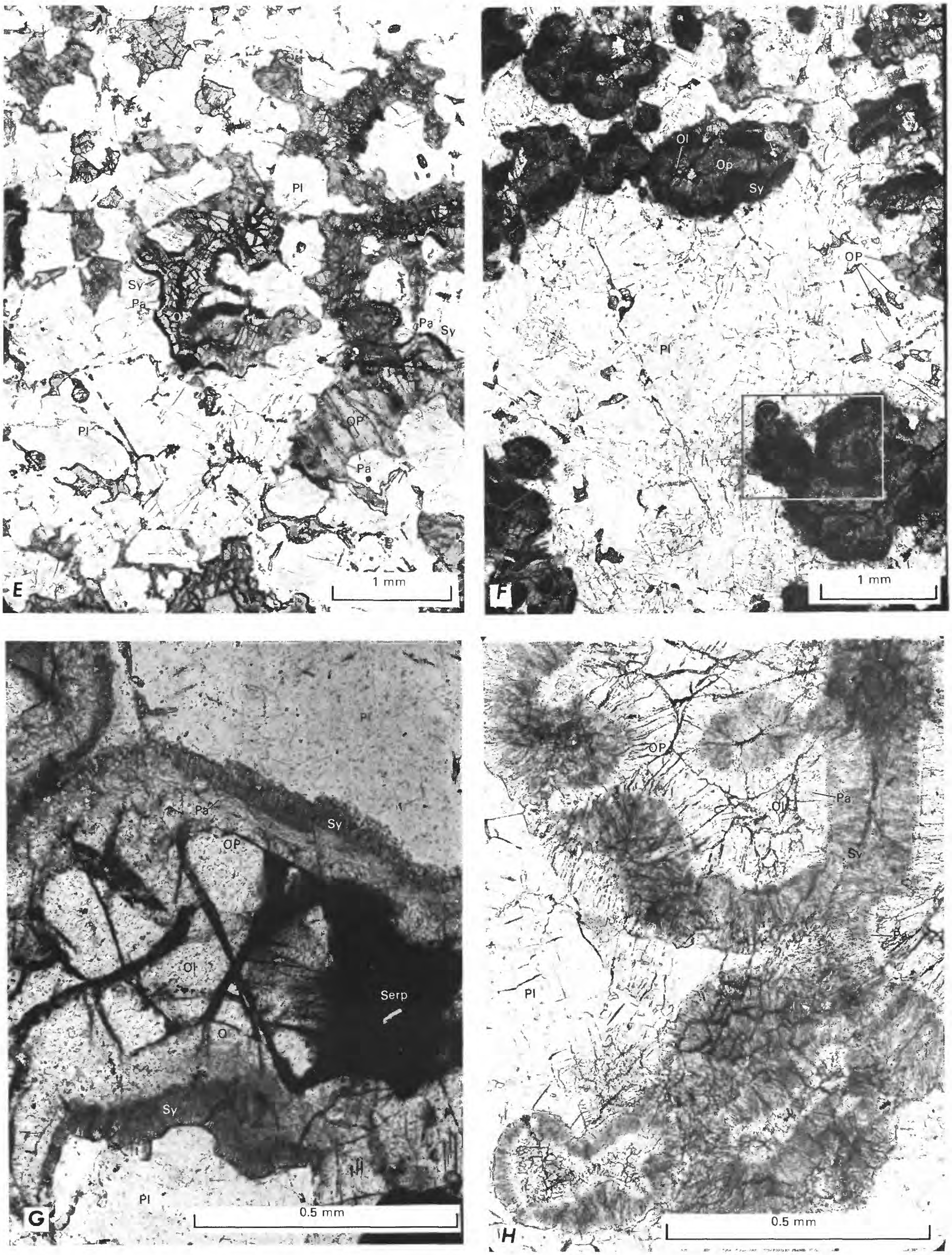
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FIGURE 18.

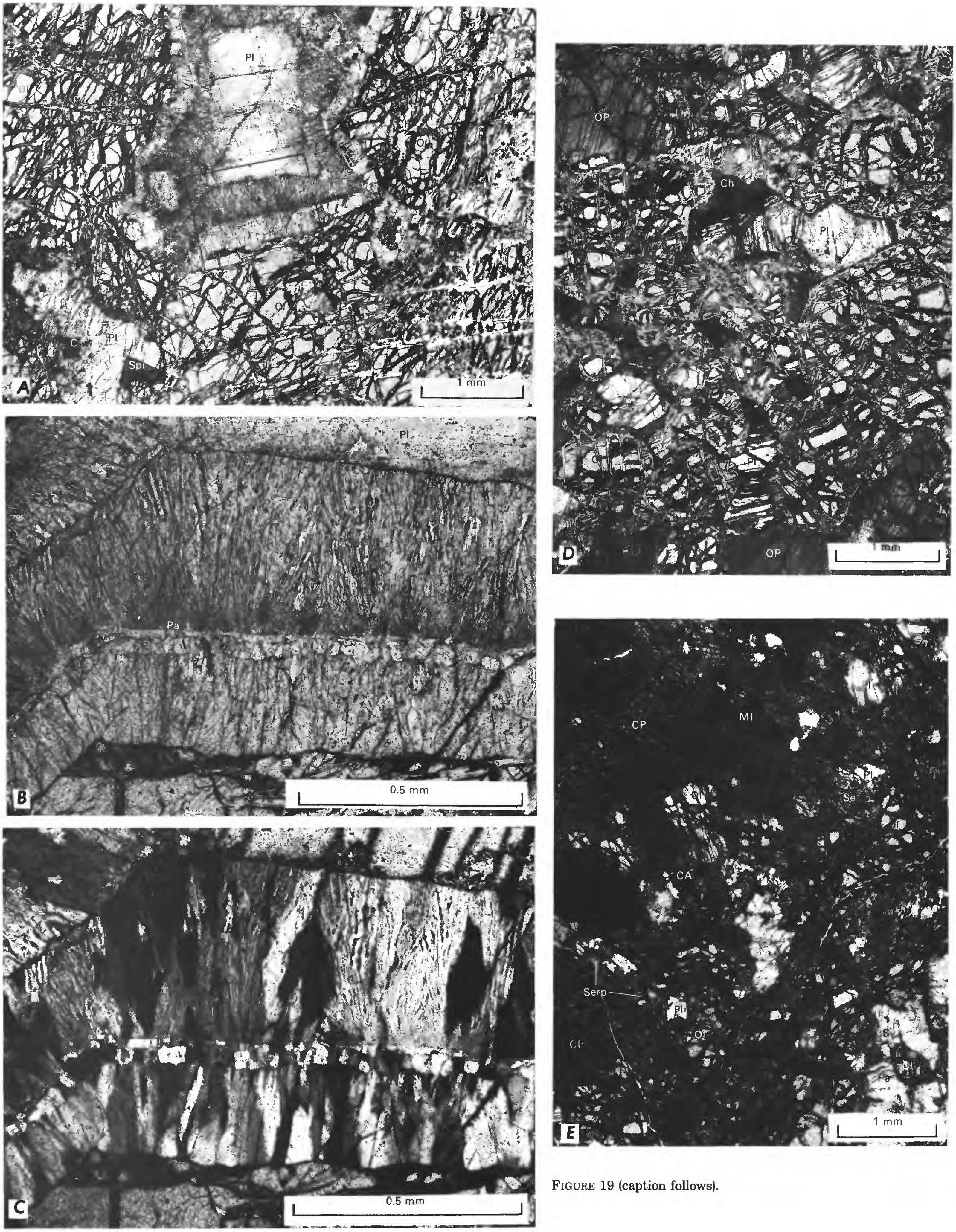

FIGURE 19 (caption follows).

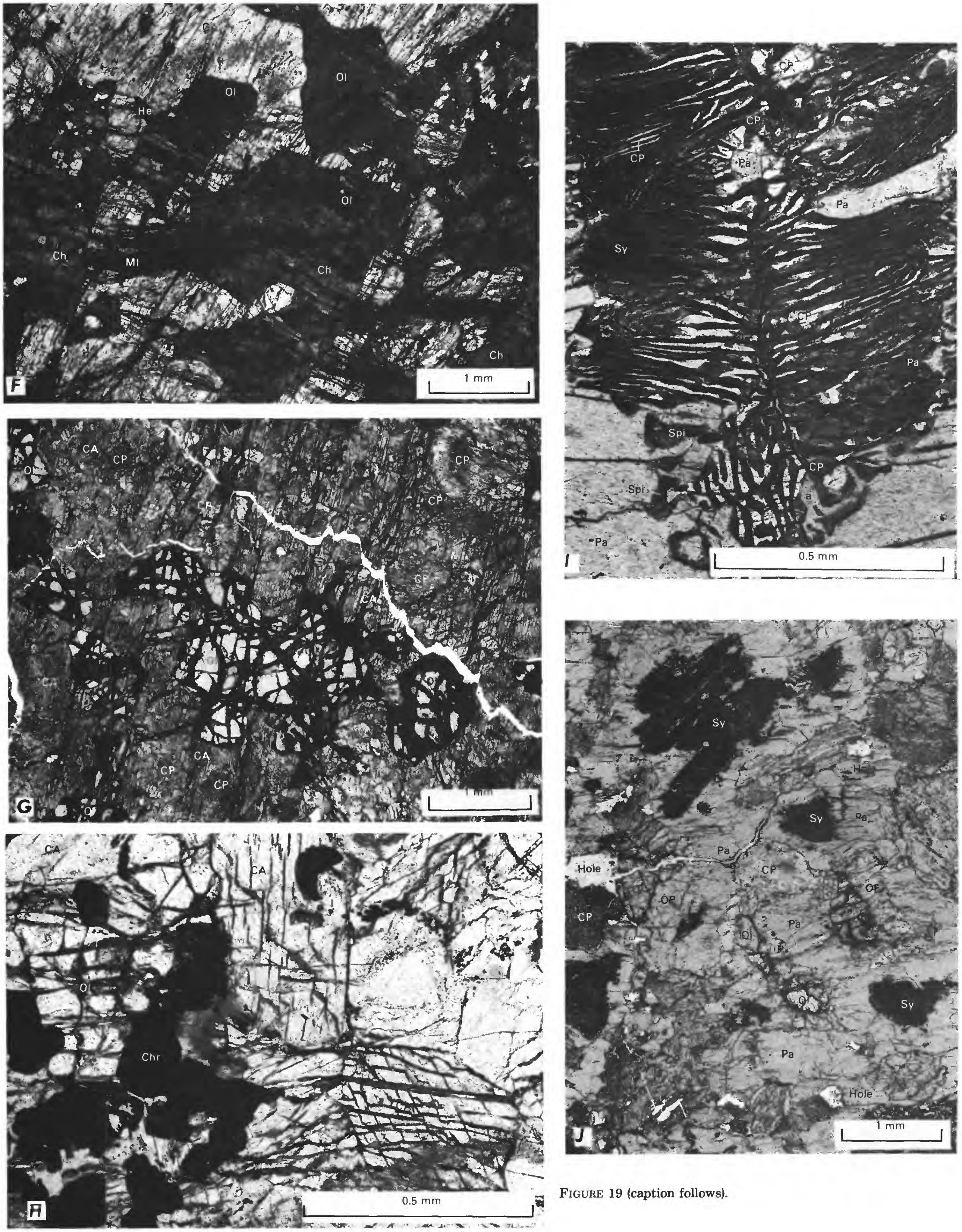

FIGURE 19 (caption follows).

Chemically the olivine gabbros and peridotites of the Elkhorn Mountain pluton are easily distinguished (table B1). Olivine gabbros contain 47–48 percent SiO_2, compared to 40–41 percent for peridotites. Olivine gabbros contain 18–21 percent Al_2O_3, compared to 6–9 percent for peridotites. There are 2.5 percent total alkalies in olivine gabbros, compared to 1 percent or less in peridotites. Olivine gabbros contain 27.5–29.5 percent mafic oxides, compared to 43–46.5 percent for peridotites; peridotites contain 2 to 3 times more MgO than any other plutonic member.

Minor-element spectrochemistry of all Park Range rocks has been summarized in another report (Snyder and others, in press). It will only be mentioned here that Cr_2O_3 has been included analytically with Al_2O_3 in analyses of mafic and ultramafic rock in the present report. Had Cr_2O_3 been measured in these analyses, it probably would have exceeded 0.1 percent seldom, and 1 percent never. Cr_2O_3, measured separately by wet chemical, colorimetric, or spectrographic techniques on 16 mafic or ultramafic Park Range rocks, was found to vary from <0.02 to 0.73 weight percent. Apparently it occurs mainly in chromite or magnetite. Also, Pt and Pd, measured in 97 samples from 33 localities of mafic and ultramafic rock, varies from <0.01 to 0.09 ppm, two orders of magnitude less than some Medicine Bow measurements (Snyder and others, in press).

Rocks containing both olivine and plagioclase (fig. 19*D*) generally show relict corona shells developed by reaction between these two minerals (figs. 18*A–H* and 19*A–C*, *I*, and *J*). The corona shells or kelyphitic rims together generally occupy one tenth to one third of the volume of the reacting minerals; single shells may range in thickness or be locally discontinuous, but if present, they usually occur in the following order:

1. Olivine.
2. Orthopyroxene. Never pleochroic; generally a comb structure in which individual crystals are oriented perpendicular to the olivine contact. Other shells below may be missing.
3. Clinopyroxene (rare, but see fig. 19*B*). (This is about the position of the original olivine-plagioclase contact; fig. 18*A* and *B*.)
4. Pargasite, clear to very light green or brown. Other shells below may be missing.
5. Symplectite, a generally thick, complex symplectic intergrowth of pargasite and spinel. Crystals elongated roughly perpendicular to the plagioclase contact.
6. Plagioclase.

Other reaction coronas commonly separate other minerals from plagioclase, as follows:

1. a. Magnetite.
   b. Light-brown pargasite.
   c. Light-brown, coarse-grained pargasite (after clinopyroxene?)-spinel symplectite.
   d. Light-brown, fine-grained pargasite-spinel symplectite.
   e. Plagioclase.

2. a. Magnetite.
   b. Orthopyroxene.
   c. Plagioclase.

3. a. Magnetite-biotite–coarse spinel aggregates.
   b. Green pargasite-spinel symplectite.
   c. Aluminous epidote (irregular).
   d. Plagioclase.

FIGURE 19 (on preceding pages).—Photomicrographs of analyzed peridotites (analyses in tables B1 through B4) arranged in general order of increasing silica from *A* (36.50 percent SiO_2) to *J* (45.13 percent SiO_2). Mineral symbol explanation in table 1. Photomicrographs by Louise S. Hedricks.

A, Sample 1116, Wapiti Ranch dunite or melatroctolite, showing both plagioclase with coronas (left center) and plagioclase without coronas (lower right). Inset is outline of figures *B* and *C*.

B, Closeup of olivine-plagioclase reaction corona in sample 1116. Note both clinopyroxene and clear pargasite rims between orthopyroxene and symplectite rims.

C, Same as *B* under crossed nicols, showing corona crystal and symplectite structure perpendicular to olivine-plagioclase contact.

D, Sample 1428, Continental Divide olivine melanorite (in olivine gabbro), an intimate mixture of plagioclase and partly chloritized olivine without apparent contact reaction.

E, Sample 1412, Continental Divide clinopyroxene-amphibole olivine melanorite (in olivine gabbro near sample 1428), showing thin olivine-plagioclase reaction coronas.

F, Sample 1017, Bear Creek altered dunite showing colorless poikilitic amphibole containing chloritized olivine. Crossed nicols.

G, Sample 1018, Bear Creek unaltered amphibole wehrlite showing very large green clinoamphibole oikocrysts (one crystal throughout this slide) containing smaller clinopyroxenes (difficult to discern here, but see similar view in plate 2*F* drawing) and olivines. For hand specimen see figure 14.

H, Closeup of chromite concentration in sample 1078, amphibole lherzolite from Spring triangulation station northeast of Steamboat Springs.

I, Closeup of complex reaction symplectite from sample 1052, Damfino Creek websterite. Pleonaste spinel is symplecticly intergrown with both colorless pargasite and clinopyroxene, the latter tending to be somewhat coarser in symplectite than the former. Symplectite like this was examined by electron probe to identify constituent minerals. (See table B17.)

J, Sample 1927, Damfino Creek websterite, from same outcrop as sample 1052 (fig. *I*), showing individual olivines containing orthopyroxene reaction coronas, clinopyroxenes, and masses of symplectite, all enclosed in a single oikocryst of light-green pargasite. For hand specimen see figure 14.

4. a. Clinopyroxene.
   b. Pargasite.
   c. Plagioclase.

These corona structures indicate disequilibrium between adjacent grains and are evidence of reaction to restore equilibrium. They are significant in that they show how incomplete recrystallization has been. Pargasite-spinel symplectites have been inferred to have originated at elevated pressure and temperature deep in the crust (Nishimori and others, 1972).

Other types of less well understood corona structures or reaction zones have also been observed (fig. 20*C*–*H*). All of these occur in highly amphibolized rocks with a particular scalloped texture. In several rocks an intergrowth of euhedral clinoamphibole and wollastonite(?) seems to have grown outward from cores of amphibolized mafic minerals, causing embayments in the surrounding plagioclase (fig. 20*C*–*F*). In another occurrence a wormy intergrowth of clinoamphobile and anorthite occupies a similar intermediate position between cores of amphibolized mafic minerals and corroded, less calcic plagioclase (fig. 20*G* and *H*).

BASALT DIKES

Dark basalt dikes are a volumetrically small but interesting part of the gabbroic plutons, especially in the western half of the Elkhorn Mountain pluton. They are typically much finer grained than the gabbros or diorites they cut. They range from moderately fine grained, in which all the mineral constituents are resolvable in thin section (figs. 14, and 15*A*), to so fine grained that only phenocrysts are determinable. The coarser grained dikes tend to have diabasic textures similar to those of the still coarser gabbros and diorites (fig. 15*A*). The resolvable mineral grains typically include hornblende, plagioclase, magnetite, and biotite with or without clinopyroxene remnants. Except in one locality, phenocrysts are not abundant; they compose less than 5 percent of the rock. Where present, they may be either fresh or altered; plagioclase phenocrysts that are sericitized may be surrounded by halos of biotites that have crystallized from the matrix. In one dike (samples 1755 and 1756 in fig. 17) from 1.3 mi (2 km) northeast of the junction of King Solomon Creek and the Middle Fork of the Little Snake River, giant (1–6 in., or 2.5–15 cm, in average size) fresh labradorite phenocrysts form as much as 40 percent of the dike rock throughout its exposure.

One chemically analyzed basalt dike appears to occupy an intermediate chemical position with respect to other plutonic members (based on either percent of SiO_2 or the presence or absence of olivine) (table B1).

SMALL ISOLATED ULTRAMAFIC BODIES

Many small bodies of ultramafic rocks of various ages are found outside the gabbro of Elkhorn Mountain and generally are not associated with mafic rocks. They range in size from inclusions (fig. 20*A*) as small as a centimeter to elongate intrusive bodies as much as 1.9 mi (3 km) long. Contacts with surrounding rocks are commonly obscured, but are generally sharp where visible. Some equant bodies are clearly inclusions within 1.7-b.y. granites or quartz diorites, but other tabular ones are discordant to metavolcanic or metasedimentary wall rocks, pegmatites, or 1.7-b.y. granites (figs. 20, 21, and 22). Some appear to be gradational with calc silicate rocks. All have been at least partly amphibolized in one or more regional metamorphic episodes, and some are completely amphibolized. Apparently the amphibolization has been accomplished without appreciable change in the overall chemistry. Amphibolization either can create randomly oriented small poikiloblasts or aggregates of small grains smaller than the host minerals (plate 2*D* and *E*) or can create poikilitic grains larger than the host minerals (plate 2*C* and *F*).

Most rocks from the small ultramafic bodies are dark green to black and have granular to interlocking texture. One to nine thin sections were studied from each of 50 different bodies. Of these, more than half consist entirely of mafic minerals, and only four have less than 90 percent mafic minerals. The average rock consists of three or four of the following five main mineral groups in this average order of abundance: clinoamphibole (most abundant), clinopyroxene, biotite or phlogopite, oligoclase to bytownite plagioclase, and partly serpentinized olivine. The clinoamphibole ranges from colorless pargasite or tremolite to green hornblende. Several hornblendites are nearly monomineralic. Other minerals are local major constituents: orthopyroxene, talc, chlorite, epidote, garnet, quartz, magnetite, scapolite, and spinel. Accessories include allanite, sphene, apatite, carbonate, pyrite(?), and chromite (fig. 19*H*).

Small, isolated peridotites outside of the Elkhorn Mountain pluton are chemically similar to those within it but have more extended chemical ranges. The extended ranges of SiO_2 and total alkalies overlap those of other Elkhorn plutonic members to a minor extent, but Al_2O_3 and total mafic oxides are always distinctive.

One body of hornblendite on the northwest side of Buffalo Ridge is gradational into a coarse carbonate rock. The gradation is exposed over many yards (or meters). The hornblendite is probably derived from a calcareous sediment of appropriate composition, but it is possible that it is a metamorphosed ultramafic intrusive rock that interfingered with sedimentary or igneous carbonate.

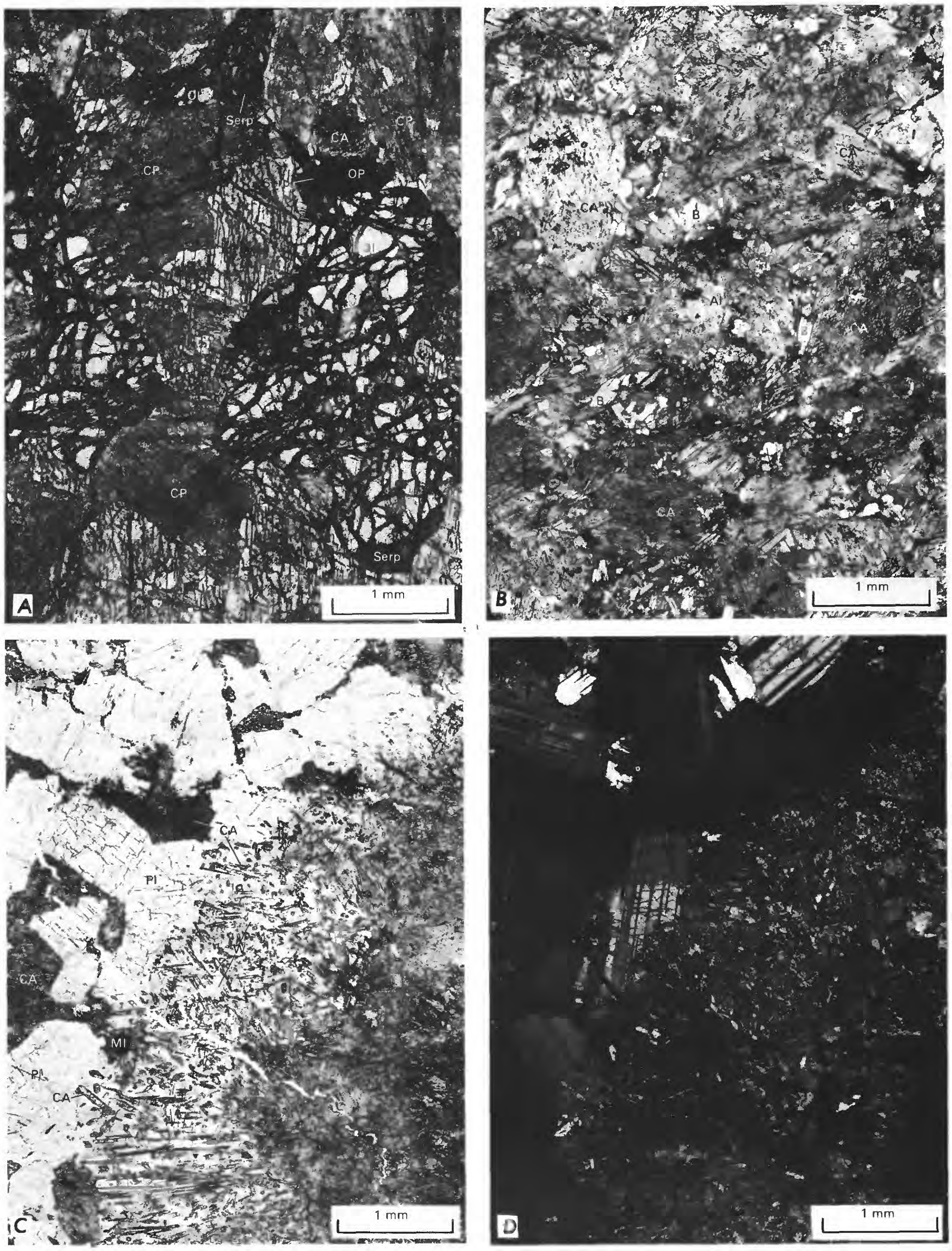

FIGURE 20.—Photomicrographs of miscellaneous textures from rare ultramafic and mafic rocks. Mineral symbol explanation in table 1. Photomicrographs by Louise S. Hedricks.

A, Sample 1217, olivine-hornblende clinopyroxenite inclusion in quartz diorite of Gilpin Lake, collected south of Seedhouse Campground.

B, Sample 2081, hornblendite (altered peridotite), from ridge-top dike south of Long Park Creek and west of Fishhook Lake. Field exposure shown in figure 21.

C, Sample 1442, altered Continental Divide olivine(?) gabbro, showing late-developed wollastonite(?)-clinoamphibole reaction zone between amphibole and plagioclase. Note that elongation of euhedral reaction clinoamphibole crystals is generally perpendicular to zone boundary.

D, Same as *C*, under crossed nicols, showing aggregate nature of central amphibole and abrupt truncation of plagioclase twins by wollastonite(?)-clinoamphibole reaction zone.

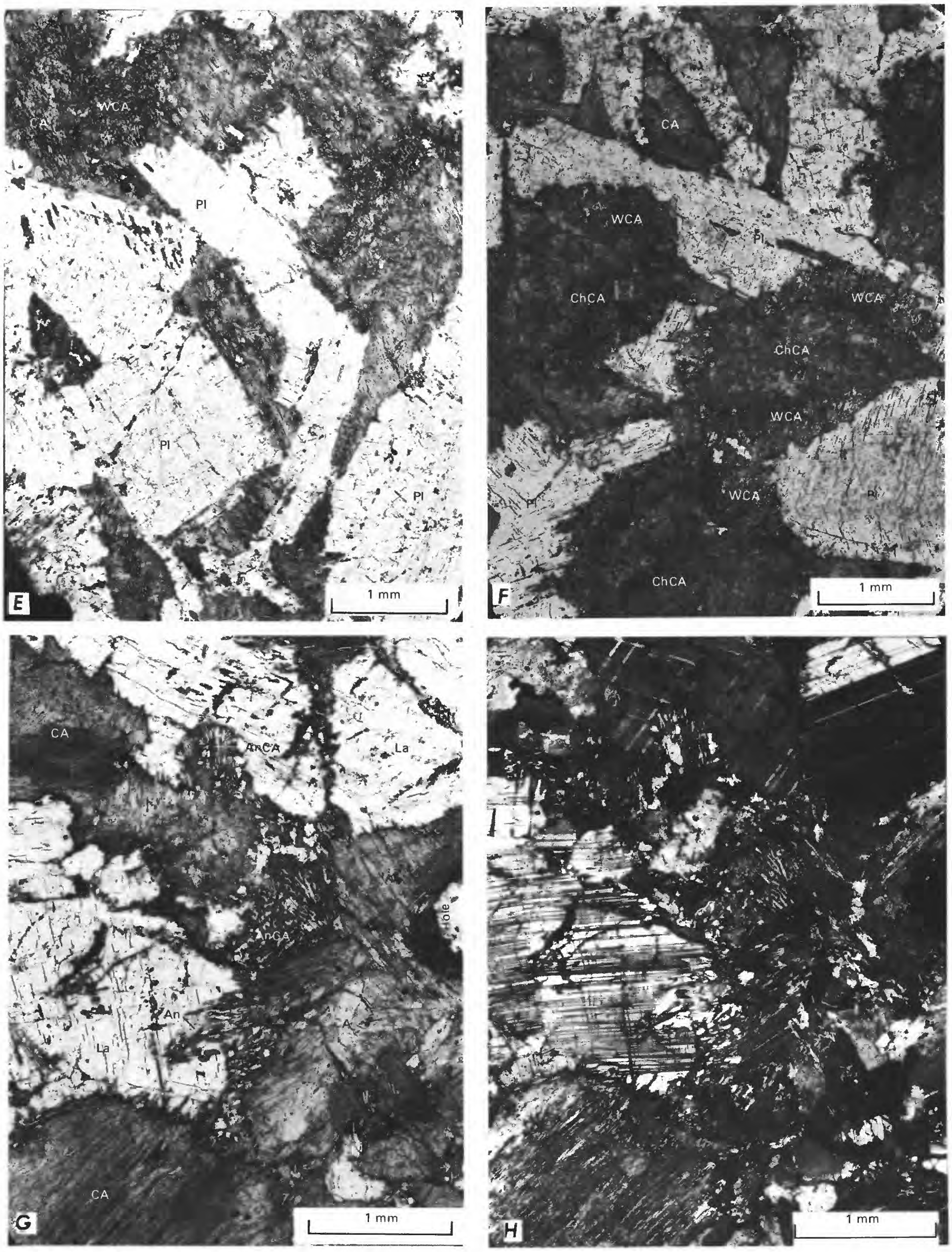

FIGURE 20.—Continued:

E–F, Two views of sample 1679, altered gabbro from northeast of Whiskey Park, showing wollastonite(?)-clinoamphibole intergrowths replacing plagioclase lathes.

G, Sample 2040, from small altered gabbro body cut by quartz monzonite dikes north of Mount Werner, showing anorthite-clinoamphibole intergrowths locally between original labradorite and larger clinoamphiboles.

H, Same as *G*, under crossed nicols. Note that amphibole in anorthite intergrowth has wormy outlines as compared to the euhedral crystals in the wollastonite(?) intergrowths in figures *C–F*.

FIGURE 21.—View of horizontal glaciated surface showing vertical 1-foot (30-cm)-wide-epidotitic hornblendite (altered peridotite) dike (sample 2081) cutting vertically layered amphibolite of the layered metasedimentary sequence at left and a pegmatitic quartz monzonite sill on right. From ridge-top exposure south of head of Long Park Creek, west of Fishhook Lake, and 2.6 mi (4.2 km) east-southeast of Mount Werner. For thin section see figure 20*B*.

WAPITI DUNITE

The east side of the top of the 9,035-foot (2,754-m) hill ¾ mile (1.2 km) east-southeast of Wapiti Ranch is covered with barren, beet-red soil. The soil contains numerous fragments of dark-grayish-green ultramafic rock containing some white plagioclase insets ringed by green corona rims. This olivine-rich rock has been the subject of repeated petrographic and chemical investigation. Analyses of one sample (116) are given by Snyder (1978, tables 5 and 6). Analyses of sample 1116 are given in tables B3 and B4 of this report. The average composition of bytownite plagioclase in the dunite is An_{78}, and bytownite grains are surrounded by coronas of pyroxene, pargasite, and spinel (fig. 19*A* through *C*). The top of the 9,035-foot (2,754-m) hill consists of a hornblendic anorthosite (89 percent bytownite plagioclase, average composition An_{74}) whose relationship to the beet-red-weathering dunite or lherzolite is not exposed. Possibly the bytownite is an original precipitate from the Wapiti magma that became unstable when the olivine crystallized, or possibly the bytownite crystals are xenocrysts obtained from the neighboring anorthosite.

Bear Creek Peridotite

The largest isolated body of peridotite extends for 2.5 miles (4 km) across the high ridge between Bear Creek and Lone Pine Creek. The body is generally concordant to the regional strike of the surrounding amphibolites and garnet amphibolites (metaandesites?). The enclosing rocks contain small inclusions of clinopyroxene hornblendite. The peridotite (analyses 1017 and 1018 in tables B3 and B4; figs. 14 and 19*F* and *G*; and plate 2*F*) is nearly everywhere highly altered, mainly to chlorite and iron oxide, with or without pargasite. Aggregates of chlorite and iron oxide form pseudomorphs after olivine. These pseudomorphs suggest that various parts of the body originally contained between 30 and 100 percent olivine. Locally (plate 2*F*), poikilitic, pargasitic hornblende grains contain swarms of fresh euhedral olivine and clinopyroxene. Zones of tiny magnetite inclusions in some olivine and clinopyroxene suggest that these olivines and clinopyroxenes have not been resorbed, and that at least some of the pargasite surrounding these olivines and clinopyroxenes may date from the original crystallization, when olivine, clinopyroxene, and clinoamphibole were all stable together. Later alteration increased the clinoamphibole at the expense of some clinopyroxene, and even later alteration, at shallow depths, has increased chlorite at the expense of olivine.

Spring Melanorite

An ultramafic suite that has several unusual characteristics is present near the 9,552-foot (2,911.4-m) elevation Spring triangulation station on the end of the ridge between Steamboat Springs and Buffalo Mountain. Analyzed samples 1078 and 1079, the latter the more altered of the two, are described in tables B3 and B4. Some rocks of this suite are unusual in containing more than 2 percent chromite (fig. 19*H*), here interpreted as an original igneous precipitate. The ultramafic pargasite-olivine rocks are cut by a 1.4-b.y. porphyry dike northeast of Spring station.

Three Island Lake Peridotite

The high ridges south and southwest of Three Island Lake are held up by a tough green peridotite composed mainly of edenite(?) and clinopyroxene. Analyzed samples 1070 and 1072 are described in tables B3 and B4. This rock intrudes a metasedimentary section containing marbles. Malachite coats weathered surfaces of both the peridotite and the marbles.

Damfino Creek Pargasite Websterite

Lithology.—An unusual pargasite websterite occurs in at least three dikes in a northeast trending zone parallel to the regional strike across the headwaters of Damfino Creek. One websterite body is closely associated with an amphibolized quartz gabbro in a natural outcrop beside the road between Pearl, Colo., and Hog Park, Wyo. Because of its accessibility and the unusual size of its corona minerals (figs. 19*I* and *J*), websterite from this outcrop was chosen for a detailed mineralogic investigation (table B17). Chemical and petrographic analyses of the rock (samples 1052 and 1927) are presented in tables B3 and B4, and histograms of plagioclase composition in the websterite and associated rocks are given in figure 22. More work is needed to properly explain the wide variety of contiguous rock compositions shown on figure 22. The wide variance between the modal and normative plots of samples 1052 and 1927 on figure 3*C* probably indicates that much more of the orthopyroxene and pargasite should be assigned to olivine and plagioclase as coronitic alteration products.

Mineral chemistry.—Mineral separates from websterite (sample 1927) have been analyzed by electron probe[3]. Symplectite minerals in sample 1927 were coarse enough (figs. 19*I* and *J*) to permit determination of each symplectite species without beam scatter across the mineral contacts. These data are summarized in table B17. The elemental data are converted to oxides and, with some reasonable assumptions about Fe_2O_3/FeO ratios and H_2O+, are summed and recalculated to 100 percent for intercomparison. The compositions of minerals representing nearly 97 percent of the rock were determined. In table 3, these mineral analyses are combined in their measured petrographic proportions along with ideal compositions of minerals that make up the remainder of the rock (plagioclase (An_{82}), pyrite, and calcite) to

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[3] For the electron microprobe analyses, ultrasonically cleaned mineral separates were mounted in 1/8-inch (3.2-mm)-diameter holes in 1-inch (25-mm)-diameter aluminum disks. The mounts were polished with 6-, 3-, and 1-μm diamond paste on cotton laps followed by mechanical buffing with 0.05-μm Al_2O_3. Electron microprobe instrument conditions were as follows: (1) Take-off angle=51.5°, (2) emission current=2×10^{-4} A, (3) operating voltage=15 kV, (4) sample current=15×10^{-9} A on benitoite, (5) fixed count of beam current using a counting period for each point analysis of about 13 seconds. The beam was moved randomly around the grain during each such 13-second count. A wavelength-dispersive system was used to measure Si, Al, Mg, Ca, and Na, three elements at a time, and an energy-dispersive system was used to measure Si, Al, Fe, Ca, K, Ti, and Mn; duplicate measurements by these two systems were averaged. Counts were calibrated using conventional wet-chemical-analyzed standards of quartz, glass (NBS standard GSC), fayalite, and two orthopyroxenes, and the standards were counted prior to and after the unknown samples.

estimate bulk composition of the rock. Comparison with the actual (average) rock analysis (derived from columns 6 and 7 of table B3) shows that, although general agreement is good and the determinations of some components are very close, there are some significant unexplained discrepancies.

The mineral names deducible from the probe chemistry in table B17 are low-alkali pargasite, augite, bronzite, hyalosiderite, and pleonaste, although some compositions are not ideal. For example, the formula of ideal pargasite can be written

$$Na_2O \cdot 4CaO \cdot 8(MgO+FeO) \cdot 3Al_2O_3 \cdot 12SiO_2 \cdot 2H_2O.$$

The formula deducible from the probe analysis of the large amphibole grains in sample 1927 is

$$0.5(Na_2O+K_2O) \cdot 3.6CaO \cdot 7.4(MgO+FeO+MnO+TiO_2) \cdot 2.2(Al_2O_3+Fe_2O_3) \cdot 12SiO_2 \cdot 2.2H_2O$$

or (expressing Fe_2O_3 as FeO):

$$0.5(Na_2O+K_2O) \cdot 3.6CaO \cdot 7.7(MgO+\Sigma FeO+MnO+TiO_2) \cdot 2.0Al_2O_3 \cdot 12SiO_2 \cdot 2.2H_2O.$$

The proportions of alumina and alkalies, relative to silica, are significantly lower than expected, but the identification as pargasite is confirmed. The symplectite pargasite is also low in alkalies but is very similar to the pargasite in the large grains, the main differences being that it has slightly higher alumina, slightly lower magnesia, and only half as much TiO_2 and MnO as the large-grain pargasite. The large-grain clinopyroxene has a calculable formula of $1CaO \cdot 1(MgO+FeO) \cdot 2SiO_2$ (plus $0.1Al_2O_3$ and $0.01(Na_2O+K_2O)$)—a nearly ideal augite, variety fassaite. Symplectite clinopyroxene is remarkably similar except for its higher silica and lower alumina contents. The orthopyroxene calculates out as a central bronzite (Fe_{23-26}) containing minor impurities that have the compositions of quartz, corundum, anorthite, and (unless Fe is taken as FeO) magnetite. The olivine is a hyalosiderite near chrysolite (Fa_{31-33}) that has some impurities, mainly of quartz and magnetite composition. The spinel was confirmed as a low-chromium spinel by checking with the electron-probe chromium peak. However, calculation of a balanced spinel formula is impossible using the Fe_2O_3/FeO ratio given in table B17, because the divalent oxides do not match the trivalent oxides in molecular amounts. They

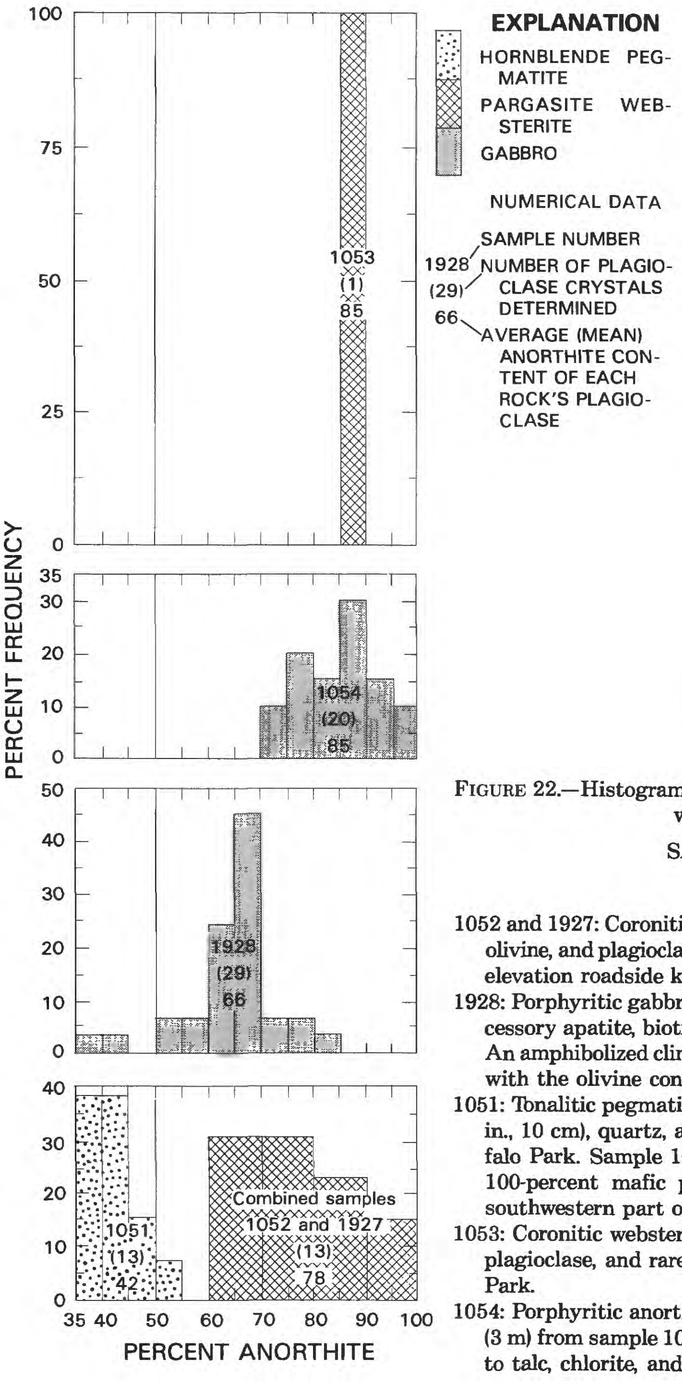


FIGURE 22.—Histograms of plagioclase compositions from 76 crystals in five rocks associated with the pargasite websterite of Damfino Creek.

SAMPLE DESCRIPTIONS AND LOCALITIES

[Minerals listed in order of decreasing abundance]

1052 and 1927: Coronitic websterite containing pargasite, clinopyroxene, orthopyroxene, spinel, olivine, and plagioclase and accessory sulfide, carbonate, and biotite. From 9,660-foot (2,944-m) elevation roadside knob between Damfino Park and Buffalo Park.

1928: Porphyritic gabbro containing plagioclase, hornblende, clinopyroxene, and quartz and accessory apatite, biotite, carbonate, and sphene. From same knob as samples 1052 and 1927. An amphibolized clinopyroxene porphyry containing quartz that is believed to be gradational with the olivine containing websterite, represented by samples 1052 and 1927.

1051: Tonalitic pegmatite in surface boulders containing plagioclase, hornblende (crystals to 4 in., 10 cm), quartz, and rare epidote. From 9,860-foot (3,005-m) elevation knob west of Buffalo Park. Sample 1051 believed to represent an unusual intrusive pegmatite cutting the 100-percent mafic pargasite peridotite and serpentinized dunite cropping out in this southwestern part of the websterite of Damfino Creek.

1053: Coronitic websterite containing pargasite, orthopyroxene, clinopyroxene, olivine, spinel, plagioclase, and rare carbonate. From 9,700-foot (2,957-m) elevation nose east of Damfino Park.

1054: Porphyritic anorthositic gabbro containing clinopyroxene phenocrysts. Collected 10 feet (3 m) from sample 1053. Contains plagioclase, pargasite, clinopyroxene, olivine(?) (all altered to talc, chlorite, and carbonate), and orthopyroxene.

TABLE 3.—*Comparison of rock chemistry reconstituted from mineral analyses of sample 1927 with average wet-chemical rock analyses of samples 1927 and 1052 from the northern Park Range, Colorado*

[All data expressed as percent of whole rock. Leaders indicate constituent not known to be present]

Constituent	Known mineral composition × mineral content determined in sample 1927								Reconstituted rock[1]	Actual rock analysis[2]
	Average pargasite ×33.14%	Average clinopyroxene ×32.19%	Orthopyroxene ×15.29%	Spinel ×12.79%	Olivine ×3.31%	Plagioclase (An_{82}) ×2.86%	Pyrite ×0.25%	Calcite ×0.17%		
SiO_2-----	15.14	17.06	8.42	.71	1.35	1.36	---	---	44.04	45.04
Al_2O_3----	4.49	1.08	.35	7.68	---	.96	---	---	14.56	12.26
Fe_2O_3----	.63	.41	.23	.76	.05	---	---	---	2.08	2.90
FeO------	1.89	1.05	1.87	1.96	.70	---	0.12	---	7.59	6.38
MgO------	4.98	4.63	4.31	1.69	1.19	---	---	---	16.70	18.67
CaO------	4.29	7.74	.05	.04	---	.47	---	0.10	12.69	12.70
Na_2O-----	.56	.03	---	---	---	.06	---	---	.65	.59
K_2O------	.15	.08	---	---	---	---	---	---	.23	.10
H_2O^+-----	.83	---	---	---	---	---	---	---	[3] .83	[3] .83
TiO_2-----	.15	.05	.02	.02	.01	---	---	---	.25	.24
MnO------	.03	.05	.04	.02	.01	---	---	---	.15	.16
S--------	---	---	---	---	---	---	.13	---	.13	([4])
CO_2------	---	---	---	---	---	---	---	.07	.07	.13
Total----------									[5] 99.97	[6] 100.00

[1] Totals of columns at left.

[2] Average of two analyses.

[3] H_2O^+ adjusted to come out the same.

[4] Rocks not analyzed for S.

[5] Mineral contribution of 0.02 percent biotite-phlogopite (unanalyzed) not added to reconstituted rock.

[6] Original rock analyses included 0.04 percent P_2O_5.

can be made to match by adjusting the Fe_2O_3 to 0.66 percent and FeO to 20.21 percent (making Fe_2O_3 3 percent of FeO rather than the 26 percent assumed in table B17). This recalculation results in a pleonaste composition (44.24 percent $MgAl_2O_4$, 48.66 percent $FeAl_2O_4$, 0.93 percent $Fe^{+2}Fe^{+3}{}_2O_4$, and 0.45 percent Fe_2TiO_4) including minor impurities of quartz and anorthite composition.

RELATIONS BETWEEN GABBROS AND ULTRAMAFIC ROCKS

The groups of analyzed gabbros and analyzed olivine gabbros are clearly distinct from one another in composition (fig. 3*B*), but the observed presence or absence of olivine was apparently fortuitous. The norms indicate that olivine should be stable in all of these rocks except sample 1781 (table B1). The olivine gabbros may have formed by gravity separation of olivine from melts similar in composition to the gabbros, but it is not possible to tell on the basis of either the chemistry or petrography whether the original magma was compositionally like (1) the average mapped gabbro, (2) the average mapped gabbro plus a certain unspecified increment of olivine, or (3) the matrix of the average mapped olivine gabbro. The compositional similarity suggests that, if differentiation took place, it was close to the present crustal position, but the asymmetry of geographic location of the olivine gabbro suggests that such differentiation was at a lower crustal position than the present one.

Sample 1413 is from a dike of gabbro cutting olivine gabbro. It is compositionally similar to the other mapped gabbros (tables B1 and B2). The occurrence of this gabbro as a dike shows that some gabbros were liquid when the mapped olivine gabbros were solid at this level of the crust.

The separation between the compositional fields of the gabbros and ultramafic or near-ultramafic rocks (fig. 3*B*) has a bearing on the origin of some of the latter rocks. Pods of near-ultramafic rocks (samples 1412 and 1428) within the mapped olivine gabbros in the gabbro of Elkhorn Mountain are compositionally distinct from the surrounding mafic rocks, but no gradational intermediate phases have been observed. This circumstance strongly suggests that the pods were not formed by gravity differentiation of any phase of the gabbro in place. The favored interpretation is that the near-ultramafic pods are giant, raftlike inclusions carried by the gabbroic magma from some lower depth; alternatively, it is possible but less likely that they are dikes intruding the olivine gabbros, in which case they also would have been derived at a lower depth before intrusion.

Some small isolated bodies of ultramafic and near-ultramafic rock are clearly intrusive (fig. 21). Most of the ultramafic rocks (including all of those described in tables B3 and B4) are compositionally distinctive and very different from their wall rocks. They lack flow structures and must have been emplaced as liquids which then crystallized in place in an amphibolite-grade environment to produce the common corona structures and the profusion of complex, giant poikilitic or poikiloblastic crystals (plate 2). Samples from the same body are generally more similar to each other than to random samples from another ultramafic body (fig. 3*A*), suggesting either (1) a laterally inhomogeneous or layered mantle or some other lower source that could have been tapped in many different places to provide the different isolated bodies, or (2) different degrees of partial melting from a homogeneous mantle or lower crustal source. The similarity of 1.8-b.y. Rocky Mountain neodymium isotope ratios apparently militates against suggestion 1 above, suggesting instead a magma source "homogeneous over distances of several hundred kilometers" (DePaolo, 1981, p. 194).

The geographic distribution of rock types and selected minerals within the gabbro of Elkhorn Mountain gives clues to its nature and origin. Contacts between different lithologies are generally gradational but locally are sharp. It seems likely that most gradational contacts occur between lithologies that crystallized in place and have not had significant subsequent movement. Most sharp contacts are between lithologies that were emplaced as separate entities before crystallization. Later pervasive but incomplete amphibolization has partially masked all the above relations. The general distribution of most mappable lithologies is shown in fig. 23*A* and by Snyder (1980b).

Peridotite occurs in small masses within the northeastern part of the gabbro of Elkhorn Mountain and in separate small plutons in the country rocks. All peridotite contacts are believed to be sharp, but very few of them are exposed well enough to be located with certainty within 10 ft (3 m). Those bodies within the gabbro are apparently always in sharp contact with gabbro or olivine gabbro and generally are partly serpentinized. No internal sedimentary structures suggestive of olivine crystal settling are known, and so the bodies may all be solid rafts or inclusions of a more ultramafic substrate transported from an unknown depth. All peridotite bodies within the gabbro are believed to be at least as old or older than the rest of the gabbro, and they may be the only directly available traces of the mantle from which the rest of the gabbro was partially melted. Some peridotite bodies outside the gabbro of Elkhorn Mountain crosscut wall-rock structures (fig. 21); thus they must have been intruded at a later time than the gabbro of Elkhorn Mountain and in an at least partially liquid condition. Because they are compositionally similar to the inclusion-like bodies within the gabbro, they may represent complete or nearly complete melts of the deeper mantle from which they were drawn. Some of the small bodies outside the main gabbro mass are younger than felsic intrusives (fig. 21), and therefore the external bodies may have been emplaced over a much longer period of time than the internal bodies, all of which are believed to be older than the felsic quartz monzonite.

Olivine gabbros are also concentrated in the northeastern part of the Elkhorn Mountain pluton, but there are also some in the central part of the pluton and in the southwestern part of the Farwell Mountain pluton (fig. 23*A*). Olivine gabbros grade into normal gabbro over distances of tens of feet. It seems likely that the olivine gabbros originated from the rest of the gabbro mass probably by slow crystallization of an originally inhomogeneous magma body, perhaps modified by some jostling and mild disruption.

Gabbros or diorites compose most of the Elkhorn Mountain and Farwell Mountain plutons. The distribution of these two predominant rock types (fig. 23*B*) seems to indicate a partially zoned magma body. In the Elkhorn Mountain pluton, diorites occur along the northern and southern margins peripheral to gabbros and norites. Elkhorn Mountain itself sits astride one gabbro-diorite contact. Diorite makes up the bulk of the Farwell Mountain pluton, but gabbro occurs in the center. Contacts between gabbros and diorites are generally gradational, and there is no discontinuity in the distribution of plagioclase compositions (figs. 16*E* and 23*B*)—convincing evidence that crystallization occurred in place. Hypersthene is present locally in amounts as large as 15 percent, and biotite reaches 7 percent. Generally, high hypersthene correlates with high-anorthite plagioclase and low biotite, but southeast of lat 41° N., long 107° W., a somewhat anomalous area is lower in anorthite content of plagioclase and low in biotite even though it possesses major amounts of orthopyroxene, demonstrating again that the generally parallel regional composition pattern may be locally superimposed on an initially inhomogeneous magma.

Some internal contacts between various phases of gabbro and diorite are present within the Elkhorn Mountain pluton. These may be most common in the more silicic rocks (fig. 17). These contacts generally are

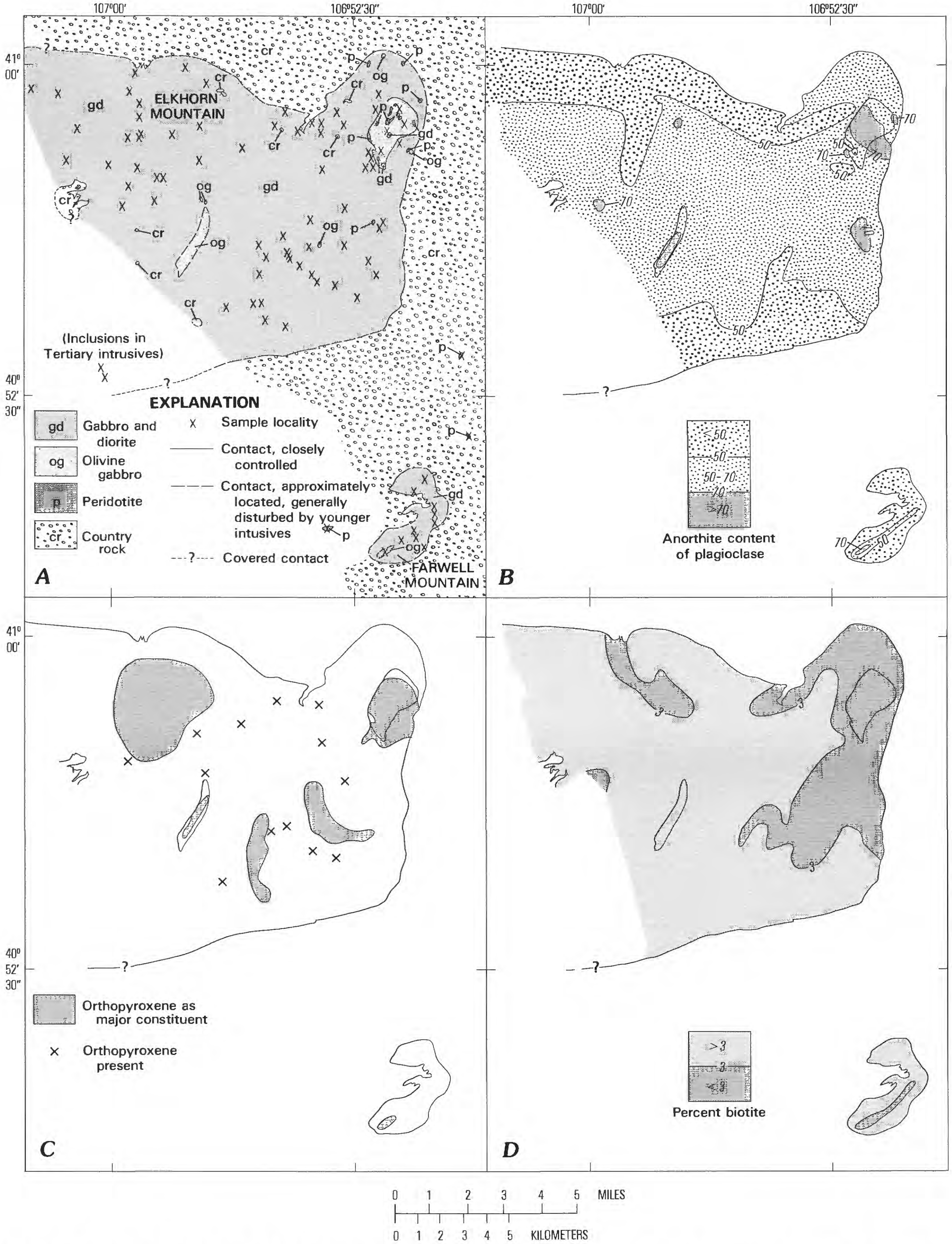


FIGURE 23.—Restored distribution of the gabbro of Elkhorn Mountain (*A*) and selected mineral parameters within the gabbro and diorite (*B–D*).

TABLE 4.—*Summary of evidence relating to origin of mafic and ultramafic rocks in the northern Park Range, Colorado*

<table>
<tr><th>Repeated intrusions from inhomogeneous source</th><th>Intrusion of inhomogeneous magma</th><th>Magmatic differentiation in place</th></tr>
<tr><td>Wide compositional disparity of small ultramafic intrusives or inclusions (fig. 3B) suggests different degrees of mantle melting or an inhomogeneous mantle or lower crustal source.
Rare gabbro dikes in olivine gabbro, abundant fine-grained basalt dikes in gabbro and diorite, and small mafic and ultramafic bodies cutting associated quartz monzonite (see fig. 21) outside of Elkhorn Mountain pluton demonstrate long availability of a supply of diverse mafic magma types.</td><td>Partly asymmetric geographical distribution of rock compositions gradational with each other. Note distribution of An_{50-70} and <3 percent biotite along east margin of Elkhorn Mountain pluton (figs 23B and D). Main mass of olivine gabbro and most peridotites are in northeast part of pluton (fig. 23A; Snyder, 1980b). Also, some areas are high in sodic plagioclase (figs. 23B and C).</td><td>Partly symmetric geographical distribution of rock compositions gradational with each other. Note zonal distribution of plagioclase from north to south in western part of Elkhorn Mountain pluton (fig. 23B). Also note central location of some orthopyroxene rocks (fig. 23C) and their correlation with main calcic plagioclase areas (fig. 23B).</td></tr>
<tr><td>A few faint, regional internal contacts within gabbros and diorites of Elkhorn Mountain parallel mapped regional foliation trends (Snyder, 1980b).
Absence of red-rock differentiates suggests that small magma batches were combined in sequence.</td><td>Most sharp internal contacts within gabbros and diorites of Elkhorn Mountain are traceable for only short distances.</td><td rowspan="2">Uniform fine-grained basalt dikes have a median plagioclase composition (fig. 16).</td></tr>
<tr><td colspan="2">Statistical frequency distribution of plagioclase compositions different for olivine and non-olivine rocks (figs. 16B–F).
No observed sedimentation structures caused by crystals settling in a gravitational field. Peridotite bodies within gabbro look more like tabular inclusions than graded beds.</td></tr>
</table>

exposed only in a single outcrop and may represent minor movements of magma after partial differentiation. Relative movements of the two may be only tens or hundreds of feet in these situations. In contrast, primary foliations within the Elkhorn Mountain pluton trend generally east-west in the northern part of the pluton but bend gradually around to northwest-southeast or north-south in the southern part of the pluton (Snyder, 1980b). West of Crane Park some of the internal gabbro contacts are traceable across several series of outcrops parallel to the regional north-south foliation trend in this part of the pluton. These internal contacts could represent major boundaries between different batches of magma that combined, in sequence, to make up the entire Elkhorn Mountain pluton. Relative movements in this situation could aggregate many miles. Also, if the large Elkhorn Mountain pluton is made up of separate batches of gabbro which differentiated semi-independently, the volume of each batch may have been too small to derive red-rock differentiates.

Basalt occurs as dikes 1 inch to 50 ft (3 cm to 15 m) wide in north-northeast-trending swarms, mainly in the western half of the Elkhorn Mountain pluton, but also in a few places on Farwell Mountain. Most dikes are completely contained within the gabbro or diorite masses, although a few on Farwell Mountain cut wall rocks very near the gabbro contacts. The finer grain size of the dikes suggests that they were intruded after the greater part of the pluton had crystallized and had cooled regionally, but the restriction of these dikes to the gabbro and its immediate environs indicates a similar source magma and similar channelways at depth. Also, some gabbro was remobilized after emplacement of the basalt dikes (Snyder, 1980b, cross section *A-A'*). The basalt dikes, in fact, may be our best indication of what the gabbro magma was like before some differentiation. Supporting this idea is the fact that the basalt dikes have median compositions between those of the gabbros and diorites on the one hand and the olivine gabbros on the other, with respect to both overall chemistry (table B1, sample 1985) and modal anorthite content (fig. 16*F*).

In summary, three processes appear to have shaped the present distribution of mafic and ultramafic rocks (table 4): (1) derivation of magma from an inhomogeneous source followed by repeated intrusions of similar or different magmas into the same crustal position; (2) intrusion of magmas that had self-contained initial inhomogeneities; and (3) some differentiation of all magmas after emplacement. Although portions of the three processes may be competitive, mostly they are complementary. Probably all three processes took place to greater or lesser degree in the roots of the Park Range.

1.7-B.Y. FELSIC INTRUSIVES

Rock series grouped here as 1.7-b.y. felsic intrusives consist of the quartz diorite of Gilpin Lake, miscellaneous mafic intrusives, the quartz monzonite of Buffalo Pass, and the quartz monzonite of Seven Lakes. Most bodies are syntectonic; many occur in small, tightly folded or contorted plutons, some in large batholiths. Rb-Sr ages range from 1.65 to 1.7 b.y. on Farwell Mountain (Segerstrom and Young, 1972, p. 16) and from 1.8 b.y. near Buffalo Pass (Snyder, 1978, p. 18) to 1.7 b.y. near Buffalo Park (Snyder, 1980c). Contact relations between different phases in different areas are complex. (See summary in table 2.)

Intermediate compositions predominate, but samples show a wide spectrum of compositional variation. Many quartzofeldspathic distributions fall in the quartz monzonite or adamellite field of common usage (right half of Streckeisen's granite field) (fig. 27*D*). The average quartz monzonite of Seven Lakes is compositionally similar to the analyzed pegmatites (samples 985 and 1011) that are grouped with it (fig. 27). Chemically there is much overlap between all analyzed representatives but, as might be expected, quartz diorites are uniformly lower in total alkalies than any quartz monzonites (tables B5 and B7).

QUARTZ DIORITE OF GILPIN LAKE

The typical quartz diorite of Gilpin Lake is a uniform, medium- to coarse-grained, speckled-gray tonalite to granodiorite consisting of major amounts of oligoclase, quartz, biotite and hornblende, in that order of abundance; variable amounts of epidote and microcline; minor amounts of muscovite, magnetite or ilmenite, carbonate, sphene, allanite, apatite, pyrite, zircon, and prehnite; and rare tourmaline (figs. 24 and 26). Rocks resembling typical quartz diorites grade into rocks typical of the quartz monzonite of Seven Lakes west of the Upper Slavonia Mine and west of Three Island Lake (see fig. 30 photomicrographs for gradational examples), but the overall CaO-alkali distribution is more continuous with that of the gabbros and diorites of Elkhorn Mountain than with any quartz monzonites (fig. 33). The quartz diorite of Gilpin Lake has not been dated directly. Ultramafic inclusions are prominent in the type Gilpin Lake and South Fork Elk River plutons (fig. 20*A*), and swarms of mafic inclusions are present in the Hole-in-Wall Canyon body (Snyder 1980b; Snyder and others, in press, fig. 10*A*).

Quartz diorites occur in small plutons of simple curviplanar outline in the drainage of the Elk River (Snyder, 1980a and b). The simple shape of the bodies may imply a late tectonic or posttectonic time of intrusion.

The striking similarity of plagioclase distributions in the Three Island Lake, South Fork Elk River, and Hole-in-Wall Canyon plutons and the equally striking statistical differences from plagioclase in the Upper Slavonia Mine and type Gilpin Lake plutons (figs. 24*D*–*G*) suggests at least three source batches for the quartz diorite magmas. The first three plutons above have modal An maxima in the same 2-percent An interval and must have had extremely similar sources and histories, whereas the latter two have modal An maxima separated by a 4-percent to 8-percent An interval and therefore must have been derived from different sources or had different histories. The skewed high-An tails of the plagioclase distributions for the Three Island Lake and South Fork Elk River plutons suggest that they are related to the Gilpin Lake pluton. Plagioclase of the type Gilpin Lake body has a minor frequency blip in the same 2-percent An interval as the mode of the Upper Slavonia Mine plagioclase histogram. These observations suggest that

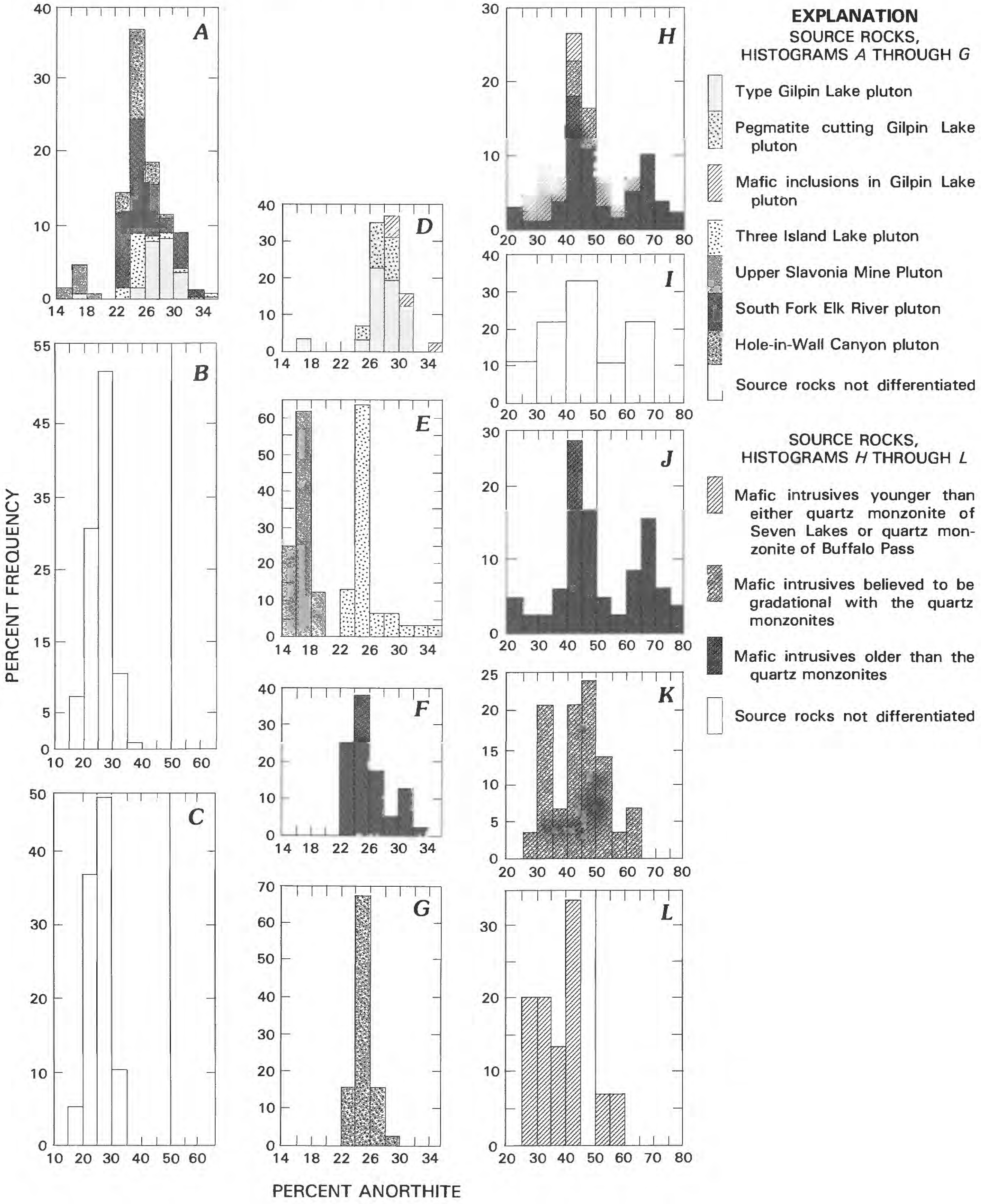
(1) The quartz diorite magmas were derived from a single relatively homogeneous source that was broadly inhomogeneous over great distances.

(2) The Three Island Lake, South Fork Elk River, and Hole-in-Wall Canyon plutons split off from this source chamber as a single mass, which then split again into three parts on its way between the source and the final sites of emplacement. Because the plutons are relatively small, solidification proceeded rapidly and evidence of their common origin is well preserved.

(3) The type Gilpin Lake and Upper Slavonia Mine plutons either split off from different parts of the same source magma, or split off at slightly different times if compositional differentiation was proceeding in the parent mass. Source and tectonic conditions were similar enough for these two batches that their sites of emplacement were in the same general vicinity as the other related plutons.

MISCELLANEOUS MAFIC INTRUSIVES

Miscellaneous mafic intrusive bodies consist of dark, uniform, medium-grained metamorphic rocks that contain predominant hornblende; a few contain relict pyroxene. Some small mafic bodies occur as inclusions within the quartz monzonites of Seven Lakes and Buffalo Pass, and others are cut by dikes of one or the other of these quartz monzonites (Snyder and others, in press, fig. 10*B*). However, some of the mafic rocks grade into quartz monzonite, some contain inclusions of quartz monzonite, and some cut quartz monzonite. Apparently, small mafic intrusives were emplaced either continuously or episodically over the same span of time as the quartz monzonites. The textures and mineral compositions of the mafic rocks are not invariably related to age as determined by contact relations with the enclosing rocks. (See descriptions of samples 1735 and 2033, fig. 30.) Plagioclase in the younger mafic rocks is somewhat more albitic than that in older rocks of the group (figs. 24*I–L*). The older mafic intrusive rocks are



chiefly hornblende-biotite diorite or gabbro containing various amounts of quartz, garnet, orthopyroxene, clinopyroxene, microcline, magnetite or ilmenite, apatite, and epidote, and accessory chlorite, carbonate, pyrite, wollastonite(?), and sphene. The typical mafic rocks gradational with quartz monzonite are quartz-plagioclase-biotite diorite containing various amounts of hornblende or tremolite and microcline, and accessory apatite, chlorite, carbonate, muscovite, epidote, allanite, and magnetite or ilmenite. The youngest mafic intrusive rocks are mostly hornblende-plagioclase-biotite diorite containing various amounts of quartz or clinopyroxene and accessory sphene, apatite, pyrite, epidote, chlorite, and prehnite(?).

Plagioclase compositions in small mafic intrusives older than, gradational into, and younger than the quartz monzonites are presented in figures 24*H–L*. The plagioclase compositional distribution in the older rocks is distinctly bimodal (fig. 24*J*) perhaps because several distinct groups of rocks have been included. A number of diorites that have plagioclase An_{40-45} are included with a smaller, but distinct, population of gabbros having plagioclase An_{65-70}. There are some similarities in plagioclase composition between the older gabbros and the basalt dikes of the Elkhorn Mountain batholith (compare figs. 24*J* and 16*F*), but it is not certain they were derived from the same source or emplaced at precisely the same time. The older diorites have not been recognized as discrete bodies elsewhere, although many similar appearing diorites are included in the population of Elkhorn gabbros and diorites (fig. 16*E*).

FIGURE 24 (facing).—Plagioclase composition histograms for 380 individual crystals from the quartz diorite of Gilpin Lake (*A* through *G*) and miscellaneous mafic intrusives (*H* through *L*). All frequency histograms, except *C* and *I*, are based on data from different single crystals, *C* and *I* are based on average plagioclases of different rock samples. For comparing different figures, the An_{50} line is shown where appropriate. Histograms show anorthite contents for the following:

A, 252 individual plagioclase crystals from quartz diorite of Gilpin Lake (all bodies). Two-percent class intervals.

B, Same as *A*, at 5-percent An class intervals, for comparison of quartz diorite plagioclase distribution with those of other figures.

C, Average (mean) plagioclase in 19 quartz diorite samples in which five or more plagioclase crystals have been measured. Five-percent An class intervals.

D, 57 individual plagioclase crystals from rocks associated with the type Gilpin Lake pluton: 35 crystals from typical rocks of the main body, 16 from pegmatite dikes or veins cutting the main plutonic rocks, and 6 from mafic inclusions (see text) in the main plutonic rocks. Two-percent An class intervals.

E, Plagioclase from two quartz diorite plutons, both believed to be gradational with quartz monzonite of Seven Lakes: body northwest of Upper Slavonia mine (sample 1140, 16 crystals, avg= $An_{16.5}$), and body west of Three Island Lake (30 crystals).

F, 103 plagioclase crystals from the quartz diorite pluton exposed along the South Fork of the Elk River south of Seedhouse Campground.

G, 46 plagioclase crystals from the quartz diorite pluton exposed along Hole-in-Wall Canyon northwest of Seedhouse Campground.

H, 128 plagioclase crystals from miscellaneous mafic intrusives. Five-percent class interval.

I, Average (mean) plagioclase in nine miscellaneous mafic intrusives in which five or more plagioclase crystals have been measured. Ten-percent class intervals.

J, 84 plagioclase crystals from miscellaneous mafic intrusives older than either the quartz monzonite of Seven Lakes or the quartz monzonite of Buffalo Pass.

K, 15 plagioclase crystals from miscellaneous mafic intrusives believed to be gradational with either the quartz monzonite of Seven Lakes or the quartz monzonite of Buffalo Pass.

L, 29 plagioclase crystals from miscellaneous mafic intrusives younger than either the quartz monzonite of Seven Lakes or the quartz monzonite of Buffalo Pass.

The plagioclase compositions in the small mafic intrusive rocks gradational into quartz monzonite are shown in figure 24*K*. The observed gradational behavior is similar to that observed for two of the Gilpin Lake quartz diorite plutons (see fig. 24*E*) but the subsidiary peak between An_{30} and An_{35} in figure 24*K* (small mafic bodies) seems to be significantly different from either of the peaks in figure 24*E* (gradational quartz diorite).

The plagioclase compositions in rocks of the small mafic intrusive bodies younger than quartz monzonite are shown in figure 24*L*. The peak at An_{25-35} matches a peak on the plagioclase composition histogram of the type Gilpin Lake pluton in figure 24*D*, but there is nothing about the type Gilpin Lake body to suggest that it is as young as the rocks grouped in figure 24*L*.

Besides the small mapped bodies of mafic intrusive rocks, there are many mafic dikes too small to map. The glaciated exposures on top of the cliff north of the road due west of Seedhouse Campground display amphibolite dikes cutting gneisses at such a low angle that the discordant relations with the gneiss might have been missed in a poorer exposure. Some contact relations are extremely complex. For example, in an area at 9,640 feet (2,938 m) elevation 1 mile (1.6 km) east of Dome Peak, two ages of amphibolite dikes cutting a granitic phase of the quartz monzonite of Seven Lakes have been reintruded by remobilized granite and pegmatite. In addition the older of the two amphibolite dikes has been remobilized enough to intrude parts of the younger one (fig. 25). Such small-scale relations are fairly common in the northern Park Range and adjoining areas (Houston and Karlstrom, 1979, fig. 3.5, p. 297).

QUARTZ MONZONITES OF BUFFALO PASS AND SEVEN LAKES

Quartz monzonites emplaced about 1.7 b.y. ago (fig. 26) comprise two groups of plutons, the Buffalo Pass pluton on the south and the Seven Lakes pluton on the north. They are separated by the 1.4-b.y.-old Mount Ethel

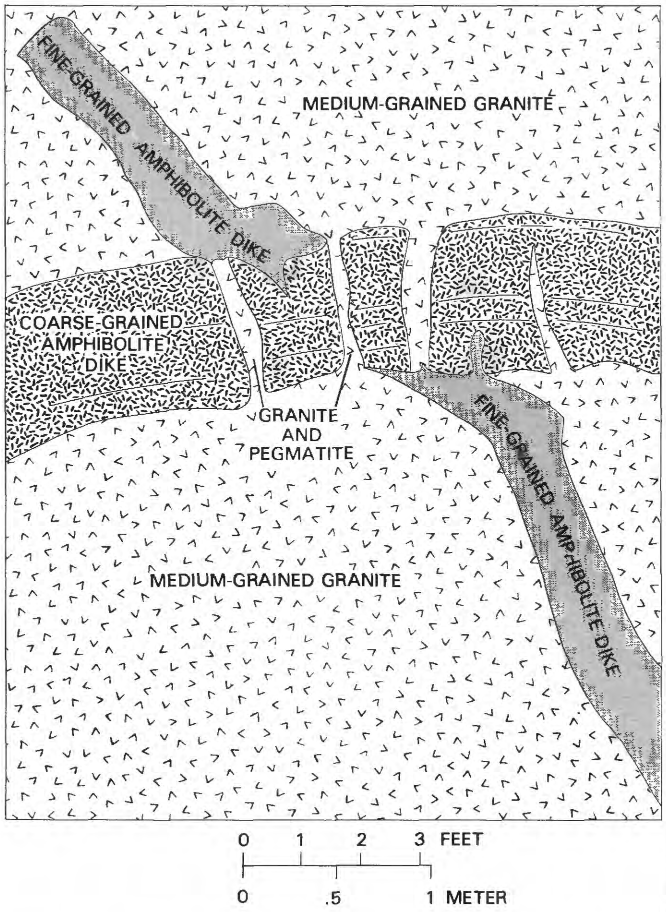


FIGURE 25.—Metamorphically remobilized granite and amphibolite cropping out at 9,640 feet (2,938 m) elevation 1 mile (1.6 km) east of Dome Peak, Farwell Mountain 7 1/2-minute quadrangle, Colorado.

quartz monzonite pluton. The quartz monzonite of the Buffalo Pass pluton was originally thought to be limited to small pretectonic or syntectonic sills and other discordant tabular bodies (Snyder, 1978, 1980a), but it has been found to expand southward into a batholith that is exposed at Rabbit Ears Pass and in the area to the south (Snyder, 1980c; Tweto, 1976b). North of the Mount Ethel pluton the metamorphic rocks and older intrusives have been injected with a plexus of tabular to irregular large to small bodies of pretectonic or syntectonic quartz monzonite, previously called the quartz monzonite of Seven Lakes (Snyder, 1980b). The quartz monzonite in these small bodies is lithologically similar to that of the Buffalo Pass batholith, but there are some differences in radiometric age and in chemical and lithologic character (figs. 27 and 33; Snyder and others, in press) that make it useful to retain the distinction.

As here used, the name quartz monzonite is applied to the right (plagioclase-rich) half of the granite field of Streckeisen (1973 and 1976) or the adamellite field of Lyons (1976). The rock groups in which such quartz monzonites predominate include rocks that range from granodiorite through the quartz monzonites of Streckeisen (quartz-rich monzonites of Lyons) to Streckeisen syenogranites (fig. 27). All of them are light-colored pink, red, gray, or white, fine- to coarse-grained rocks (fig. 28). They range from equigranular aphanites through augen gneisses containing subhedral to euhedral, fluidally arranged microclines as much as 2 in (5 cm) in maximum dimension (fig. 29) to flaser gneisses and migmatites containing xenoliths of pelitic schist. The various textural phases are commonly intergradational but are locally in sharp contact, as in the areas north of Seven Lakes (Snyder, 1980b) and south of Rabbit Ears Pass (Snyder, 1980c). The Buffalo Pass batholith is zoned from a discontinuous outer 2-mi (3-km)-wide zone of pelitic-xenolithic gneiss or sillimanitic quartz monzonite to an inner mass of randomly intermixed fluidal augen gneiss (fig. 29) and equigranular gneiss.

Mineralogically, the Buffalo Pass and Seven Lakes rocks are quite similar (figs. 27 and 30). The Buffalo Pass rocks are oligoclase-microcline-quartz-biotite quartz monzonites containing various amounts of hornblende and muscovite and accessory epidote, sphene, magnetite-ilmenite, apatite, allanite, carbonate, zircon, prehnite and pyrite (Snyder, 1978, tables 4 and 5). In the Buffalo Pass rocks microcline generally predominates over quartz, but in the quartz monzonite of Seven Lakes (fig. 30) the reverse is true. Trace amounts of garnet and fluorite are more characteristic of the Seven Lakes rocks than of the Buffalo Pass rocks.

None of the Seven Lakes bodies is large enough to be termed a batholith, although they may merge at depth to form such a mass. One bit of geochemical evidence suggests that they do. Sediments in streams draining the Seven Lakes highland in the central part of the northernmost Park Range between Davis Peak and Mount Zirkel, an area mainly underlain by quartz monzonite, are slightly higher in beryllium and uranium than most other stream sediments in the surrounding region (Snyder and others, in press). This geochemical concentration may be a flue effect from a quartz monzonite mass that becomes increasingly larger with depth, that is, batholithic in dimensions.

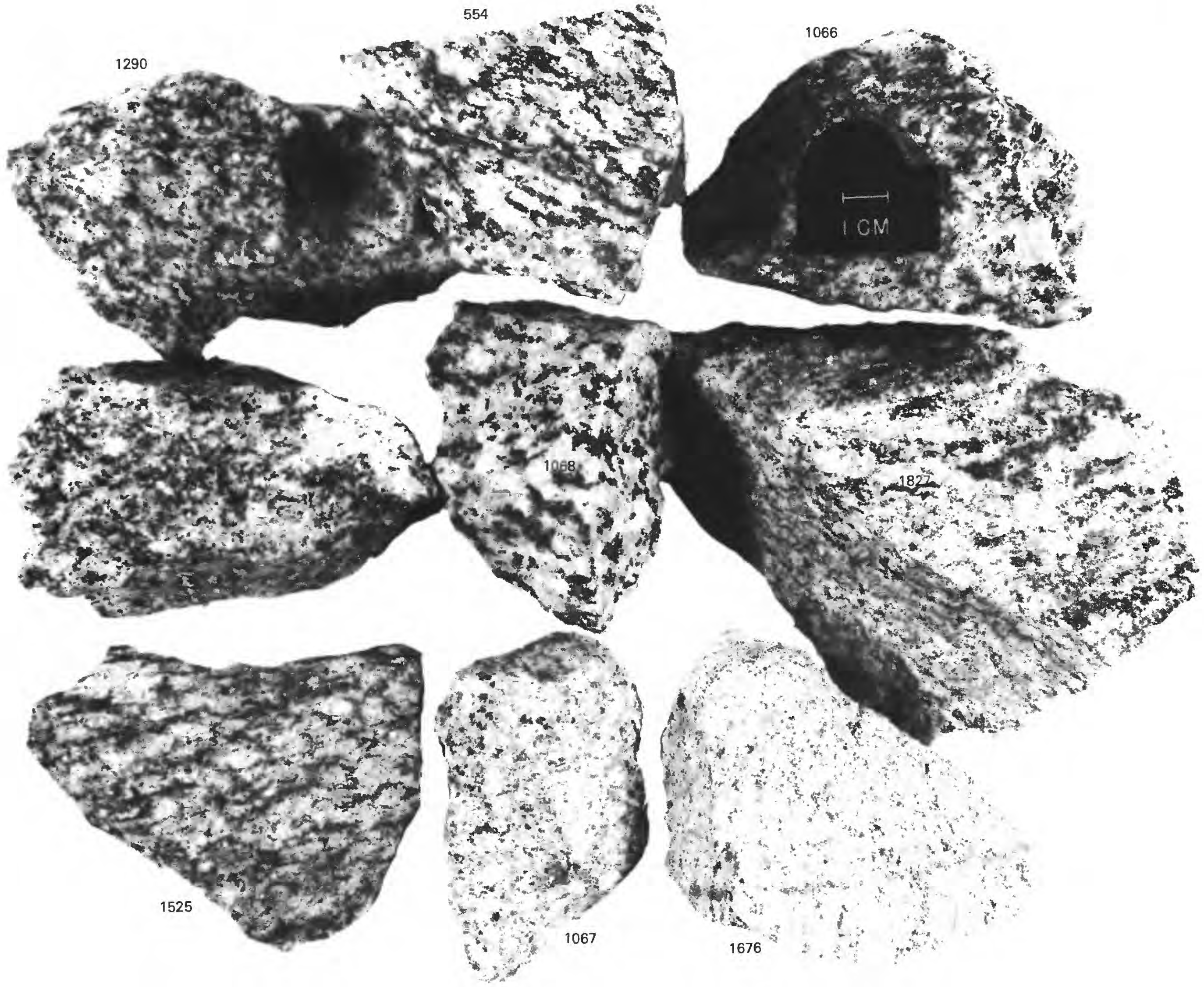


FIGURE 26.—Hand specimens of selected analyzed 1.7-b.y.-old quartz monzonites (adamellites) and granodiorites, arranged in general order of increasing silica content from upper left to lower right (65.80 percent to 77.38 percent SiO_2). Photograph by Louise S. Hedricks.

SAMPLE DESCRIPTIONS

1290, Granodiorite from quartz diorite of Gilpin Lake in Hinman Creek (tables B5 and B6). See figure 28*A* for thin section.

554, Quartz monzonite augen gneiss on Buffalo Mountain. This rock contributes to a five-point Rb/Sr isochron by Carl Hedge indicating an age of 1.8±0.1 b.y. (Snyder, 1978, table 5 and p. 18).

1066, Granodiorite augen gneiss southwest of Big Creek Lakes (tables B7 and B8). See figure 28*B* for thin section.

984, Quartz monzonite gneiss from ditch exposure east of Big Creek Lakes (tables B7, B8).

1068, Quartz monzonite augen gneiss from Seven Lakes (tables B7 and B8). See figure 28*D* for thin section.

1827, Quartz monzonite augen gneiss from crest of Black Mountain (tables B7 and B8). See figure 28*E* for thin section.

1525, Quartz monzonite gneiss from southeast Farwell Mountain (tables B7 and B8), the area where Carl Hedge measured an Rb/Sr isochron of 1.65-1.7 b.y. (Segerstrom and Young, 1972, p. 16).

1067, Granular quartz monzonite from summit of Davis Peak (tables B7 and B8). See figure 28*F* for thin section.

1676, Granular quartz monzonite from a body cutting the gabbro of Elkhorn Mountain northeast of Whiskey Park (tables B7 and B8). See figure 28*G* for thin section.

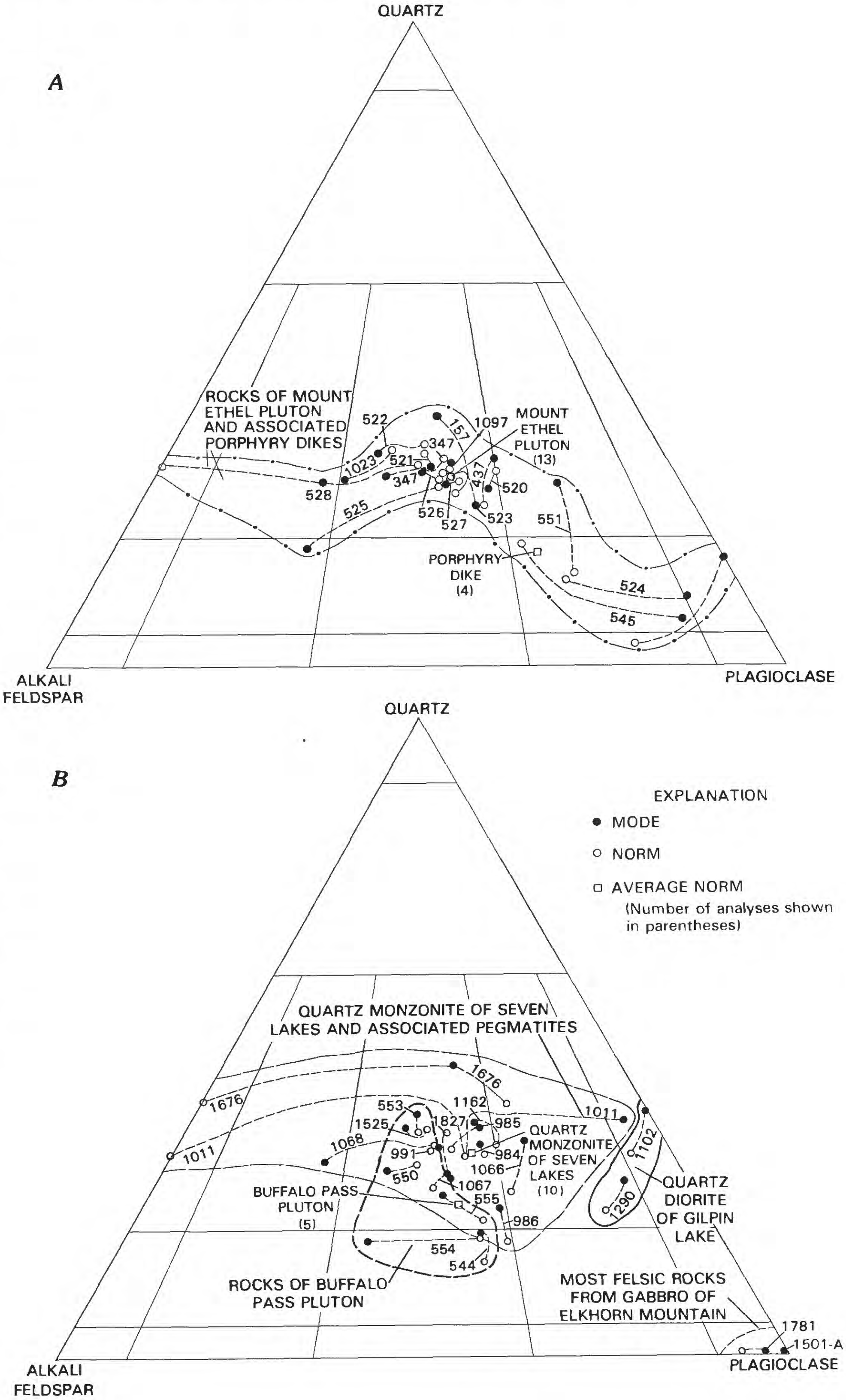


FIGURE 27.—Modal and normative quartz-alkali feldspar-plagioclase triangular graph plots of selected analyzed rocks of the northernmost Park Range, Colo. Two norms are plotted for several samples, and two modes are plotted for sample 1028. These rocks have plagioclase compositions ranging from An_0 to An_5, so the plots along the left margins of the triangular diagrams are for Streckeisen nomenclatural purposes (plagioclase lumped with alkali feldspar) while the other, more central plots are for consistent comparison with the other rocks in the same families (plagioclase plotted as plagioclase).

A, 1.4-b.y.-old analyzed intrusive rocks of the Mount Ethel pluton and associated porphyry dikes. Average norm of Mount Ethel pluton includes one rock from this report (1023, tables B5 and B6) and twelve numbered rocks from Snyder (1978, table 5), with the average recalculated to 100 percent minus H_2O^-. Average norm of porphyry dike includes one rock from this report (1097, tables B5 and B6) and three numbered rocks from Snyder (1978), with the average recalculated to 100 percent minus H_2O^-.

B, 1.7- to 1.8-b.y.-old analyzed intrusive rocks of the northernmost Park Range, including the four families of rocks outlined. All five numbered rocks of the Buffalo Pass pluton are described by Snyder (1978), and the average is recalculated to 100 percent minus H_2O^-. All other rocks plotted here are described in this report (tables B1, B2, and B5-B8); average norm of quartz monzonite of Seven Lakes is from column 11 of table B7.

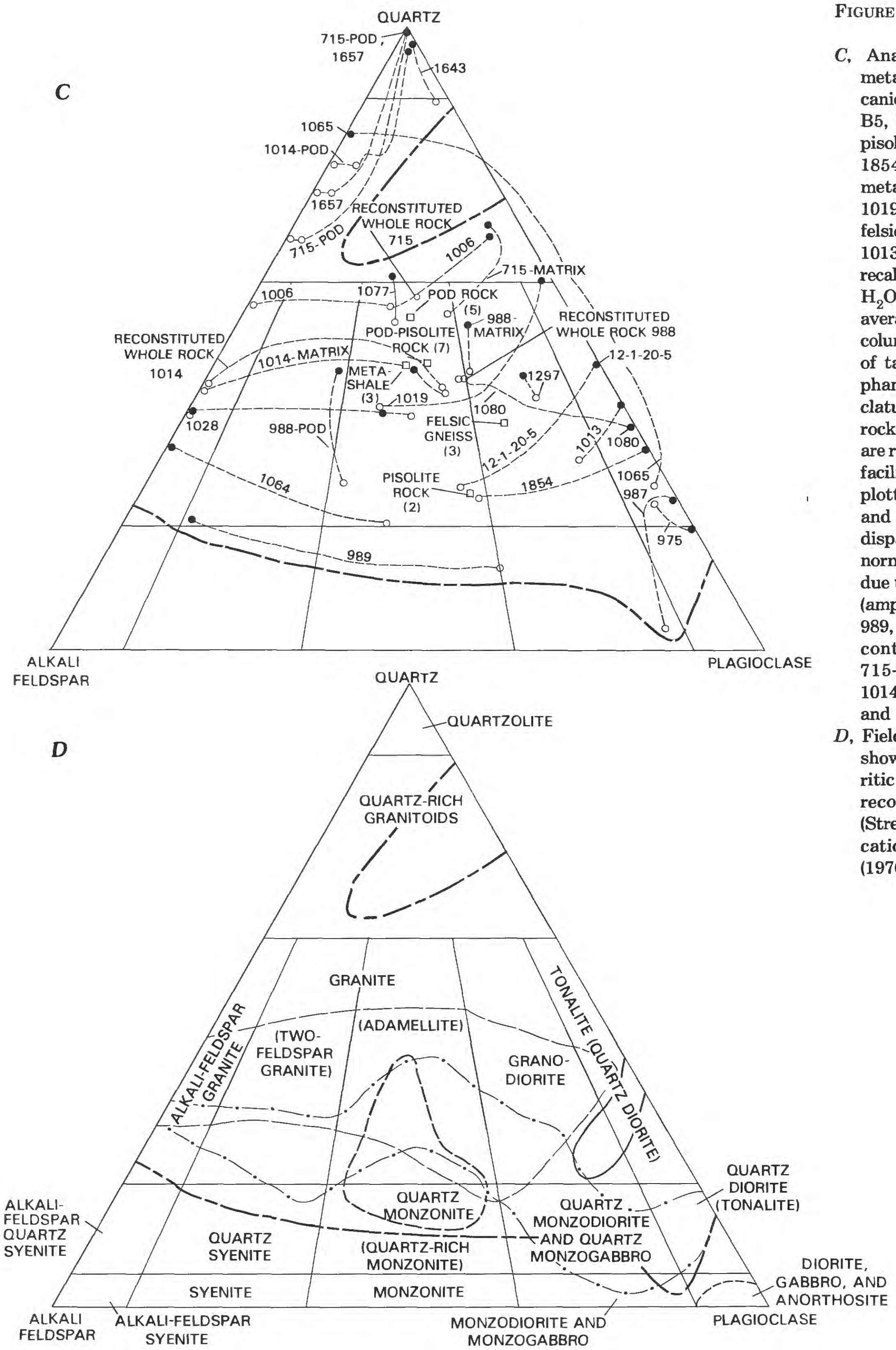
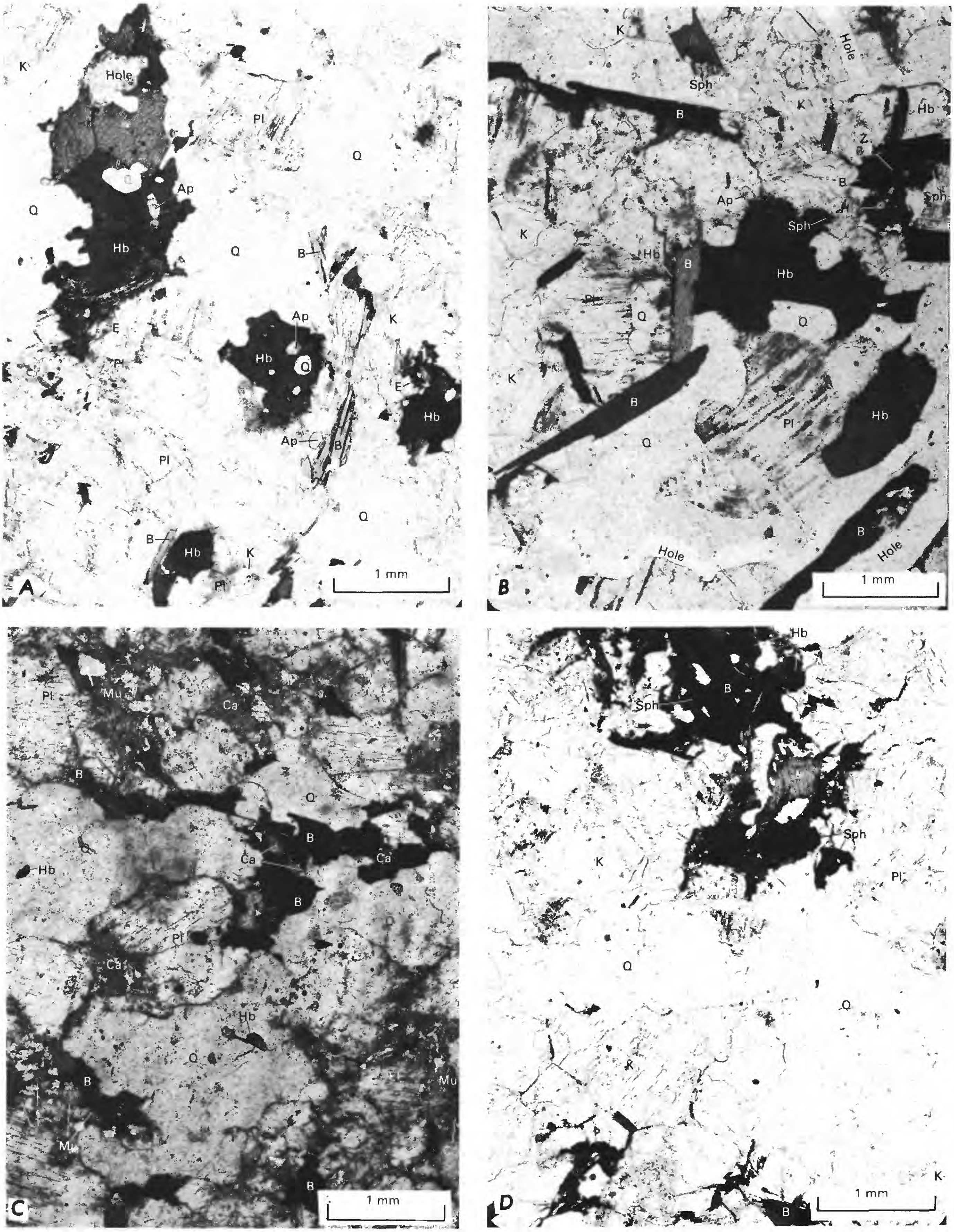


FIGURE 27.—Continued.

C, Analyzed 1.8-b.y.-old layered metasedimentary and metavolcanic rocks (described in tables B5, B6, and B9–B12). Average pisolite rock is mean of samples 1854 and 12-1-20-5; average metashale is mean of samples 1019, 1077, and 1080; average felsic gneiss is mean of samples 1013, 1028, and 1297 (all means recalculated to 100 percent minus H_2O^-). Average pod rock and average pod-pisolite rock are from columns 1B and 2B, respectively, of table B11. Even though the phaneritic intrusive rock nomenclature is inappropriate for these rocks, the nomenclatural fields are repeated here, as elsewhere, to facilitate comparison with the plotted intrusives of plots *A*, *B*, and *D*. The unusually large disparity between modes and norms on this plot is probably due to low felsic mineral content (amphibolite 987 and marbles 989, 1064, and 1065) or high mica content (samples 715-pod, 715-matrix, 988-pod, 1006, 1014-pod, 1019, 1080, 1657, 1854, and 12-1-20-5).

D, Fields from plots *A*, *B*, and *C*, shown superimposed on phaneritic igneous rock nomenclature recommended by the IUGS (Streckeisen, 1973, 1976). Modifications suggested by Lyons (1976) in parentheses.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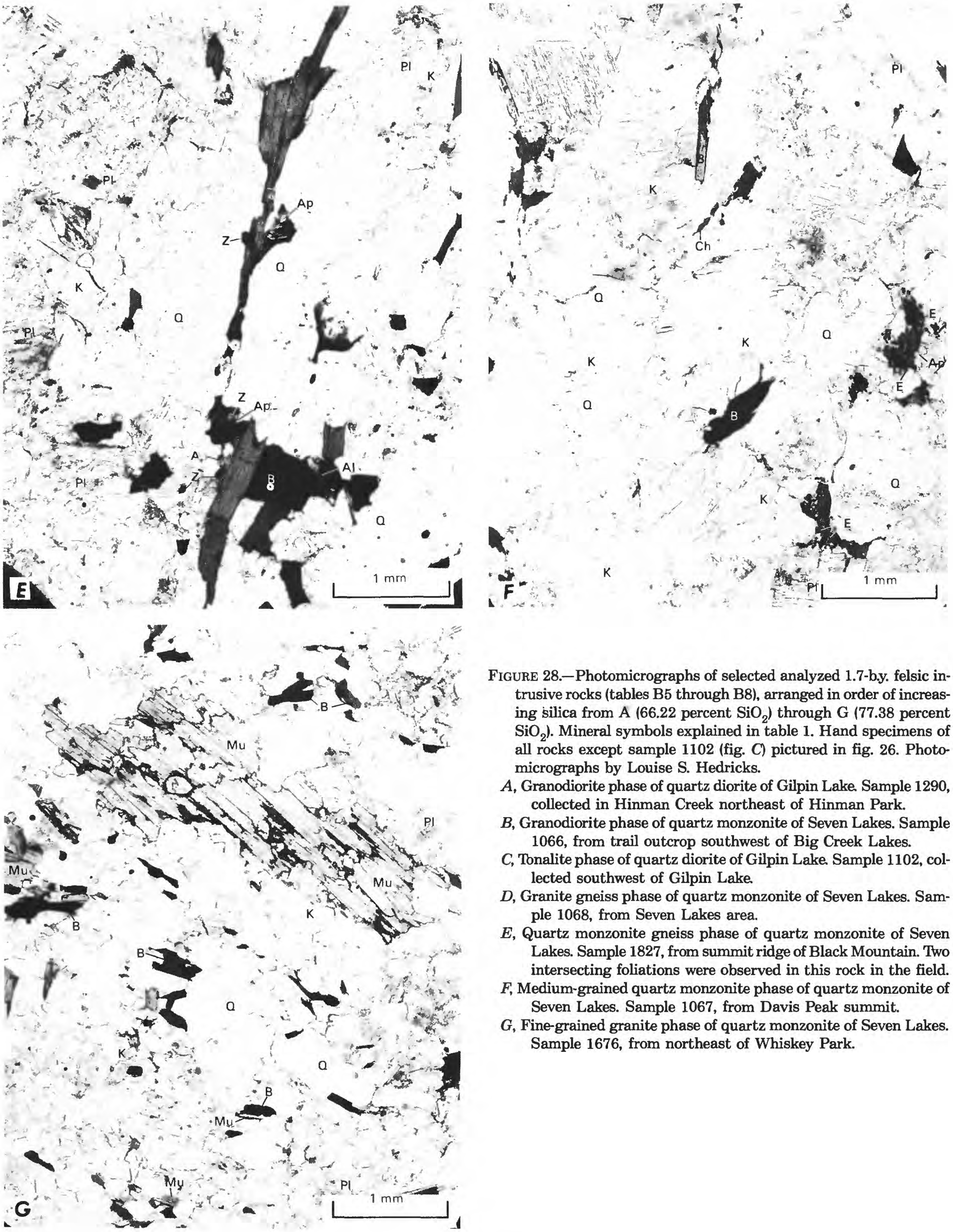

FIGURE 28.—Photomicrographs of selected analyzed 1.7-b.y. felsic intrusive rocks (tables B5 through B8), arranged in order of increasing silica from A (66.22 percent SiO_2) through G (77.38 percent SiO_2). Mineral symbols explained in table 1. Hand specimens of all rocks except sample 1102 (fig. C) pictured in fig. 26. Photomicrographs by Louise S. Hedricks.

A, Granodiorite phase of quartz diorite of Gilpin Lake. Sample 1290, collected in Hinman Creek northeast of Hinman Park.

B, Granodiorite phase of quartz monzonite of Seven Lakes. Sample 1066, from trail outcrop southwest of Big Creek Lakes.

C, Tonalite phase of quartz diorite of Gilpin Lake. Sample 1102, collected southwest of Gilpin Lake.

D, Granite gneiss phase of quartz monzonite of Seven Lakes. Sample 1068, from Seven Lakes area.

E, Quartz monzonite gneiss phase of quartz monzonite of Seven Lakes. Sample 1827, from summit ridge of Black Mountain. Two intersecting foliations were observed in this rock in the field.

F, Medium-grained quartz monzonite phase of quartz monzonite of Seven Lakes. Sample 1067, from Davis Peak summit.

G, Fine-grained granite phase of quartz monzonite of Seven Lakes. Sample 1676, from northeast of Whiskey Park.

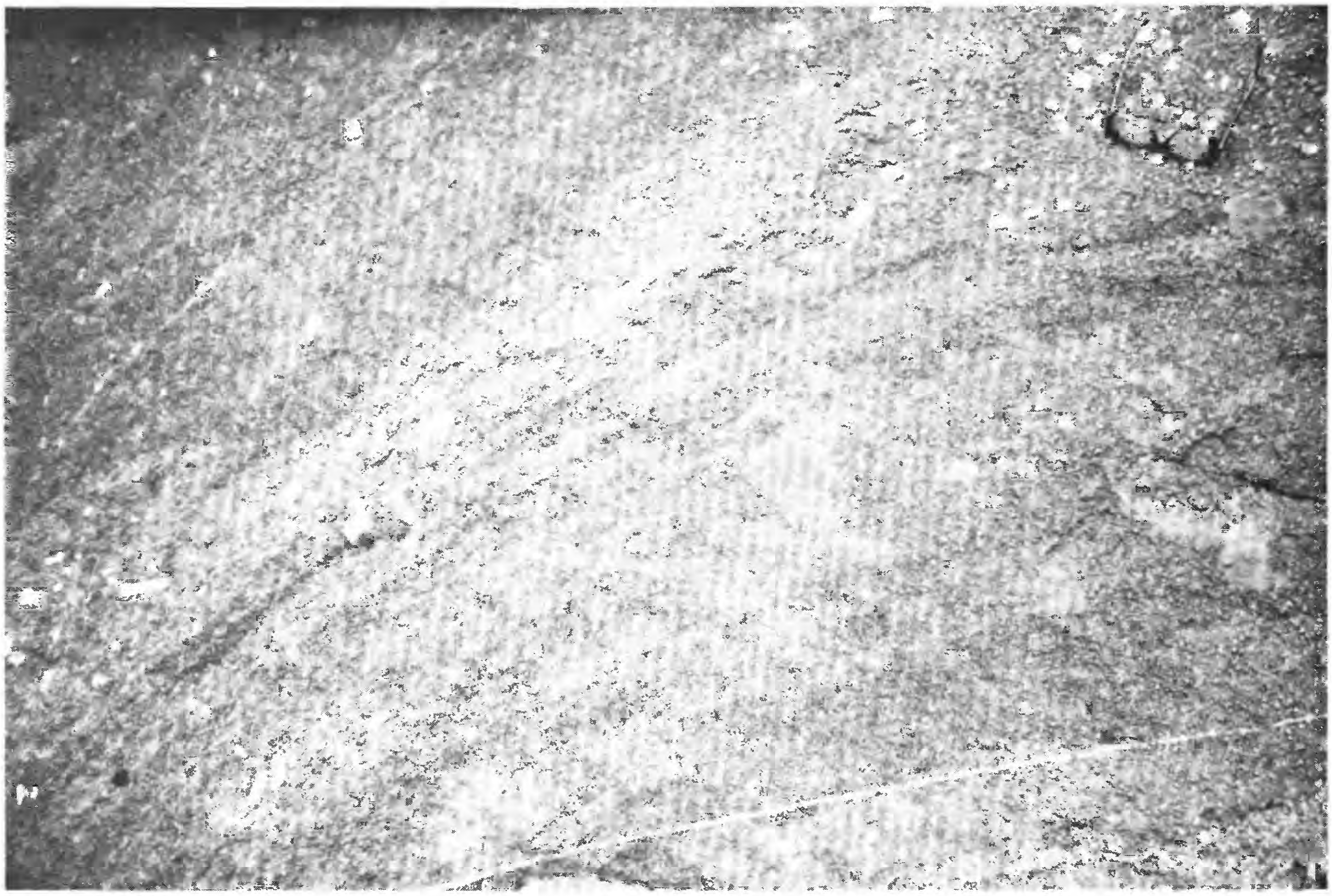

FIGURE 29.—Quartz monzonite of Buffalo Pass between head of Harrison Creek and the 10,296-foot (3,138.2-m) peak 1.6 mi (2.6 km) S. 15° W. of the summit of Walton Peak, showing fluidal swarms of euhedral potassium feldspar phenocrysts parallel to biotite folia. Eyeglasses for scale.

1.4-B.Y. FELSIC INTRUSIVES

A large, steep-sided batholith of granitic rocks emplaced about 1.4 b.y. ago is centered on Mount Ethel and extends northeast beneath the Mesozoic and Tertiary sedimentary deposits in North Park. The batholith consists mainly of quartz monzonite, but the rocks range from diorite to leucogranite. Five mappable lithologic variants (Snyder 1980a, 1980b) have sharp dilational contacts with one another and increase in average SiO_2 content from oldest to youngest. In addition, cogenetic porphyry dikes occur partly inside and partly outside the batholith (Snyder, 1980a, 1980b, 1980c). Contact relations of all phases are summarized in figure 13. Field relations, petrography, and chemistry of the rocks of the Mount Ethel pluton have been described in detail by Snyder (1978). A few new analyses are reported here (tables B5 and B6 and fig. 31), and the analyzed samples and a few other typical hand specimens are pictured in figure 32. Chemically 1.4-b.y. plutonic rocks are coextensive with and generally indistinguishable from 1.7-b.y. plutonic rocks. Although their quartzo-feldspathic distribution fields are different in detail (fig. 27), the average rock of the Mount Ethel pluton (1.4-b.y.) is intermediate between the average quartz monzonite of Seven Lakes and the average rock of the Buffalo Pass pluton (both 1.7 b.y.); all cluster near petrogeny's residua system.

ORIGIN OF INTRUSIVE ROCKS

Based on the "Peacock chemical index" (that is, the SiO_2 value where the CaO variation line of an intrusive suite intersects the Na_2O+K_2O variation line on a silica variation diagram; Peacock, 1931), the Park Range intrusives range from calc-alkalic through alkali-calcic to alkalic. Most of the suites have distinctive Peacock indices, but some of the suites are quite similar, and more data might show that some of them merge into one another. And there are some similarities involving the gabbros, ultramafics, and quartz diorites. Taken in order of their presentation on figure 33, the following Peacock indices and descriptive terms seem appropriate:

Rock body	Peacock index	Character
Mount Ethel pluton ---	56	Near boundary between alkali-calcic and calc-alkalic.
Porphyry dikes -------	56	Do.
Buffalo Pass pluton ---	45	Alkalic (projected).
Seven Lakes plutons ---	49.5	Do.
Gilpin Lake plutons ---	58.5	Calc-alkalic.
Gabbro of Elkhorn Mountain.	59	Do.
Ultramafic rocks ------	≈ 33.5	Alkalic.

The porphyry dikes listed above are considered part of the suite from the Mount Ethel plutons, so the identical index is not surprising. Values for the Buffalo Pass pluton and the Seven Lakes plutons both represent long projections from the last data points near 64. The index for the Gilpin Lake plutons is based on only four points, but it is quite distinct from the trend for the Seven Lakes plutons, with which this unit intergrades locally. The Elkhorn Mountain index is also a projection, but this is the most calcic of all suites, and there seems no way it could be anything other than calc-alkalic. The Elkhorn Mountain and Gilpin trends come closer to intersecting in the same point than any others, and they are broadly continuous with one another, perhaps because some Elkhorn Mountain material was assimilated in an initial Seven Lakes magma—an interpretation consistent with the observation of mafic and ultramafic inclusions in the Gilpin Lake plutons.

Most ultramafic rock samples fall on a narrow alkali trend (horizontal at about 0.5 percent alkali) and a broad lime trend that intersect near 33.5 (anomalous samples are 1112, the phlogopitic soapstone, and 1194, the poikilitic enstatite). These trends lie at angles of 160° and 120°, respectively, to the comparable trends of the Elkhorn Mountain pluton, supporting the view that these two mafic, partly geographically contiguous suites probably have different origins. (The CaO values of the ultramafic pods (samples 1412 and 1428) within the mapped olivine gabbro of the Elkhorn Mountain pluton fit the regional ultramafic trend, *not* the regional Elkhorn trend.)

The following history is consistent with the field relations and petrochemical character of the intrusive rocks of the northern Park Range:

(1) Partial mantle melting prior to 1.8 b.y. ago supplied granitoid intrusives (here unstudied) on Wyoming continent to north.

(2) Clastic, chemical, and volcanic sediments and some massive volcanics accreted on flanks of the old continent about 1.8 b.y. ago. Isotope data "require that the Colorado crust be derived from the mantle *in toto* 1,800 Myr ago with the crust formation process involving no reconstitution of older crust" (DePaolo, 1981, p. 195).

(3) Gabbros and diorites of Elkhorn Mountain intruded the sedimentary and volcanic rocks 1.8 b.y. ago after stabilization of new crust but prior to climax of regional dynamothermal metamorphism and tectonism. The gabbros and diorites originated in a deep mantle source possibly tapped by vertical shearing (Warner, 1978) controlled by the old continental margin. Gabbro-diorite magma was emplaced accompanied by solid rafts of ultramafic mantle, some of which is also intruded in separate small bodies. The last stage of intrusive activity in the vicinity of the present Elkhorn Mountain batholith was the emplacement of basalt dikes, derived from some lower level of the still-liquid batholith and injected into its near-solid roof. Some small bodies of mafic gabbro compositionally and temporally similar to these basalts may have been intruded far away from the Elkhorn Mountain batholith at this time.

(4) Buffalo Pass and Seven Lakes plutons intruded during peak of regional dynamothermal metamorphism and tectonism after being formed as new partial melts of mantle or conceivably as remelted subducted crust (Hills and Houston, 1979; Condie, 1982). Some intermediate rocks formed at the contact between the Elkhorn Mountain and Seven Lakes bodies by partial assimilation; possibly some or all of the Gilpin Lake plutons formed in this manner. The details of the Gilpin Lake plagioclase distributions suggest an unusual intrusive history. The main part of the Buffalo Pass batholith, to the south, brought along solid rafts of more mafic phases including many ultramafic pods. A few small mafic and ultramafic intrusives were emplaced late in this intrusive sequence.

(5) Area stabilized and cooled over a span of 0.3–0.4 b.y.

(6) Melting of lower continental crust was renewed 1.4 b.y. ago, and quartz monzonite (Mount Ethel) magma intruded in six separate phases by block caving and cauldron subsidence. Wall rocks were warm but not as hot as previously. Porphyry dikes overlap the middle phase of the phaneritic batholith in age (Snyder, 1978).

(7) Major left-lateral northeast-trending transcurrent faulting 1.2 b.y.(?) ago, partly along old Wyoming continental margin, possibly along traces of previous faults. All previous Precambrian rocks selectively mylonitized along these cool shear zones.

(8) Extremely minor intrusions of quartz trachyte dikes south of the area about 1 b.y. ago (in Gore Canyon, southwest of Kremmling; C. S. V. Barclay, oral communs. prior to 1976).

ESTIMATES OF PRECAMBRIAN CRUSTAL COMPOSITION

Although it is now nearly universally agreed that the Earth's crust must have been differentiated or derived from the deeper zones of the Earth (for example, Ringwood, 1975; Kerr, 1979), strict mathematical constraints are seldom placed on the chemistry of this derivation, partly because volume-weighted crustal chemistry is rarely available. The following sections will attempt to fill this lack of volume-weighted crustal chemistry, in as rigorous a way as possible for the Park Range and as an approximation for Colorado as a whole.

PARK RANGE

All available chemical analyses of rocks from the northern Park Range in the area of plate 1 have been used in arriving at a quantitative estimate of the chemical composition of the crust at four separate times in the Precambrian (table B13; figs. 34 and 35). The analyses used are as follows:

SAMPLE DESCRIPTIONS AND LOCALITIES FOR FIGURE 30

[Samples in order from lower left up each succeeding column to upper right. Table references given for samples listed in tables. For others, minerals are listed in order of decreasing abundance]

1014 composite: Combined (mainly matrix) data from seven thin sections from 1-cubic-foot (0.03-m^3) sample of analyzed metavolcanic(?) siliceous pod rock from Independence Mountain (tables B11C and B12).

1014F14, 1014A, and 1014F10: Data from three of the thin sections that contributed to the 1014 composite. Sections chosen to illustrate maximum spread of data.

1006: Data from analyzed metavolcanic(?) siliceous pod rock from Independence Mountain (tables B9 and B10).

715: Data from analyzed metavolcanic(?) siliceous pod rock from Independence Mountain (tables B11B and B12).

Composite analyzed quartz monzonite of Seven Lakes: Combined data from all 10 analyzed intrusive rocks in tables B7 and B8, data distributed as follows (number in parentheses is number of plagioclase crystals determined): 986 (2), 1066 (7), 984 (5), 1162 (3), 1068 (2), 1827 (18), 991 (2), 1525 (4), 1067 (4), and 1676 (27).

988: Data from analyzed metavolcanic(?) siliceous pod rock from Independence Mountain (tables B11A and B12).

1854 and 12-1-20-5 composite: Combined data from two analyzed pisolite rocks on Farwell Mountain (tables B10 and B11).

1290: Data from analyzed intrusive quartz diorite of Gilpin Lake, Hole-in-Wall Canyon body (tables B5 and B6).

1283: Data from another sample of intrusive quartz diorite of Gilpin Lake 0.85 mile (1.37 km) N. 30° E. of sample 1290 and near rim of Hole-in-Wall Canyon. Plagioclase-quartz-hornblende-microcline-biotite granodiorite containing minor epidote, apatite, magnetite-ilmenite, allanite, and sphene.

1843 composite: Combined data from three thin sections of intrusive quartz diorite of Gilpin Lake from an 8-acre (3¼-hectare) roche moutonnée outcrop on the northwest shore of Gilpin Lake. The three samples were independently collected from the same general area by three different geologists at intervals of 2 years between each visit, and the individual sample data are shown in the next three histograms. Poikilitic plagioclase-quartz-biotite-hornblende quartz diorite containing minor epidote, apatite, zircon, prehnite? (pods dilating biotite), and allanite.

1843 GS: Type quartz diorite of Gilpin Lake collected by George Snyder, July 1973.

1843 PG: Type quartz diorite of Gilpin Lake collected by Paul Graff, August 1971.

1843 AF: Type quartz diorite of Gilpin Lake collected by Arthur French, August 1975.

1107: Type quartz diorite of Gilpin Lake located at 9,700 feet elevation between analyzed sample 1102 (tables B5 and B6) and sample 1843 (above). Plagioclase-quartz-biotite-hornblende quartz diorite containing minor epidote, apatite, magnetite-ilmenite, and zircon and rare potassium feldspar and pyrite.

975 composite: Combined data from six thin sections of analyzed "turkey-track-gedrite" metavolcanic(?) rock in Line Creek road cut (tables B5 and B6).

1735 and 2033 composite: Combined data from two samples of a small mafic intrusive containing angular inclusions of quartz monzonite, exposed in road cuts near runaway-truck ramp 0.7 mile (1.1 km) northwest of Ferndale Picnic Area on west side of Rabbit Ears Pass. Poikilitic hornblende (poikilitic with randomly oriented biotites)-poikilitic plagioclase-quartz-biotite diorite containing minor prehnite(?) (pods dilating biotite), apatite, magnetite or ilmenite, and sphene, and rare chlorite.

2036 and 2040 composite: Combined data from two samples of a small gabbro intrusive body cut by dikes of quartz monzonite of Buffalo Pass ⅓ and ⅔ miles (½ and 1 km) north-northeast of the summit of Mount Werner. Tabular plagioclase–poikilitic hornblende-biotite gabbro containing minor chlorite rosettes, carbonate, magnetite-ilmenite, and quartz, and a symplectite of intergrown amphibole and anorthite near some hornblende-labradorite contacts (figs. 20*G* and *H*). Possibly this pluton is an equivalent to the larger Elkhorn Mountain and Farwell Mountain plutons, which it resembles.

987 composite: Combined data from three thin sections of analyzed sample 987, layered amphibolite metavolcanic rock (tables B5 and B6). Except for the faint layering, this is a uniform rock, and there is no chance whatsoever that the actual rock plagioclase represented by this histogram could have an anorthite content as high as An_{56}, as predicted by the norm (table B5). The necessary theoretical anorthite constituents missing from the actual rock plagioclase must be present in other rock minerals (mainly hornblende).

2045: Data from inclusion of mafic quartz diorite in quartz monzonite of Buffalo Pass batholith at 9,500 feet (2,896 m) elevation north of Green Creek and 3.28 miles (5.28 km) S. 54° W. of the summit of Walton Peak. Hornblende-plagioclase-quartz-biotite mafic quartz diorite containing minor magnetite-ilmenite and apatite.

76: Data from diabasic plagioclase-hornblende-orthopyroxene-clinopyroxene-biotite norite containing minor magnetite-ilmenite and apatite, located just southwest of 10,227-foot (3,117.2-m) summit on ridge top 1 1/2 miles (2.4 km) S. 78° E. from the junction of the tributary issuing from Bear Canyon and the South Fork of the Elk River (Snyder, 1978, p. 16).

Forty-five analyses of 1.8-b.y. average metavolcanic and metasedimentary rocks.

Twenty-four analyses of 1.8-b.y. average mafic to ultramafic intrusive rocks.

Twenty-seven analyses of 1.7-b.y. average felsic intrusive rocks.

Twenty-one analyses of 1.4-b.y. average felsic intrusive rocks.

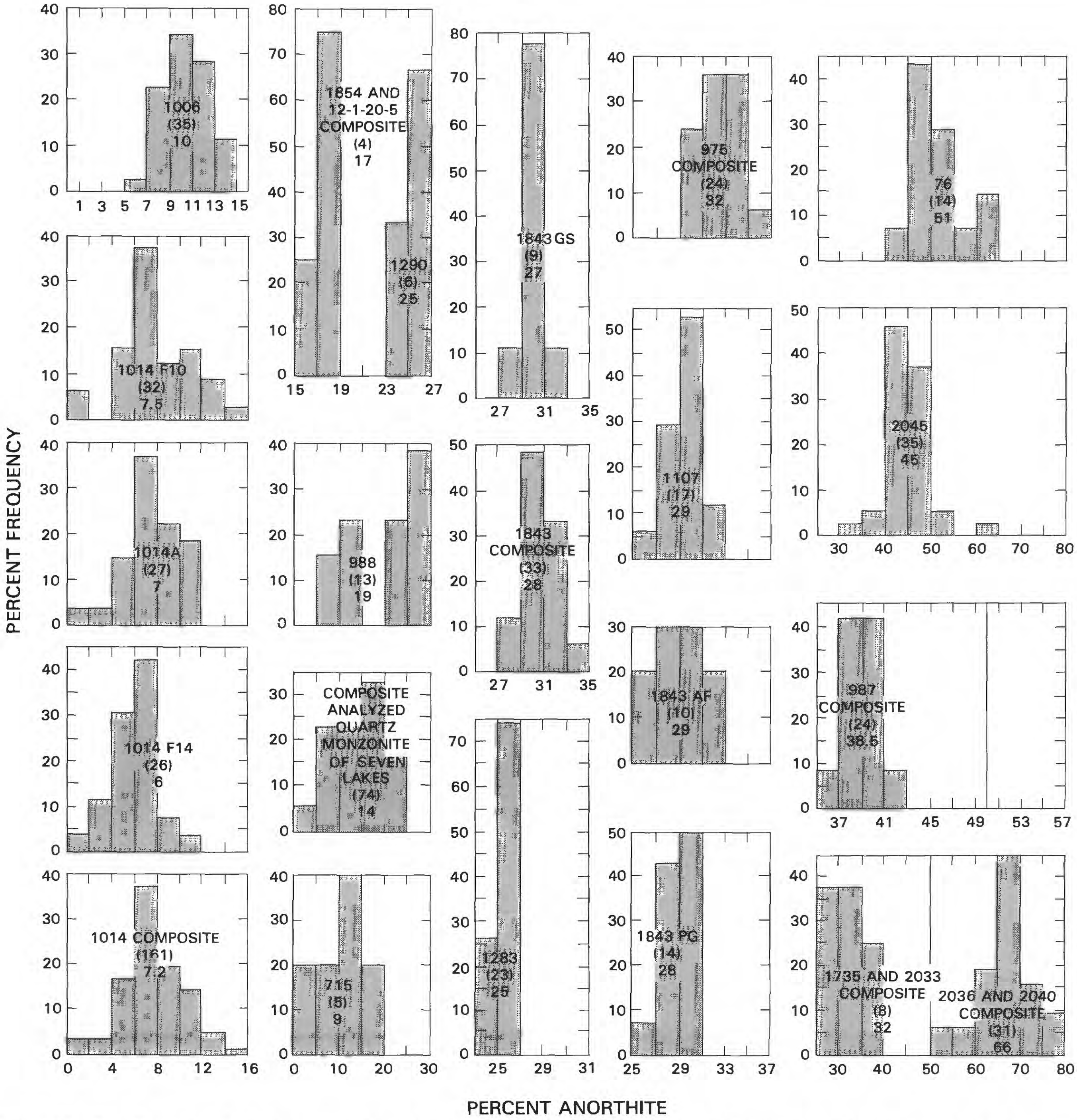

FIGURE 30.—Distribution of plagioclase compositions from 507 individual crystals in several selected individual and composite Precambrian intrusive and layered metasedimentary and metavolcanic rock samples, northern Park Range, Colo. All histograms give percent frequency on the same scale along the ordinate, and percent anorthite on two scales and three class intervals along the abscissa. Histogram numbers show sample number(s) at top, number of different plagioclase crystals determined in middle in parentheses, and average (mean) anorthite content of each histogram's plagioclase at bottom. See sample descriptions on facing page.

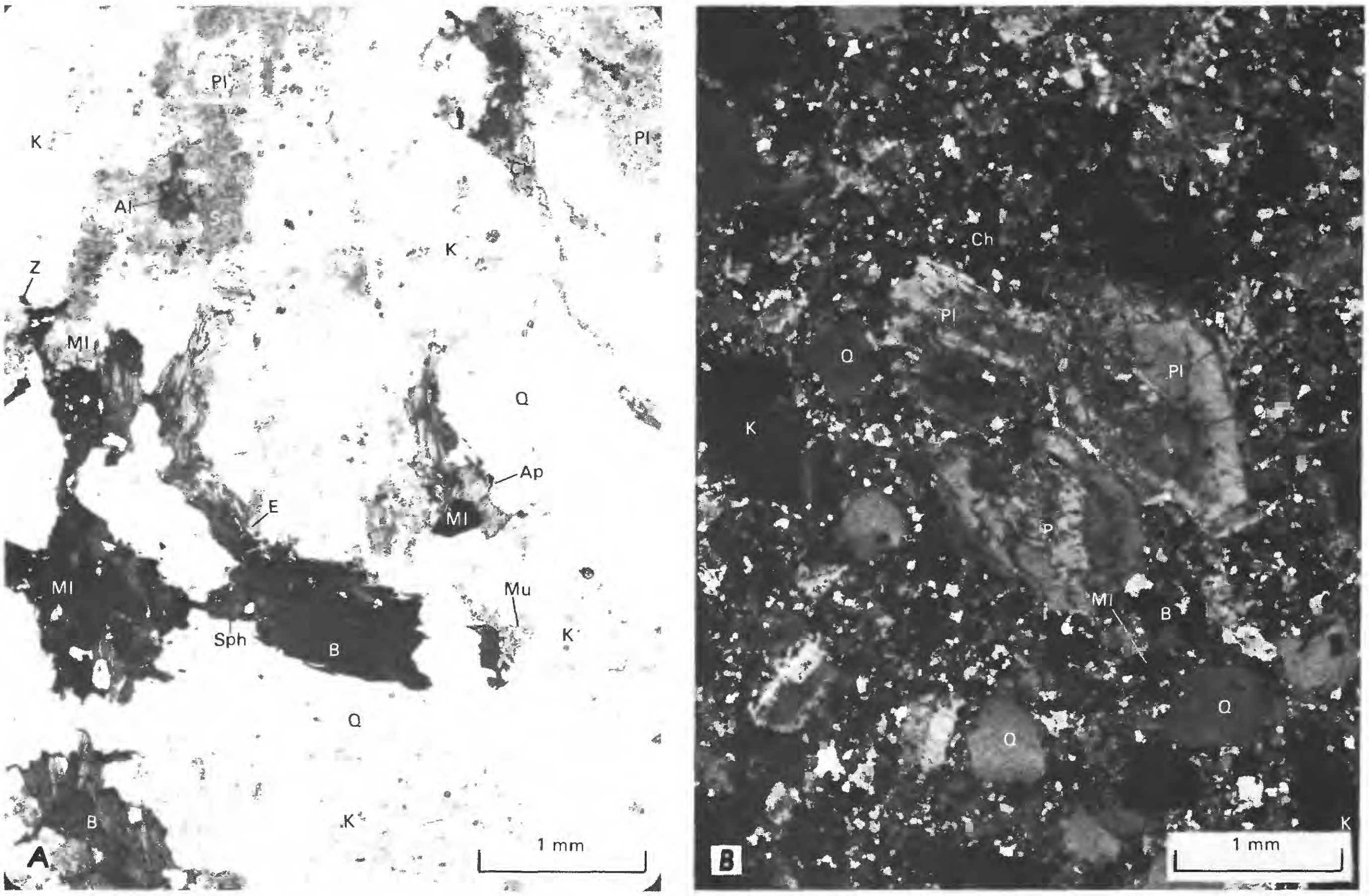

FIGURE 31.—Photomicrographs (both 22×) of analyzed 1.4-b.y.-old felsic intrusive rocks (tables B5 and B6). Photomicrographs by Louise S. Hedricks. *A*, Quartz monzonite from Roxy Ann Lake phase of Mount Ethel pluton. Sample 1023, from near contact on north rim of north fork of Red Canyon. See figure 32 for hand specimen, and Snyder (1978, p. 9, fig. 5*D*) for field association. *B*, Rhyolite porphyry dike. Sample 1097, from 1/3 mile (1/2 km) west of Mica Creek.

These total 117 rock analyses, but subtracting 24 repetitions of the same analyses between the four categories for minor parts of each total and adding 11 (14 new chemical analyses were required to arrive at 3 average pod-rock analyses in table B11) gives a total of 104 *different chemical analyses* that entered into the calculations.

Estimating the average chemical composition of the rocks in a large mountain range at different times is a complicated undertaking. First, all homogeneous map units must be adequately analyzed; second, account must be taken of the fact that some map units are markedly heterogeneous; third, the age of all lithologic units must be determined; and, fourth, the outcrop areas must be determined. The outcrop areas determined must be assumed, or should be adjusted, to represent relative volumes. Although all these problems have been addressed and many solutions suggested (see footnotes in table B13), there are still some areas in which potentially controversial compromises should be spotlighted. Among others, the following decisions and assumptions have been made:

(1) Pegmatites of two or three ages are present but are lithologically indistinguishable (Snyder, 1978, p. 15, 16, 24, and 25). For averaging purposes, clusters of pegmatites mapped near the contacts of the Mount Ethel pluton (generally within a mile or two (1.5–3 km) of these contacts) are lumped with this 1.4-b.y. pluton; other mapped pegmatites (generally discordant) away from the Mount Ethel contact are lumped with the 1.7-b.y. felsic intrusives; unmapped pegmatites within the layered metasedimentary and metavolcanic rock unit (generally concordant leucosomes) are lumped as part of this layered unit. Pegmatites of all three types total about 2.12 percent of exposed Precambrian rocks in the northern Park Range.

(2) Ultramafic rocks of three types are present in the northern Park Range. Although most of these rocks may be genetically distinct from any of the four time-groupings listed above, two have been lumped with the

gabbros and one with the layered metasedimentary and metavolcanic rocks. Peridotites within the gabbro of Elkhorn Mountain are lumped with that body; mapped peridotites outside of the gabbro of Elkhorn Mountain are also lumped with this body; unmapped hornblendite pods within the layered rocks, some of which are associated with carbonate or calc-silicate rocks, are lumped with the layered rocks. Because no analyses of hornblendite pods

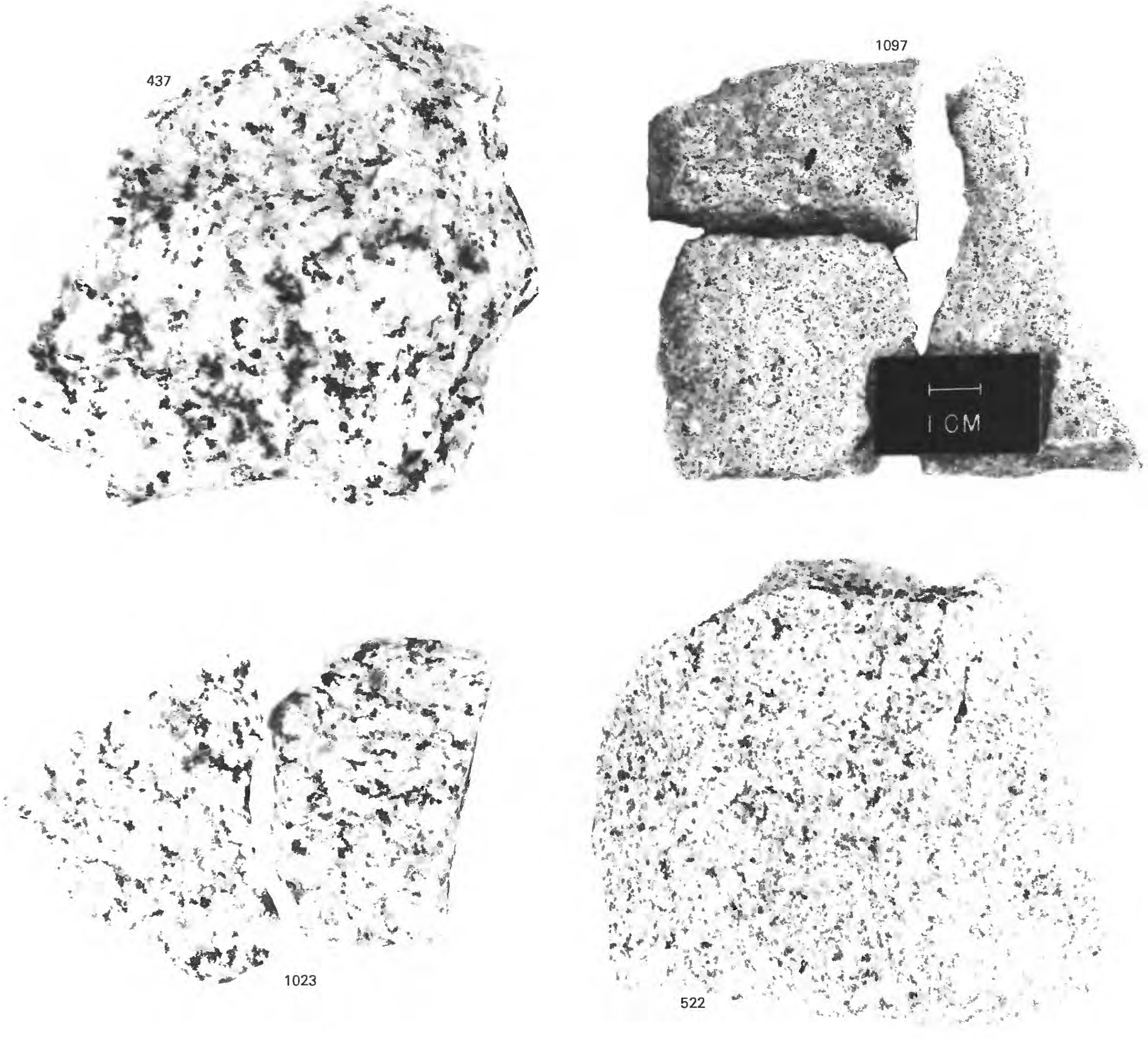

FIGURE 32.—Hand specimens of selected analyzed 1.4-b.y. quartz monzonites of the Mount Ethel pluton, arranged in order of increasing silica content from top left to bottom right (67.09 to 73.98 percent SiO_2). Photograph by Louise S. Hedricks.

SAMPLE DESCRIPTIONS

437, Quartz monzonite porphyry of Rocky Peak, from east-southeast of Swamp Park (Snyder, 1978, tables 5 and 6).

1023, Quartz monzonite of Roxy Ann Lake, from north fork of Red Canyon (tables B5 and B6). See figure 31*A* for thin section.

1097, Quartz monzonite or rhyolite porphyry dike, from west of Mica Creek (tables B5 and B6). See figure 31*B* for thin section.

522, Quartz monzonite from west of Luna Lake. This rock contributes to a seven-point Rb/Sr isochron by Carl Hedge indicating an age of 1.47 ± 0.05 b.y. (Snyder, 1978, tables 5 and 6, p. 17).

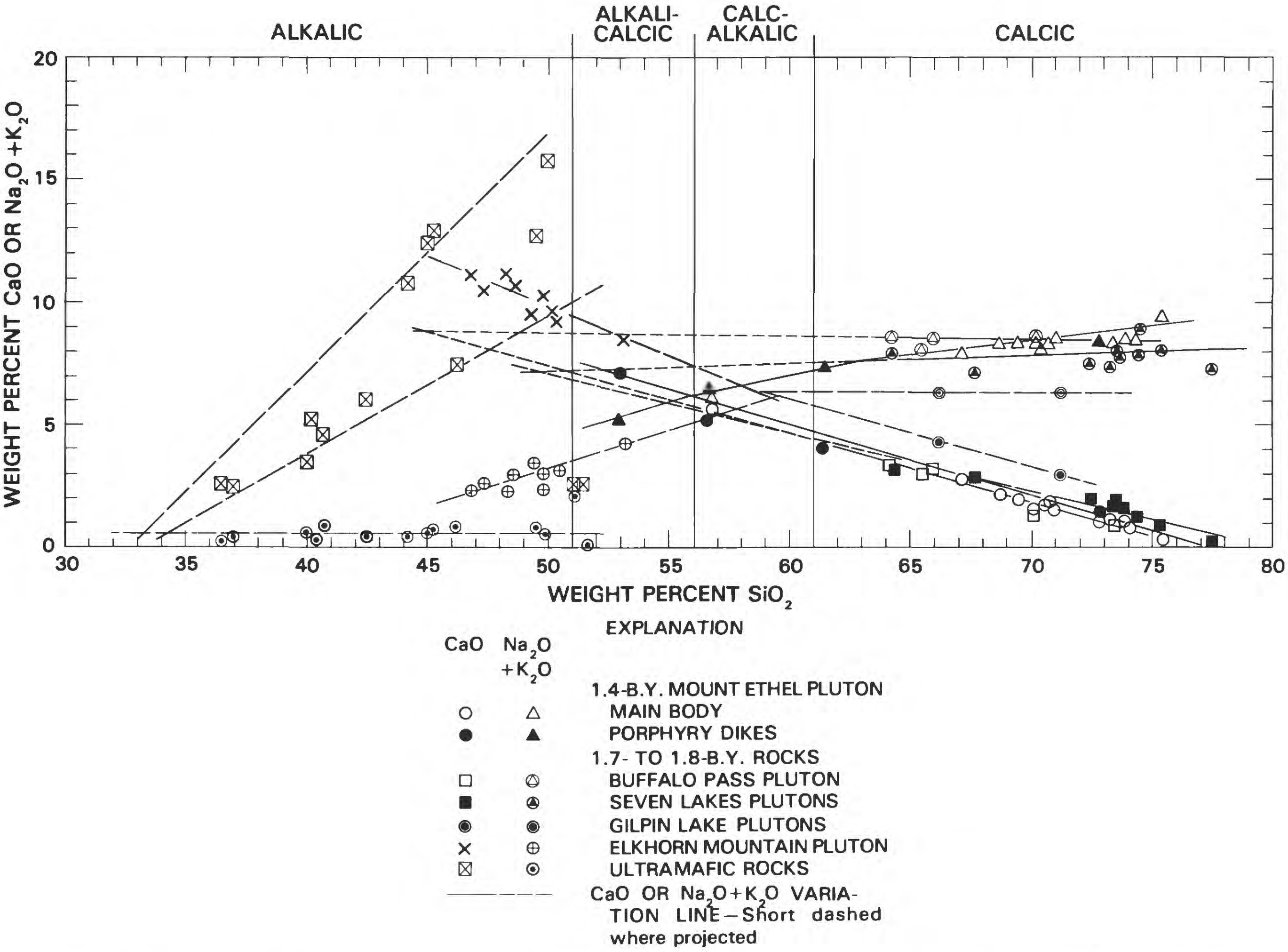

FIGURE 33.—Silica-variation diagrams showing classification of Park Range intrusive rocks according to the system of Peacock (1931).

are available, the peridotite average in table B3 was utilized as the best available chemical description. Ultramafic rocks of all types are only 0.25 percent of all exposed northern Park Range Precambrian rocks.

(3) Part of the Buffalo Pass batholith near its contact with pelitic rocks west of Rabbit Ears Pass is choked with inclusions of sillimanitic schist. Although these rocks are themselves unanalyzed and may have a different origin than the Independence Mountain pod rocks (which consist of quartz-sillimanite-muscovite pods in a matrix of quartz monzonitic composition), the pod-rock average was used as the best available chemical approximation for these Buffalo Pass rocks, which represent 1.22 percent of exposed northern Park Range Precambrian rocks.

(4) As noted earlier, rocks classed as small mafic intrusives are partly older than, partly gradational with, and partly younger than the 1.7-b.y. felsic intrusives. They represent only 0.19 percent of exposed northern Park Range Precambrian rocks and have been lumped with the 1.8-b.y. mafic and ultramafic intrusives.

(5) Also as noted earlier, there is a problem in dealing with the quartz diorite of Gilpin Lake, which is lithologically and geographically associated with the quartz monzonite of Seven Lakes but which has some chemical characteristics that suggest a close association with the gabbro of Elkhorn Mountain (fig. 33). For convenience, these quartz diorites have been lumped here with the 1.7-b.y. felsic intrusives; they represent only 0.49 percent of all exposed northern Park Range Precambrian rocks.

(6) No time allowance has been made for thin amphibolite dikes that are present (but generally unrecognizable) in the country rocks; their contribution to the average chemical composition is probably accounted for within the 43.68 percent amphibolite country rock

fraction. No chemical weight has been apportioned for thin amphibolite dikes or inclusions that are present locally, mainly within the 1.7-b.y. felsic intrusives (fig. 25), but these are considered to be volumetrically miniscule.

The total of all the above uncertainties is 4.27 percent. If the approximations recommended are correct to within only 5 percent, then the average chemistry of any individual temporal segment is correct within several tenths of a percent, and the final average, which would be unaffected by the temporal uncertainties, must be much closer than this.

In order to estimate surface volumes, a systematic rectilinear point count was run of the mapped units in the 1,200 square miles (3,100 km^2) of the northern Park Range. East-west and north-south traverse lines were set up on 1:48,000 geologic maps at a 1.5-inch (3.8-cm) spacing, and 11 points were counted per inch (5 per cm). Separate surveys of the Elkhorn Mountain and Farwell Mountain plutons were run on a 1:48,000-scale version of figure 23*B* to estimate the gabbro-diorite ratio within these plutons. In order to estimate the lithologic proportion in the heterogeneous undifferentiated country rocks, a systematic count of outcrops was made along every field traverse walked by G. L. Snyder during 11 years' work in the northern Park Range—probably the first detailed survey of this sort in the Rocky Mountains. The map and outcrop surveys together resulted in a total of 35,299 counted points or equivalent observations, which constitute the statistical base for the estimate of relative outcrop areas of all significant rock units in the range. Both the great vertical relief (>1 mi or 1.6 km) and the generally steep dips (see cross sections on Snyder, 1980a, b, and c) suggest that the areas thus measured are a valid estimate of surface crustal volume, at least in the upper few miles (≈5 km).

Do the chemically analyzed samples adequately represent the rock units? In most cases, yes, but in some cases, there is room for limited reservations. Seven geologic units each make up more than 6 percent of the volume:

Amphibolite in layered metasedimentary and metavolcanic rock makes up 21.99 percent of the volume, represented by three analyses.

Felsic gneiss metasedimentary and metavolcanic rock makes up 18.82 percent of the volume, represented by eight analyses.

Coarse-grained gneisses of the Buffalo Pass pluton(s) make up 16.18 percent of the volume, represented by three analyses.

Quartz monzonites of the Seven Lakes pluton(s) makes up 11.40 percent of the volume, represented by 11 analyses.

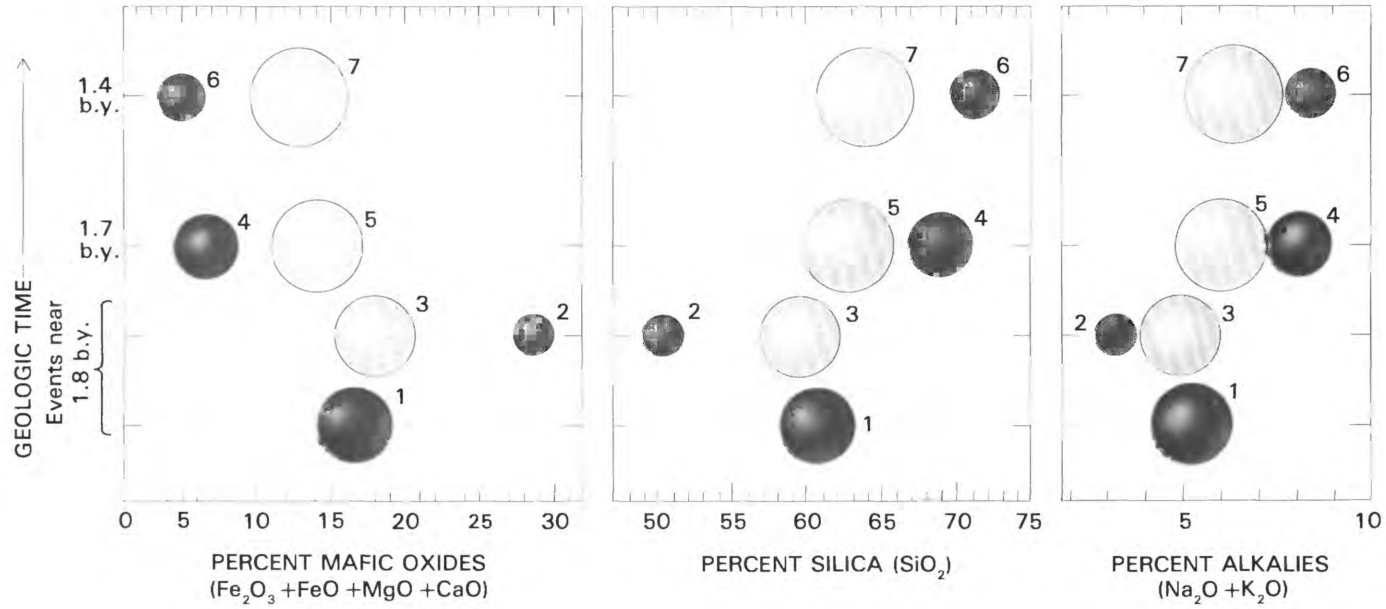

FIGURE 34.—Graph illustrating changes in composition and volume of average northern Park Range Precambrian crustal rocks through time. Centers of all spheres are located at appropriate time and composition points, and volumes of spheres are proportional to volumes of rock units estimated from outcrop areas. Numbers correspond to column numbers of table B13. Dark spheres represent new increments to this crust at a particular time, and the light-gray spheres are average local crustal composition after each increment; that is, 3 is the average of 1 and 2, 5 is the average of 3 and 4, and 7 is the average of 5 and 6.

Note that the initial 1.8-b.y. volcanic and sedimentary rocks, which are principally bimodal, were first intruded by mafic gabbro, then by successive felsic quartz monzonites of several ages without much intermediate rock represented, until, at 1.4 b.y., the volume was essentially doubled by dilational intrusives.

Quartz monzonite of Roxy Ann Lake in the Mount Ethel pluton makes up 9.81 percent of the volume represented by five analyses.

Gabbros and diorites (see table B13) of the Elkhorn Mountain pluton(s) make up 6.06 percent of the volume, represented by five analyses.

Pelitic schist of the layered metasedimentary rocks makes up 6.02 percent of the volume, represented by five analyses.

Although two of the most abundant rocks, the layered amphibolite rock and the coarse-grained gneisses of the Buffalo Pass pluton(s), are analytically underrepresented for their relative volumes, these are among the simplest rocks mineralogically in the Park Range suite. Thus a small number of samples may be an adequate representation of the total rock mass.

Note, in table 5, the similarity in composition between the average layered amphibolite (former basaltic ash) and the average mafic-ultramafic intrusive (table B13, col. 2), despite the fact that the former is slightly quartz normative and the latter is slightly olivine normative (fig. 35). It is possible that magma bodies similar to those composing the Elkhorn Mountain pluton supplied the extrusive basalts to the surface while working their way upward through and intruding their own earlier-deposited daughter products.

TABLE 5.—*Comparison of volume-weighted chemical averages for mafic and felsic Park Range rocks*

[---, not determined]

Constituent	Volume-weighted averages (percent) Mafic to ultramafic intrusive rock	Layered amphibolite in metasedimentary rock	Felsic gneiss in metasedimentary and metavolcanic rock
SiO_2	50.40	50.77	68.99
Al_2O_3	16.00	16.03	14.37
Fe_2O_3	2.04	2.26	1.49
FeO	8.81	8.55	3.41
MgO	8.23	6.32	1.23
CaO	9.51	10.12	1.79
Na_2O	2.66	2.49	3.31
K_2O	.59	1.12	3.68
H_2O	.95	.89	.81
TiO_2	.88	1.04	.58
P_2O_5	.18	.17	.19
MnO	.18	.19	.10
CO_2	.09	.05	.03
F	---	---	.04
Subtotal	100.00	100.00	100.02
Less O	---	---	.02
Total	100.00	100.00	100.00

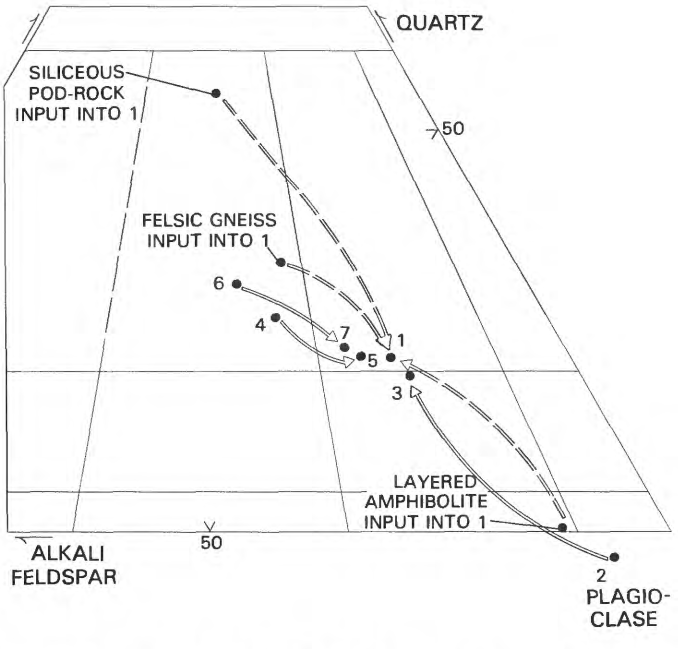

FIGURE 35.—Partial triangular plot of normative minerals of volume-weighted average northern Park Range Precambrian rocks at successive times between 1.8 and 1.4 b.y. Triangular plot and nomenclatural fields are same as those shown in figure 27*D*, and numbers refer to equivalent column numbers of table B13. Dashed arrows show major volcanic(?) input to make an early crust (1). Solid arrows show successive major intrusive inputs of 2, 4, and 6 to successively change the average chemistry from 1 to 3, 5, and 7. Note that the northern Park Range average composition (1, 3, 5, and 7) has never strayed far from a low-silica granodiorite composition despite some inputs much different from this.

The input into the volume-weighted average layered metasedimentary and metavolcanic rock is described in detail in table B13. Definite sedimentary rocks of clastic or chemical origin are estimated to make up 12.87 percent of the layered rocks; probable or definite volcanic or volcaniclastic rocks make up 81.06 percent; and possible volcanic rocks or clastic sediments make up as much as 2.62 percent. The remaining 3.45 percent of the layered rocks are classified as intrusives, partial melts, or of uncertain origin. Most of the metasedimentary-metavolcanic rocks are massive to faintly layered to well-layered gneisses that probably originated as volcanic materials, as suggested by a few exposures of recognizable volcanic agglomerate on Farwell Mountain and a few exposures of pillows in amphibolite along the Hog Park–Whiskey Park road just north of the Colorado-Wyoming border. There is a profusion of rock types ranging from mafic amphibolite through hornblende and biotite gneiss to leucocratic gneiss, but the intermediate rocks are volumetrically minor. The chief rock types are amphibolites and felsic gneisses. These two rocks are about equally abundant (table B13) but quite different in chemical composition; for example, average amphibolite has 51 percent SiO_2, whereas average felsic gneiss has 69 percent SiO_2 (table 5). This bimodal character of the layered rocks has been noted by Divis (1976, p. 61) in the Sierra Madre in Wyoming; he estimates the felsic gneiss/amphibolite ratio at 4/1, but he does not describe how he arrived at this estimate. The bimodal character of the initial 1.8-b.y.-old crust has been maintained by subsequent intrusive events. Most intrusive rocks have been gabbros or quartz monzonites. One intermediate rock, the quartz diorite of Gilpin Lake, is only 1.64 volume percent of the rocks lumped as 1.7-b.y.-old quartz monzonites, and intermediate rocks form less than 0.1 percent of the Mount Ethel batholith. Nevertheless, the average composition is that of a granodiorite or rhyodacite (fig. 35 and table B13). If this part of the crust were melted completely and stirred thoroughly it would supply an intermediate magma.

COLORADO

The Precambrian rocks of the northern Park Range are only 7 percent of the exposed Precambrian in Colorado. They are slightly atypical of the Precambrian of the entire State in several respects: clastic metasediments make up a smaller proportion of the country rocks; mafic and ultramafic intrusives are more abundant; and 1.4-b.y. intrusive rocks are less abundant here than in many other State areas. How important are these differences, and what effect do they have on the volume-weighted average chemical compositions? To answer these questions, a systematic rectilinear point count was run of all the Precambrian rocks shown on the 1:500,000-scale preliminary geologic map of Colorado (Tweto, 1976a; now superseded by Tweto, 1979) using the system described above for the Park Range volumetric survey. A total of 44,324 points were thus counted, to provide the basis for the following estimate of relative volumes.

Precambrian rocks are exposed in 12.4 percent of Colorado, and most of these are concentrated in less than one quarter of the State, namely the Laramide mountain block between 38° and 41° N. lat and 105° and 107° W. long. The Precambrian rocks have the relative volumes shown below (*, unit considered chemically equivalent to similar unit in the northern Park Range):

Map unit	Description	Volume percent
Yp	1.0-b.y. Pikes Peak batholith --------------	8.46
Yu	0.95- to 1.4-b.y. Uinta Mountain Group -----	2.69
*Yam	Mafic dikes ----------------------------	.22
*Yg	1.4-b.y. granitic rocks --------------------	18.87
*YXu	1.4- to 1.7-b.y. Uncompahgre Formation ----	.61
*Xg	1.7-b.y. granitic rocks --------------------	25.72
*Xm	1.7-b.y. mafic rocks ---------------------	1.29
*Xq	1.7- to 1.8-b.y. quartzite and conglomerate --	.14
*Xb	1.7- to 1.8-b.y. other metasediments --------	21.48
*Xfh	1.7- to 1.8-b.y. metavolcanics --------------	20.52
Wr	>2.5-b.y. Red Creek Quartzite -------------	<.04

TABLE 6.—*Comparison of relative percentages of equivalent geologic units in Colorado and in the Park Range*

Geologic unit	Colorado	Park Range
1.4-b.y. felsic intrusive rock-----	21.62	13.22
1.7-b.y. felsic intrusive rock-----	29.16	29.95
1.8-b.y. mafic to ultramafic intrusive rock------------------	1.46	6.51
1.8-b.y. quartzite and conglomerate	.16	.13
1.8-b.y. other metasediments-------	24.35	6.58
1.8-b.y. metavolcanics-------------	23.25	43.61

Tweto's unit YXg, 1.4- and 1.7-b.y. granitic rocks undivided, which represents only 1 percent of the Precambrian rocks, has here been apportioned between Yg and Xg in proportion to the areas shown as Yg and Xg (Tweto, 1976a). Unit Yam, which occurs in about the same ratio to unit Yg in Colorado as the porphyry dikes do to other Mount Ethel rocks in the northern Park Range, is lumped with the 1.4-b.y. felsic intrusive rocks.

With the percentages recalculated and with some regrouping of northern Park Range country rocks, the time-equivalent Colorado and northern Park Range Precambrian units occur in the percentages shown in table 6. These figures provide a basis for an estimate of the average composition of Precambrian rocks in Colorado 1.8 to 1.4 b.y. ago. In making these calculations the estimated average compositions of the rocks of the northern Park Range are used as follows:

(1) For 1.4-b.y. felsic intrusive rock, the average analysis in table B13, column 6 is used. Different 1.4-b.y. plutons have different proportions of phaneritic intrusive rocks (Snyder, 1978, p. 36–38), but the average would surely be somewhere in the quartz monzonite (or adamellite) range, probably close to the suggested average.

(2) For 1.7-b.y. felsic intrusive rock the average analysis in table B13, column 4 is used; this could also differ from the average for the State, but it is probably very close.

(3) For 1.8-b.y. mafic to ultramafic intrusive rock, the average analysis in appendix table 13, column 2 is used; this is doubtless close to the Colorado average and, in any case, the effect of a mismatch is minimal because of the small volume.

(4) For 1.8-b.y. layered metasedimentary and metavolcanic rocks, the proportions of the three mapped units on the state map (table 6) are used as follows:

a. For 1.8-b.y. quartzite and conglomerate, the quartzite (1643) and pisolite rock (1854 and 12-1-20-5) analyses were combined in the northern Park Range proportions (table B13).

TABLE 7.—*Comparison of Colorado and Park Range weighted chemistry at four different Precambrian times*

Col. No., table B13	Age	SiO_2	Al_2O_3	Mafic oxides[1]	Alkalies[2]	Ratio[3]	Plagioclase composition	IUGS name	Rittman (1952) name
1	1.8 b.y., before intrusion:								
	Colorado	62.1	15.4	14.4	5.1	31/21/48	An_{47}	Granodiorite	Labradorite rhyodacite.
	Park Range	60.7	15.2	16.6	5.2	21/20/59	An_{49}	do	Dark rhyodacite or dark labradorite rhyodacite.
3	1.8 b.y., after mafic to ultramafic intrusion:								
	Colorado	61.7	15.4	14.9	5.0	30/21/49	An_{48}	do	Labradorite rhyodacite.
	Park Range	59.5	15.3	18.0	5.0	20/18/62	$<An_{50}$	Quartz monzodiorite.	Dark labradorite rhyodacite.
5	1.7 b.y., after felsic intrusion:								
	Colorado	64.5	15.3	11.7	6.2	28/25/47	An_{39}	Granodiorite	Quartz latite.
	Park Range	62.8	15.3	14.0	6.1	22/23/55	An_{43}	do	Rhyodacite.
7	1.4 b.y., after felsic intrusion:								
	Colorado[4]	65.9	15.1	10.2	6.7	29/26/45	An_{35}	Granite (adamellite).	Quartz latite.
	Park Range	63.9	15.2	12.8	6.4	23/24/53	An_{41}	Granodiorite	Dark quartz latite.

[1] $Fe_2O_3 + FeO + MgO + CaO$.

[2] $Na_2O + K_2O$.

[3] Normative quartz:potassium feldspar:plagioclase ratio.

[4] No allowance made for the relatively small chemical input of the Uncompahgre Formation.

b. For 1.8-b.y. metavolcanic rocks, the pegmatite average, the layered amphibolite average, the felsic gneiss average, and the pod-rock average were combined in the northern Park Range proportions (table B13); this assumption is the most critical one in the entire calculation because the volume of these rocks is greatest and the proportions of the various rock types outside the northern Park Range are not quantitatively known.

c. For 1.8-b.y. "other metasediments," all the other Park Range layered-rock compositions are combined in the Park Range proportions.

Table 7 summarizes the estimated average compositions of Precambrian rocks of the State at four different times in the interval between 1.8 and 1.4 b.y. ago and compares them to average Park Range rocks.

The different relative volumes of Precambrian rocks in the State as a whole (table 6) do not lead to chemical compositions that are significantly different from those of equivalent rocks in the northern Park Range (table 7). Average Colorado rocks are slightly more silicic and slightly less mafic than average Park Range rocks at comparable times; alumina and alkalies are roughly comparable. The four Colorado averages cluster around a normative quartz:potassium feldspar:plagioclase ratio of 30:24:46 (within the granodiorite field, as are three of the four temporal averages) and the four Park Range averages cluster around a similar ratio of 21:21:58 (also within the granodiorite field, as are three of the four temporal averages). All average normative plagioclases are within the andesine range. All volcanic rocks would be appropriately classified as some type of rhyodacite or quartz latite. It is safe to conclude that, if the upper few miles of Precambrian crust in Colorado were melted entirely and stirred thoroughly, it would supply an intermediate magma, just as would the crust in the Park Range.

The trend of the alkali ratio for both the Park Range and Colorado is consistent with the prediction of Engel and others (1974, fig. 7, p. 849) for the Precambrian as a whole. K_2O/Na_2O for 1.8-b.y. average layered rock is 0.9 for the Park Range and 1.2 for Colorado. By 1.4-b.y., this K_2O/Na_2O ratio had risen to 1.1 for the Park Range and 1.3 for Colorado.

CRUST-MANTLE CHEMICAL COMPARISONS AND CONSTRAINTS

It is useful to compare the volume weighted compositional estimates of average Park Range Precambrian rocks (table B16, col. 2A or 2B) and of average Colorado Precambrian rocks (table B16, col. 6A or 6B) with other estimates of average crustal composition (tables B15 and B16, cols. 2C, 6C, and 10C). The estimated average composition of Colorado Precambrian rocks (table B16) is a very close match for the average Precambrian shield (table B15) except for a slightly higher K_2O/Na_2O ratio in the former. Average Precambrian composition in the Park Range differs from average shield in being slightly lower in SiO_2 and slightly higher in FeO, MgO, and CaO, all doubtless resulting from a slightly higher proportion of mafic rocks in the Park Range than in the average crystalline shield.

Ultramafic rocks of the Park Range (table B16, cols. 1A and 1B) are higher in Al_2O_3, total iron, CaO, Na_2O, and P_2O_5 and appreciably lower in MgO than average mantle (table B16, col. 1C). As a result, norms of the Park Range ultramafic rocks are higher in plagioclase, magnetite, and apatite, and lower in olivine than average mantle. The average analyzed Park Range ultramafic rock contains significantly more normative pyroxene than average mantle, but the average of the four peridotites most like average mantle is more comparable in content of normative pyroxene. The Park Range averages in table B16 have already been adjusted for the most obvious effects of near-surface serpentinization and oxidation (higher H_2O+, higher Fe_2O_3/FeO ratio). The remaining differences probably reflect primary mantle inhomogeneities, though smaller inputs may come from metamorphic alteration (such as amphibolization (Winchell and Winchell, 1959, p. 502)) or igneous contamination. A comparably inhomogeneous mantle may have persisted under Colorado through the Paleozoic Era. (Compare fig. 3*C* with fig. 11 of McCallum and Mabarak, 1976, but also see DePaolo, 1981, p. 194.)

Whatever the origin of the Park Range ultramafic rocks, it is appropriate to proceed on the assumption that some rock of approximately this composition was the source from which Precambrian rocks in the Park Range and the remainder of Colorado were originally fractionated. These Colorado fractionation models are compared below with other Earth models, and chemical and mineralogical constraints are noted.

Numerous workers over the past half century or more have presented evidence that the Earth's crust has been segregated from the mantle (for example, Ringwood, 1975). The deepest samples are thought to be from depths of about 200–300 km (125–185 mi) (Bell, 1979, p. 788; Ringwood and Lovering, 1970; but see Sobolev, 1977, p. 246), and most samples are from less than half this depth. Thus the evidence of the evolution of the crust and mantle is largely indirect, and there is considerable uncertainty about the details of the process. It is generally agreed that the mantle approaches peridotite or pyrolite in composition (table B14; see also Anderson and others, 1972, p. 41). Engel and Engel (1965) suggested an upper mantle comparable to oceanic tholeiite or basaltic achondrite, but Engel and others (1965) suggest a tholeiite-peridotite or tholeiite-dunite mixture, perhaps similar to that in table B14, column 1. The consensus average mantle (table B14, col. 12; table B16, col. 1C) has an Fe/Mg ratio of 0.303, whereas Press' (1971, fig. 31, p. 237) successful density models for possible mantles suggest an Fe/Mg ratio nearer to 0.111.

Did most of the crust-mantle-core differentiation take place very early in geologic time (Poldervaart, 1955, p. 119; Gast, 1972, p. 30; Engel, 1966, p. 176; Ringwood, 1969, p. 14; Tozer, 1965, *in* Jacobs, 1971, p. 88), or has it been a constant process throughout geologic time (Ringwood, 1975, p. 315)? Is crust mantle differentiation irreversible (Gast, 1968, p. 1077; Dickinson and Luth, 1971), or has a significant amount of crust been returned to the mantle by subduction? Sedimentation rates indicate that 90 percent of originally exposed Precambrian rock has been removed (Garrels and others, 1972, p. 120). Has the present mantle always been chemically homogeneous (Ringwood, 1975, p. 312), or has it been in the past and is it now laterally and vertically inhomogeneous (Gorshkov, 1967, p. 51; Ringwood, 1969, p. 11; Jacobs, 1971, p. 68, 75, 79, 86; Kerr, 1979, p. 530–532; Bailey and others, 1980; P. Jon Patchett, Olayi Kouvo, Carl Hedge, and Mitsunobu Tatsumoto, written commun., Dec. 1981)? If the latter, what is the scale of the inhomogeneities? How deep do circulating motions extend within the mantle? Brown and others (1978) emphasize that the recognition of large-scale plate movements on the Earth's surface must require large-scale counterflow of mantle material at depths of at least 700 km (435 mi), and possibly over the full depth of the mantle. However, kimberlite chemistry (Basu and Tatsumoto, 1979, p. 400) indicates a uniform mantle more than 200 km (125 mi) beneath continents. Does the crust consist of silicic rock riding on an equal or near-equal amount of intermediate or basic rock (Taylor, 1964; Pakiser and Robinson, 1966; Ronov and Yaroshevsky, 1969, p. 38), or is it gradational in composition from the top to the base of the crust?[4] Many questions have unsatisfying or incomplete answers.

Gast (1968, 1972), Dickinson and Luth (1971), and many others have claimed that the crust gives valuable insights into mantle composition. Taylor (1965) noted that "the strong concentration of many elements in the crust gives it a geochemical importance out of proportion to its small bulk and its composition places severe

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[4] Note that the assumptions incorporated in table B16 accommodate either of these possibilities. The average thickness of Colorado crust is taken as 45 km (Cordell, 1978, figs. 2 and 5; data after L. C. Pakiser, W. H. Jackson, and others; see also Prodehl, 1979, p. 2); of Precambrian shield or continental crust, as 35 km (see discussions in Poldervaart, 1955; Parker, 1967; Ronov and Yaroshevsky, 1969; Jacobs, 1971; and Press, 1971); of lithosphere, as 17 km. (See discussions in Mason, 1958; Ronov and Yaroshevsky, 1969; and R. A. W. Haddon and K. E. Bullen, 1969, *in* Jacobs, 1971, p. 76). Taking half of these thicknesses as the amount of crustal composition that must be fractionated from the mantle satisfies either of the following two assumptions: that the crust (1) consists of equal sial over sima or (2) is gradational in composition from the surface to the mantle. Other models will be simple multiples of the data supplied on the basis of these dual assumptions. For example, a crust 10 percent richer in K_2O than this model or a mantle only 90 percent depleted would require 10 percent more source mantle to supply the same thickness of crust (428+43=471 km or 266+27=293 mi for the example cited). Some minor-element parameters indicate that the upper mantle may be as much as 90 percent depleted (DePaolo, 1980).

limitations on that of the upper mantle." This observation is especially true for various incompatible minor elements. (See Ringwood, 1975, p. 316; DePaolo, 1980.) But few authors (for an exception see Ronov and Yaroshevsky, 1969, table 10, p. 53) have calculated what the limitations are that are imposed by the *major* elements. This last consideration will be addressed below.

The estimated average chemical compositions of Precambrian rocks in the northern Park Range and in Colorado provide a basis for calculations that place constraints on the process of crust-mantle differentiation. In the derivation of crust or lithosphere from mantle, K_2O is the first limiting major constituent. Hundreds or even thousands of kilometers of mantle, depending upon the model, are required to provide enough crustal K_2O. For example, the average K_2O content in Colorado Precambrian crustal rock is 3.8 percent; if the 0.2 percent K_2O in the average Park Range ultramafic rock truly reflects the content of the mantle, it would take a minimum of 19 units of mantle to make one unit of Colorado crust—a partial melt of >5.26 percent. One unit of this crust (table B16, col. 6A; >5.26 percent) subtracted from 19 units of this mantle (table B16, col. 1A) would leave a residuum of depleted peridotite of the composition shown in column 7A (table B16) (after recalculation to 100 percent). To form half of the thickness of Colorado crust (22.5 km or 14 mi; see table B16) would require 19 times this much mantle, or approximately 428 km (266 mi). Of course, this estimate assumes that all K_2O in 428 km (266 mi) of mantle could be concentrated in the crust. In other words, given crustal and mantle compositions and the dictum to derive one from the other, the thickness of crust determines a minimum thickness of required mantle based on the major element that must be most highly partitioned into the crust.

Similar K_2O constraints exist for several reasonable crust-mantle models that can be suggested. Seven such models are considered in table B16 and are listed below, and the average partial melt is slightly greater than 3 percent for the K_2O-limited condition of these seven models:

1. Park Range weighted average Precambrian from Park Range average ultramafic.
2. Park Range weighted average Precambrian from the average of the four Park Range peridotites (samples 1428, 1412, 1017, and 1078) nearest to average mantle in composition.
3. Colorado weighted average Precambrian from Park Range average ultramafic.
4. Colorado weighted average Precambrian from the same four-peridotite average used in model 2.
5. Average Precambrian shield from average mantle.
6. Average continental crust from average mantle.
7. Average lithosphere from average mantle.

Note that different crustal thicknesses are accepted for different models, conditioned by a consensus of expert opinion as to what thicknesses would be most appropriate. (See table B16 and footnote 4, already given.) Note also that K_2O provides an impossible-to-satisfy constraint for some other models. For example, the Kilbourne Hole, N. Mex. undepleted upper mantle contains 0.003 weight percent K_2O (Carter, 1970). It would require 1,266.67 parts of this to form 1 part of 3.8-percent-K_2O crust; hence the creation of 22.5 km (14 mi) of crust would require 28,500 km (17,700 mi) of mantle—4.5 times the radius of the Earth!

If the K_2O limitation could be overcome in some fashion[5], then Na_2O would be the next limiting constituent. (In some models, though, P_2O_5 is about as limiting as Na_2O.) The Na_2O limitation would decrease the amount of mantle required for all constituents except K_2O, but would increase the degree of partial melting (averaging nearly 15 percent for the models considered). Calculations based on this contingency are presented in table B16 for all seven crust-mantle models. Similarly, if the Na_2O limitation could be overcome, then Al_2O_3 would be the next major limiting constituent. (TiO_2 is about as limiting as Al_2O_3 in some models.) The Al_2O_3 limitation would decrease the amount of mantle required for all constituents except K_2O, Na_2O, and, for some models, P_2O_5, but would increase the degree of partial melting to an average of 41.5 percent for Park Range or Colorado models and to 24 percent for world models. Calculations of appropate residue for Na_2O- and Al_2O_3-limiting conditions of all seven crust-mantle models are also listed in table B16.

Normative minerals calculated for each of the compositions pertinent to the seven crust-mantle models are also listed in table B16. The fractionation trend of the residuum indicated by these models as crust is removed from mantle is as follows:

1. The following parameters increase:
   a. FeO, MgO, Cr_2O_3, NiO, MnO, and the FeO/Fe_2O_3 ratio.
   b. Olivine.
   c. The An content of plagioclase.
   d. Generally, the Mg/Fe ratios of pyroxenes and olivine.
2. The following parameters decrease:
   a. K_2O, Na_2O, P_2O_5, Al_2O_3, TiO_2, SiO_2, and CaO.
   b. Total pyroxene.
   c. Amount of plagioclase.
   d. The orthopyroxene/clinopyroxene ratio.

The decrease in orthopyroxene or the orthopyroxene/

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[5] For example, if K_2O had been in the past or were continually supplied to the upper mantle by aqueous solution, convective circulation, or zone melting (see Tarling, 1978, p. 11), the volume of the upper mantle required for crustal growth by the K_2O stricture might be much less, although the involved volume of the total mantle would not be affected.

clinopyroxene ratio during fractionation holds true for all seven models, although it appears to conflict with the work of others. O'Hara (1968, p. 69, 126), Malpas (1977, p. 13), Duncan and Green (1980, p. 23, 25), and Roden and others (1982) indicate that mantle residuum can be high in orthopyroxene, that is, harzburgite or orthopyroxenite.

At 20 to 25 percent partial melt, calcium orthosilicate (shannonite) is needed to satisfy the silica requirements for these undersaturated residuum rocks. Most models assume 30 percent or less partial melt (for example, Duncan and Green, 1980, p. 22; Jacobsen and Wasserburg, 1979, p. 450; Miesch and Reed, 1979, p. H1). At higher proportions of melting the residuum would be too depleted in SiO_2 for even calcium orthosilicate, and a balanced assemblage of common solicates would not be possible. In terms of IUGS names, all three mantle candidates considered are olivine melanorites near lherzolite which, upon crustal fractionation, trend more and more toward dunite, wehrlite or melatroctolite (fig. 36), and finally to unnamed mixtures of mafic oxides.

Actually, the chemical constraints on reasonable Earth models are even greater than those indicated. For example, the derivation of the average Colorado Precambrian rock from average Park Range ultramafic rock would take 19 units of mantle to make 1 unit of this

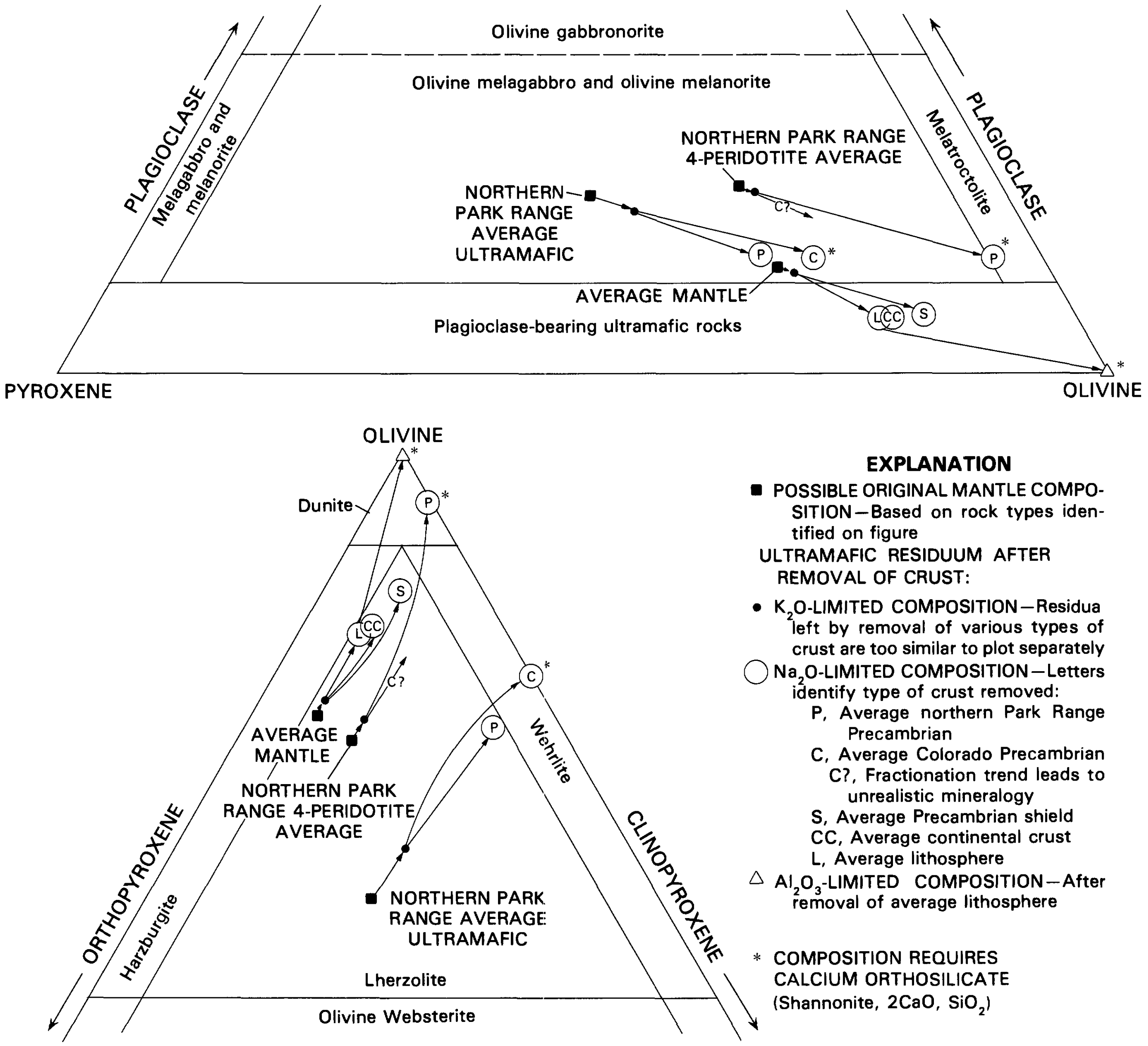

FIGURE 36.—Partial triangular diagram plots showing fractionation trends and required normative compositions of mantle residua after various types of crust have been generated from several possible mantle sources.

TABLE 8.—*Tabular- and spherical-model mantle thicknesses needed to derive various types of crust, based on K_2O limitation*

[All thicknesses in kilometers; 1 km≈0.62 mi. Avg. = average]

Type of crust	Crust half-thickness	Type of mantle	Tabular-model thickness[1] (x)	Spherical-model thickness, trial and error[2]	Increase in percent	Spherical-model thickness (y), by formula[3]
Park Range avg. Precambrian	22.5	Park Range avg. ultramafic	378	405	7	404
		Park Range four-peridotite avg.	1,080	1,351	25	1,350
Colorado avg. Precambrian--	22.5	Park Range avg. ultramafic	428	462	8	462
		Park Range four-peridotite avg.	1,221	1,591	30	1,580
Avg. Precambrian shield----	17.5	Avg. mantle---------------	992	1,210	22	1,214
Avg. continental crust-----	17.5	-----do------------------	700	798	14	801
Avg. lithosphere-----------	8.5	-----do------------------	354	376	6	376

[1] From table B16.

[2] Volume equal to that of tabular model.

[3] Based on the formula $y = \frac{x}{1.00857-0.000193x}$.

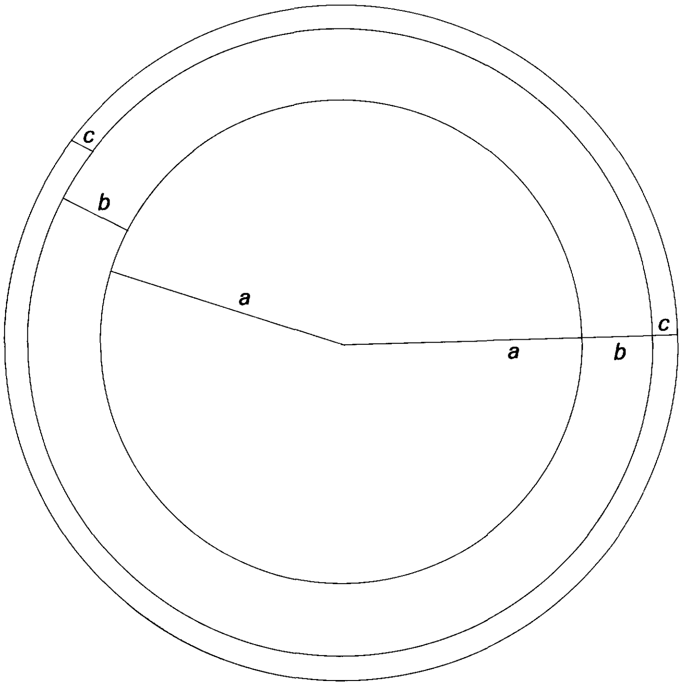

FIGURE 37.—Key to spherical shell labels used in calculations for Earth models; c = thickness of crust, b = thickness of mantle from which c is derived, and a = remaining radius of the Earth.

crust. To calculate the required mantle thickness, spherical volumes must be considered. Although such calculations are routine, they are involved and tedious because they require many trial-and-error computations, as was learned in calculating accurate mantle thicknesses based on spherical shells of appropriate volume for the K_2O-limited conditions of the seven models considered in tables 8 and B16.

With reference to the Earth cross section in figure 37, c=the thickness of crust, b=the thickness of mantle from which c is derived, and a=the remaining radius of the Earth; then the volume of the crust, $V_c=4/3\pi(a+b+c)^3-4/3\ \pi(a+b)^3$. But $a+b+c$=6,371.2 km (3,958.9 mi; the average radius of the Earth), so for any assigned c, $a+b$ is known and V_c is easily calculable. V_c has been calculated for the three c's used in table B16. The K_2O-limited condition can be described by a pair of equivalent ratios, $V_c/V_b=K_2O_b/K_2O_c$, or $V_b=V_c(K_2O_c/K_2O_b)$, but V_b is also equal to $4/3\pi(b^3+3a^2b+3ab^2)$, so for any c, a single real a and a single real b can be chosen by trial and error to exactly satisfy the equation $4/3\pi(b^3+3a^2b+3ab^2)=V_c(K_2O_c/K_2O_b)$. Values for a and b have been calculated to the nearest integer for the seven models considered. (For b, the thickness of each mantle in each spherical model, see table 8.)

It is intuitively obvious that the greater the needed mantle thickness indicated in the tabular model, the greater the increase in mantle thickness necessitated by the spherical model. It turns out that, for the smallest tabular model mantle thickness considered, the spherical model mantle thickness is 6 percent greater, while the largest tabular thickness considered requires a 30 percent spherical thickness increase. Plotted against each other, as in figure 38, these equivalent

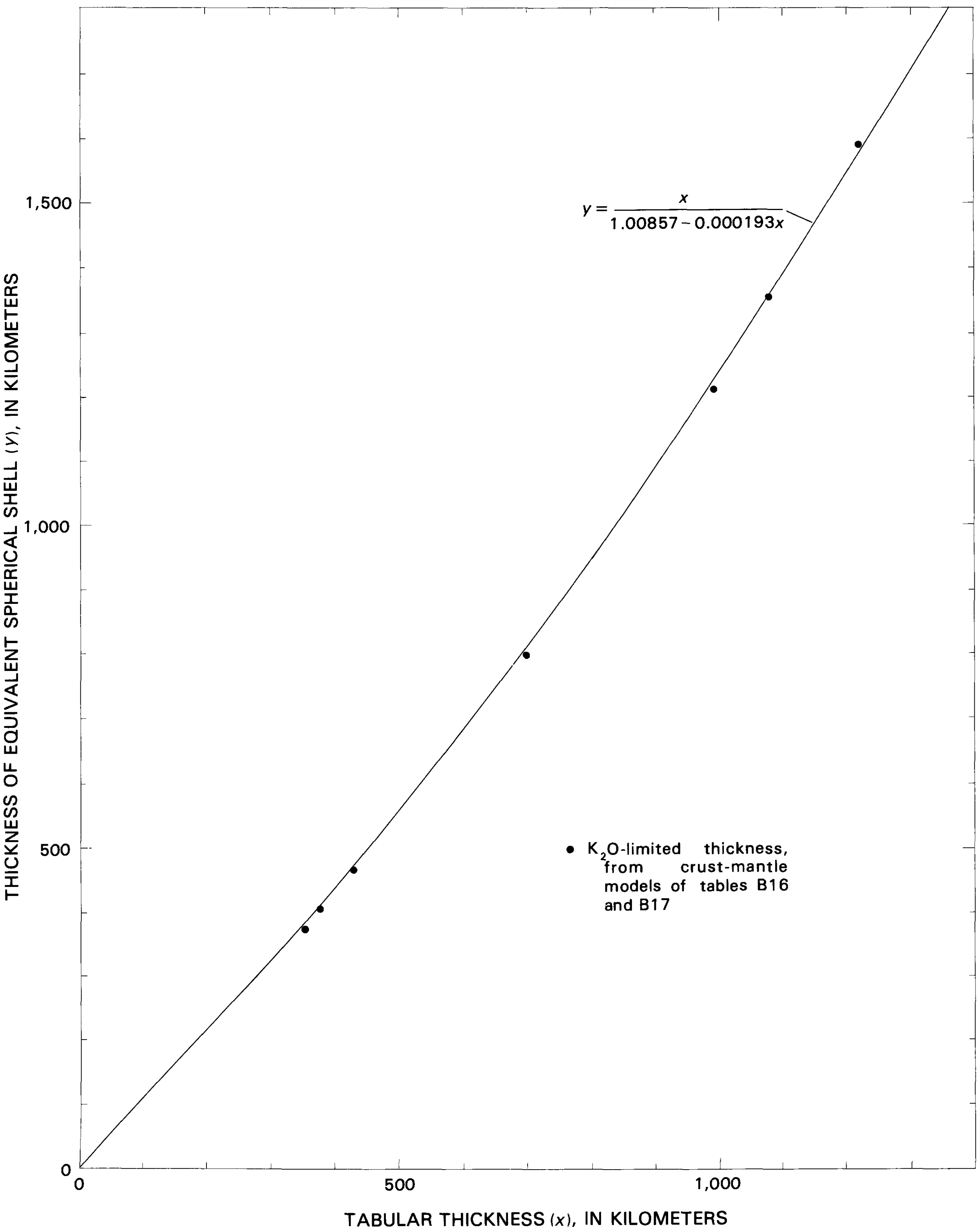

FIGURE 38.—Graph for converting mantle tabular thickness to thickness of mantle spherical shell.

model thickness values fall along a smooth, nonlinear curve. The approximate equation of the curve is $y=\frac{x}{1.00857-0.000193x}$, where y is the spherical model thickness predicted from x, the tabular model thickness (A. T. Miesch, oral commun., 1979). Solved for y using the tabular-model thicknesses given in table 8, this equation gives an average y within 3 km (1.9 mi) of the actual value (within 1 km (0.6 mi) below 1,350 km (840 mi)). The curve or the formula can be used to generate acceptable Na_2O- or Al_2O_3-limited spherical thicknesses from the data presented in table B16. Other curve formulae were also considered. For example, $y=0.4259x^{1.1541}$ gives an average spherical thickness within 11.3 km (7.0 mi) of the correct value for all seven models. Several additional formulae considered were poorer than this.

Na_2O and K_2O would be even more limiting if the amount of either removed from the system (that is, dissolved by water and transported to the ocean) were added back in to the average crust. However, it is believed that this sort of recalculation would have a very slight effect. For example, soda in modern ocean water in an area the size of Colorado is less than one thousandth of a percent of that in a 22.5-km (14-mi) Colorado crust, and the effect for potash would be at least an order of magnitude smaller.

Thus major-element amounts in mantle and crust, particularly K_2O, provide constraints on the minimum thicknesses of mantle and the expected mineralogy of residuum. Deriving any reasonable crystalline shield from any reasonable peridotitic mantle would require 400 to 1,200 km (250 to 750 mi) of mantle even if the mantle could be completely purged of K_2O. Such a derivation could be accomplished by a 2- to 6-percent partial melt and would result in a residuum theoretically enriched in olivine and, more importantly, **depleted in orthopyroxene**, compared to the starting material. Deriving the entire lithosphere from average mantle would be less constrictive because of the smaller average thickness required and the higher proportion of oceanic tholeiite in the average chemistry. Still, the K_2O limitation requires more than 370 km (230 mi) of mantle, a partial melt of 2.4 percent, and a residuum whose mineral content would be as stated (table B16). If the K_2O limitation could be overcome (and a convincing mechanism for accomplishing this is not readily apparent), the required amount of mantle could be reduced an order of magnitude before unrealistic mineralogy would result near a maximum partial melt of some 25 percent.

REFERENCES CITED

Abbott, J. T., 1972, Rb-Sr study of isotopic redistribution in a Precambrian mylonite-bearing shear zone, northern Front Range, Colorado: Geological Society of America Bulletin, v. 83, no. 2, p. 487–493.

Anderson, D. L., Sammis, Charles, and Jordan, Tom, 1972, Composition of the mantle and core, *in* Robertson, E. C., Hays, J. F., and Knopoff, Leon, eds., The nature of the solid earth (Francis Birch Symposium at Harvard University, April 1970): [New York] McGraw-Hill, Inc., p. 41–66.

Antweiler, J. C., Doe, B. R., and Delevaux, M. H., 1972, Lead isotope and other evidence on the bedrock source of placer gold at Hahns Peak, Colorado: Economic Geology, v. 67, p. 302–314.

Bailey, D. K., Tarney, J., and Dunham, Kingsley, eds., 1980, The evidence for chemical heterogeneity in the Earth's mantle: Royal Society of London, 357 p.

Barth, T. F. W., 1961, Abundance of the elements, areal averages and geochemical cycles: Geochimica et Cosmochimica Acta, v. 23, p. 1–8.

Basu, A. R., and Tatsumoto, Mitsunobu, 1979, Samarium-Neodymium systematics in kimberlites and in the minerals of garnet lherzolite inclusions: Science, v. 205, no. 4404, p. 398–401.

Bell, P. M., 1979, Ultra-high-pressure experimental mantle mineralogy: Reviews of Geophysics and Space Physics, v. 17, no. 4, p. 788–791.

Bickford, M. E., Bowring, S. A., and Gray, J. E., 1982, Chronology of igneous events in the Proterozoic of central Colorado: Geological Society of America Abstracts with Programs, v. 14, no. 6, p. 303.

Bowring, S. A., and Condie, K. C., 1982, U-Pb zircon ages from northern and central New Mexico: Geological Society of America Abstracts with Programs, v. 14, no. 6, p. 304.

Brown, G. M., O'Hara, M. J., and Oxburgh, E. R., 1978, Introduction to terrestrial heat and generation of magmas: Philosophical Transactions of the Royal Society of London, v. 288, no. 1355, p. 385–386.

Carter, J. L., 1970, Mineralogy and chemistry of the Earth's upper mantle based on the partial fusion-partial crystallization model: Geological Society of America Bulletin, v. 81, no. 7, p. 2021–2034.

Clarke, F. W., and Washington, H. S., 1924, The composition of the Earth's crust: U.S. Geological Survey Professional Paper 127, 117 p.

Condie, K. C., 1982, Plate-tectonics model for Proterozoic continental accretion in the southwestern United States: Geology, v. 10, no. 1, p. 37–42.

Cordell, Lindrith, 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin, v. 89, p. 1073–1090.

Deer, W. A., Howie, R. A., and Zussman, J., 1962a, Ortho- and ring silicates, v. 1 *of* Rock-forming minerals: New York, John Wiley and Sons, 333 p.

______ 1962b, Non-silicates, v. 5 *of* Rock-forming minerals: New York, John Wiley and Sons, 371 p.

______ 1963, Chain silicates, v. 2 *of* Rock-forming minerals: New York, John Wiley and Sons, 379 p.

DePaolo, D. J., 1980, Crustal growth and mantle evolution—Inferences from models of element transport and Nd and Sr isotopes: Geochimica et Cosmochimica Acta, v. 44, no. 8, p. 1185–1196.

______ 1981, Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic: Nature, v. 291, no. 5812, p. 193–196.

Dickinson, W. R., and Luth, W. C., 1971, A model for plate tectonic evolution of mantle layers: Science, v. 174, p. 400–404.

Divis, A. F., 1976, Geology and geochemistry of the Sierra Madre Range, Wyoming: Quarterly of the Colorado School of Mines, v. 71, no. 3, 127 p.

______ 1977, Isotopic studies on a Precambrian geochronologic boundary, Sierra Madre Mountains, Wyoming: Geological Society of America Bulletin, v. 88, p. 96-100.

Duncan, R. A., and Green, D. H., 1980, Role of multistage melting in the formation of oceanic crust: Geology, v. 8, no. 1, p. 22-26.

Dutch, S. I., 1979, Discussion *of* The Colorado lineament—A Middle Precambrian wrench fault system, by L. A. Warner, 1978: Geological Society of America Bulletin, pt. I, v. 90, no. 3, p. 313-314.

Edwards, J. S., 1981, The petrology and contact relationships of the southwestern portion of the Precambrian Mullen Creek mafic complex, Medicine Bow Mountains, Wyoming: Geological Society of America Abstracts with Programs, v. 13, no. 4, p. 195.

Engel, A. E. J., 1966, Some limitations on the composition of the upper mantle during the last 3.5×10^9 years [abs.]: American Geophysical Union Transactions, v. 47, no. 1, p. 176.

Engel, A. E. J., and Engel, C. G., 1965, Primary oceanic magma and the nature of the upper mantle [abs.], *in* Smith, C. H., and Sorgenfrei, Theodor, eds., The upper mantle symposium, New Delhi, 1964: Copenhagen, International Union of Geological Science, Det Berlingske Bogtrykkeri, p. 186.

Engel, A. E. J., Engel, C. G., and Havens, R. G., 1965, Chemical characteristics of oceanic basalts and the upper mantle: Geological Society of America Bulletin, v. 76, p. 719-734.

Engel, A. E. J., Itson, S. P., Engel, C. G., Stickney, D. M., and Gray, E. J., Jr., 1974, Crustal evolution and global tectonics—A petrogenic view: Geological Society of America Bulletin, v. 85, p. 843-858.

Feininger, Tomas, 1965, Bedrock geologic map of the Voluntown quadrangle, New London County, Connecticut, and Kent and Washington Counties, Rhode Island: U.S. Geological Survey Geologic Quadrangle Map GQ-436.

Garlick, G. D., and Epstein, Samuel, 1967, Oxygen isotope ratios in coexisting minerals of regionally metamorphosed rocks: Geochimica et Cosmochimica Acta, v. 31, p. 181-214.

Garrels, R. M., Mackenzie, F. T., and Siever, Raymond, 1972, Sedimentary cycling in relation to the history of the continents and oceans, *in* Robertson, E. C., Hays, J. F., and Knopoff, Leon, eds., The nature of the solid earth (Francis Birch Symposium at Harvard University, April 1970): [New York] McGraw-Hill, Inc., p. 93-121.

Gast, P. W., 1968, Trace element fractionation and the origin of tholeiitic and alkaline magma types: Geochimica et Cosmochimica Acta, v. 32, p. 1057-1086.

______1972, The chemical composition of the Earth, the Moon, and chondritic meteorites; *in* Robertson, E. C., Hays, J. F., and Knopoff, Leon, eds., The nature of the solid earth (Francis Birch Symposium at Harvard University, April 1970): [New York] McGraw-Hill, Inc., p. 19-40.

Gimmel'farb, G. B., Nikolayev, Yu. T., and Belonozhko, L. B., 1969, Origin of quartz-sillimanite inclusions in biotite gneiss of the lower Proterozoic Udokan Series (Olekma-Vitim highlands): U.S.S.R. Academy of Sciences Doklady, Earth Science Section, v. 182, p. 42-44. (Translated from Akademiya Nauk SSSR Doklady, v. 182, p. 411-414.)

Goldsmith, Richard, 1967, Bedrock geologic map of the Uncasville quadrangle, New London County, Connecticut: U.S. Geological Survey Geologic Quadrangle Map GQ-576.

Gorshkov, G. S., 1967, Volcanic phenomena and the upper mantle, *in* Vinogradov, A. P., ed. Chemistry of the Earth's crust: Jerusalem, Israel Program for Scientific Translations v. 2, p. 41-53. (Translation by N. Kaner (edited by R. Amoils) *of* Khimiya zemnoi kory: Moscow, Izdatel'stvo Akademiya Nauk SSSR, 1964.)

Graff, P. J., 1973, The areal geology of the West Fork Lake quadrangle, northern Colorado: DeKalb, Ill., Northern Illinois University M.S. thesis, 59 p.

______ 1978, Geology of the lower part of the early Proterozoic Snowy Range Supergroup, Sierra Madre, Wyoming, *with chapters on* Proterozoic regional tectonics and uraniferous quartz-pebble conglomerates: Laramie, Wyo., University of Wyoming Ph. D. thesis, 85 p.

Grew, E. S., and Day, H. W., 1972, Staurolite, kyanite, and sillimanite from the Narragansett basin of Rhode Island: U.S. Geological Survey Professional Paper 800-D, p. D151-D157.

Haddon, R. A. W., and Bullen, K. E., 1969, An Earth model incorporating free Earth oscillation data: Physics of the Earth and Planetary Interiors, v. 2, p. 35-49.

Harris, P. G., 1967, Segregation processes in the upper mantle, *in* Runcorn, S. K., ed., Mantles of the Earth and terrestrial planets: London, New York, and Sydney, Wiley Interscience Publishers, p. 305-317.

Hickman, M. H., 1979, Discussion *of* The Colorado lineament—A middle Precambrian wrench fault system, by L. A. Warner, 1978: Geological Society of America Bulletin, pt. I, v. 90, no. 10, p. 987.

Hill, J. J., 1969, Petrology and structure of the Precambrian rocks of the Park Range of north-central Colorado: Eugene, Oreg., University of Oregon M.S. thesis, 75 p.

Hills, F. A., and Armstrong, R. L., 1974, Geochronology of Precambrian rocks in the Laramie Range and implications for the tectonic framework of Precambrian southern Wyoming: Precambrian Research, v. 1, p. 213-225.

Hills, F. A, Gast, P. W., Houston, R. S., and Swainbank, I. G., 1968, Precambrian geochronology of the Medicine Bow Mountains, southeastern Wyoming: Geological Society of America Bulletin, v. 79, p. 1757-1784.

Hills, F. A., and Houston, R. S., 1979, Early Proterozoic tectonics of the central Rocky Mountains, North America: University of Wyoming Contributions to Geology, v. 17, no. 2, p. 89-109.

Houston, R. S., and others, 1968, A regional study of rocks of Precambrian age in that part of the Medicine Bow Mountains lying in southeastern Wyoming, *with a chapter on* The relationship between Precambrian and Laramide structure: Geological Survey of Wyoming Memoir No. 1, 167 p.

Houston, R. S., and Ebbett, B. E., 1977, Geologic map of the Sierra Madre and western Medicine Bow Mountains, southeastern Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF-827.

Houston, R. S., and Karlstrom, K. E., 1979, Uranium-bearing quartz-pebble conglomerates: Exploration model and United States resource potential: U.S. Department of Energy Report (Contract No. EY-TG-C-14-1664; Bendix Subcontract No. 78-22-E), 510 p.

Houston, R. S., Karlstrom, K. E., and Graff, P. J., 1979, Progress report on the study of radioactive quartz-pebble conglomerate of the Medicine Bow Mountains and Sierra Madre, southeastern Wyoming: U.S. Geological Survey Open-File Report 79-1131, 43 p.

Houston, R. S, Karlstrom, K. E., Hills, F. A., and Smithson, S. B., 1979, The Cheyenne belt—The major Precambrian crustal boundary in the western United States: Geological Society of America Abstracts with Programs, v. 11, no. 7, p. 446.

Jacobs, J. A., 1971, Physical properties of the Earth's mantle and core, *in* Coulomb, J., and Caputo, M., eds., Mantle and core in planetary physics (Proceedings of the Italian Physical Society's Enrico Fermi International School of Physics): New York and London, Academic Press, p. 65-93.

Jacobsen, S. B., and Wasserburg, G. J., 1979, Mantle-crust transport models and the mean age of mantle and crustal reservoirs: Geological Society of America Abstracts with Programs, v. 11, no. 7, p. 450.

Joesten, Raymond, 1978, Diffussion-controlled growth of pyroxene-spinel coronas between forsterite and anorthite in the system CaO-MgO-Al_2O_3-SiO_2: Geological Society of America Abstracts with Programs, v. 10, no. 7, p. 429.

Johannsen, Albert, 1950, A descriptive petrography of the igneous rocks: University of Chicago Press, v. 1, 318 p.

Johnson, R. B., Jr., 1979, Structural and stratigraphic controls on Precambrian Pb-Zn-Cu type mineralization at the Greenville Mine, Clark, Colorado: Geological Society of America Abstracts with Programs, v. 11, no. 6, p. 275.

Karlstrom, K. E., 1977, Geology of the Proterozoic Deep Lake Group, central Medicine Bow Mountains, Wyoming: Laramie, Wyo., University of Wyoming M.S. thesis, 116 p.

Kerr, R. A., 1979, Mantle geochemistry—Probing the source of the Earth's crust: Science, v. 203, no. 4380, p. 530-532.

La Roche, Hubert de, 1974, Geochemical characters of the metamorphic domains—survival and testimony of their premetamorphic history: Sciences de la Terre, v. 19, no. 2, p. 101-117.

Losert, Jiří, 1968, On the genesis of nodular sillimanitic rocks, *in* Geology of the Pre-Cambrian: International Geologic Congress, 23d, Prague 1968, Report, Proc. sec. 4, p. 109-122.

Lyons, P. C., 1976, IUGS classification of granitic rocks—A critique: Geology, v. 4, p. 425, 426.

Maaløe, Sven, and Aoki, Ken-ichiro, 1977, The major element composition of the upper mantle estimated from the composition of lherzolites: Contributions to Mineralogy and Petrology, v. 63, p. 161-173.

Macaudière, Jean, and Touret, Jacques, 1969, La fibrolitisation tectonique—Un mécanisme possible de formation des gneiss nodulaires du Bamble (Norvege méridionale): Sciences de la Terre, v. 14, no. 3, p. 200-213.

Malpas, J., 1977, Petrology and tectonic significance of Newfoundland ophiolites, with examples from the Bay of Islands, *in* Coleman, R. G., and Irwin, W. P., eds., North American ophiolites: Oregon Department of Geology and Mineral Industries Bulletin 95, p. 13-23.

Mason, Brian, 1958, Principles of geochemistry (2d ed.): New York, John Wiley & Sons, Inc., 310 p.

McCallum, M. E., and Mabarak, C. D., 1976, Diamond in state-line kimberlite diatremes, Albany County, Wyoming, and Larimer County, Colorado: Geological Survey of Wyoming Report of Investigations no. 12, 36 p.

Miesch, A. T., and Reed, B. L., 1979, Compositional structures in two batholiths of circumpacific North America: U.S. Geological Survey Professional Paper 574-H, 31 p.

Mueller, R. E., 1982, The Cheyenne belt, southeastern Wyoming—Part I, Descriptive geology and petrography: Laramie, Wyo., University of Wyoming M.S. thesis, 98 p.

Nicholls, G. D., 1967, Geochemical studies in the ocean as evidence for the composition of the mantle, *in* Runcorn, S, K., ed., Mantles of the Earth and terrestrial planets: London, New York, and Sydney, Wiley Interscience Publishers, p. 285-304.

Nishimori, R. K., Hawkins, J. W., and Fujita, Hitoshi, 1972, Mafic and ultramafic layered rocks of the ocean floor and orogenic belts—A geochemical and petrologic comparison: Geological Society of America Abstracts with Programs, v. 4, no. 3, p. 209-210.

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geological Society of America Bulletin, v. 65, p. 1007-1032.

O'Hara, M. J., 1968, The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks: Earth-Science Reviews, v. 4, no. 2, p. 69-133.

Pakiser, L. C., and Robinson, Rhoda, 1966, Composition of the continental crust as estimated from seismic observations, *in* Steinhart, J. S., and Smith, T. J., eds., The Earth beneath the continents (a volume of geophysical studies in honor of Merle A. Tuve): Washington, D.C., American Geophysical Union, p. 620-626.

Palache, Charles, Berman, Harry, and Frondel, Clifford, 1946, The System of mineralogy of James Dwight Dana and Edward Salisbury Dana, v. I, Elements, sulfides, sulfosalts, oxides, 7th ed.: New York, John Wiley and Sons, 834 p.

Parker, R. L., 1967, Composition of the Earth's crust, chap. D *of* Fleisher, Michael, ed., Data of geochemistry, 6th ed., U.S. Geological Survey Professional Paper 440-D, 19 p.

Peacock, M. A., 1931, Classification of igneous rock series: Journal of Geology, v. 39, no. 1, p. 54-67.

Peterman, Z. E., and Hildreth, R. A., 1978, Reconnaissance geology and geochronology of the Precambrian of the Granite Mountains, Wyoming: U.S. Geological Survey Professional Paper 1055, 22 p.

Poldervaart, Arie, 1955, Chemistry of the Earth's crust, *in* Poldervaart, Arie, ed., Crust of the Earth: Geological Society of America Special Paper 62, p. 119-144.

Premo, W. R., and Van Schmus, W. R., 1982, U-Pb zircon geochronology of the Sierra Madre range, Wyoming: Geological Society of America Abstracts with Programs, v. 14, no. 6, p. 346.

Press, Frank, 1971, An introduction to Earth structure and seismotectonics, *in* Columb, J., and Caputo, M., eds., Mantle and core in planetary physics (Proceedings of the Italian Physical Society's Enrico Fermi International School of Physics): New York and London, Academic Press, p. 209-241.

Prodehl, Claus, 1979, Crustal structure of the western United States: U.S. Geological Survey Professional Paper 1034, 74 p.

Raymond, W. H., Leiggi, P. A., and Sheridan, D. M., 1980, Sapphirine in Precambrian rocks associated with stratabound sulfide deposits, Custer County, Colorado: U.S. Geological Survey Bulletin 1513, 22 p.

Read, T. T., 1903, Nodular-bearing schists near Pearl, Colorado: Journal of Geology, v. 11, no. 5, p. 493-497.

Ringwood, A. E., 1969, Composition and evolution of the upper mantle, *in* Hart, P. J., ed., The Earth's crust and upper mantle: American Geophysical Union, Geophysical Monograph 13, p. 1-17.

——— 1975, Composition and petrology of the Earth's mantle: New York, McGraw-Hill Book Company, 618 p.

Ringwood, A. E., and Lovering, J. F., 1970, Significance of pyroxene-ilmenite intergrowths among kimberlite xenoliths: Earth and Planetary Science Letters, v. 7, p. 371-375.

Rittmann, Alfred, 1952, Nomenclature of volcanic rocks proposed for use in the catalogue of volcanoes, and key-tables for the determination of volcanic rocks: Bulletin Volcanologique, series 2, v. 12, p. 75-102.

Roden, M. F., Smith, D., and Frey, F. A., 1982, Mantle with oceanic affinities beneath the Colorado Plateau: Geological Society of America Abstracts with Programs, v. 14, no. 6, p. 348.

Ronov, A. B., and Yaroshevsky, A. A., 1969, Chemical composition of the Earth's crust, *in* Hart, P. J., ed., The Earth's crust and upper mantle: American Geophysical Union Geophysical Monograph 13, p. 37-57.

Sederholm, J. J., 1925, The average composition of the Earth's crust in Finland: Finlande Commission Géologique Bulletin, no. 70, 20 p.

Segerstrom, Kenneth, and Young, E. J., 1972, General geology of the Hahns Peak and Farwell Mountain quadrangles, Routt County, Colorado, *with a discussion of* Upper Triassic and pre-Morrison Jurassic rocks, by G. N. Pipiringos: U.S. Geological Survey Bulletin 1349, 63 p.

Semet, M. P., and Ernst, W. G., 1981, Experimental stability relations of the hornblende magnesiohastingsite—Summary: Geological Society of America Bulletin, pt. I, v. 92, no. 2, p. 71-74.

Shaw, D. M., Reilly, G. A., Muysson, J. R., Pattenden, G. E., and Campbell, F. E., 1967, An estimate of the chemical composition of the Canadian Precambrian shield: Canadian Journal of Earth Science, v. 4, no. 5, p. 829-853.

Sheridan, D. M., and Raymond, W. H., 1977, Preliminary data on some Precambrian deposits of zinc-copper-lead sulfides and zinc spinel (gahnite) in Colorado: U.S. Geological Survey Open-File Report 77-607, 27 p.

Snyder, G. L., 1961, Bedrock geology of the Norwich quadrangle, Connecticut: U.S. Geological Survey Geologic Quadrangle Map GQ-144.

______ 1964, Petrochemistry and bedrock geology of the Fitchville quadrangle, Connecticut: U.S. Geological Survey Bulletin 1161-I, 63 p.

______ 1978, Intrusive rocks northeast of Steamboat Springs, Park Range, Colorado, *with a section on* Geochronology, by C. E. Hedge: U.S. Geological Survey Professional Paper 1041, 42 p.

______ 1980a, Geologic map of the central part of the northern Park Range, Jackson and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1112.

______ 1980b, Geologic map of the northernmost Park Range and southernmost Sierra Madre, Jackson and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1113.

______ 1980c, Geologic map of the northernmost Gore Range and southernmost northern Park Range, Grand, Jackson, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1114.

Snyder, G. L., Patten, L. L., and Daniels, J. J., (in press), Mineral resources of the Mount Zirkel Wilderness and northern Park Range vicinity, Jackson and Routt Counties, Colorado: U.S. Geological Survey Bulletin 1554.

Sobolev, N. V., 1977, Deep-seated inclusions in kimberlites and the problem of the composition of the upper mantle: Washington, American Geophysical Union, 279 p. (Translated from the Russian by D. A. Brown; Russian edition published 1974, Izdatel'stvo Nauka, Moscow).

Stanton, R. L., 1976, Petrochemical studies of the ore environment at Broken Hill, New South Wales: Institution of Mining and Metallurgy Transactions, sec. B, v. 85, February, p. 33-46 (pt. 1); May, p. 118-131 (pt. 2); May, p. 132-141 (pt. 3); August, p. 221-233 (pt. 4).

Stanton, R. L., and Williams, K. L., 1978, Garnet compositions at Broken Hill, New South Wales, as indicators of metamorphic processes: Journal of Petrology, v. 19, no. 3, p. 514-529.

Steven, T. A., 1954, Geology of the Northgate fluorspar district, Colorado: U.S. Geological Survey Mineral Investigations Field Studies Map MF-13.

Streckeisen, A. L., 1973, Plutonic rocks—Classification and nomenclature recommended by the IUGS Subcommission on the Systematics of Igneous Rocks: Geotimes, October 1973, p. 26-30.

______ 1976, To each plutonic rock its proper name: Earth-Science Reviews, v. 12, no. 1, p. 1-33.

Sun, Shen-su, 1982, Chemical composition and origin of the Earth's primitive mantle: Geochimica et Cosmochimica Acta, v. 46, no. 2, p. 179-192.

Tarling, D. H., 1978, Evolution of the Earth's crust: London, Academic Press, 443 p.

Taylor, S. R., 1964, Abundance of chemical elements in the continental crust—A new table: Geochimica et Cosmochimica Acta, v. 28, p. 1273-1285.

______ 1965, The composition of the crust and mantle and the chondritic Earth model, *in* Ringwood, A. E., compiler, International Council of Scientific Unions Upper Mantle Project, Australian progress report, 1960-65: Canberra, Australian Academy of Science, p. 137-138.

Tröger, W. E., 1956, Optische Bestimmung der gesteinsbildenden Minerale—Teil l, Bestimmungstabellen: Stuttgart, E. Schweizerbart'sche Verlagsbuch-handlung, 147 p.

Tweto, Ogden, 1976a, Preliminary geologic map of Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-788.

______ 1976b, Geologic map of the Craig 1°X2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-972.

______ 1978, Tectonic map of the Rio Grande rift system in Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 33-56, sheet 1.

______ 1979, Geologic map of Colorado: U.S. Geological Survey.

Viljoen, M. J., and Viljoen, R. P., 1969, Evidence for the existence of a mobile extrusive peridotitic magma from the Komati formation of the Onverwacht Group, *in* South African National Committee Symposium on the upper mantle project: Geological Society of South Africa Special Publication 2, p. 87-112.

Viljoen, R. P., and Viljoen, M. J., 1970, The geology and geochemistry of the layered ultramafic bodies of the Kaapmuiden area, Barberton Mountain Land, *in* Visser, D. J. L., and von Gruenewaldt, G., eds., Symposium on the Bushveld igneous complex and other layered intrusions: Geological Society of South Africa Special Publication 1, p. 661-688.

Warner, L. A., 1978, The Colorado lineament—A middle Precambrian wrench fault system: Geological Society of America Bulletin, v. 89, no. 2, p. 161-171.

______ 1979a, Reply *to* Discussion, by S. I. Dutch, 1979, *of* The Colorado lineament—A middle Precambrian wrench fault system, by L. A. Warner, 1978: Geological Society of America Bulletin, pt. I, v. 90, no. 3, p. 314-316.

______ 1979b, Reply *to* Discussion, by M. H. Hickman, 1979, *of* The Colorado lineament—A middle Precambrian wrench fault system, by L. A. Warner, 1978: Geological Society of America Bulletin, pt. I, v. 90, no. 10, p. 988.

Winchell, A. N., and Winchell, Horace, 1959, Elements of optical mineralogy, An introduction to microscopic petrography, Part II, Descriptions of minerals, 4th edition: New York, John Wiley & Sons, Inc., 551 p.

Winkler, H. G. F., 1965, Petrogenesis of metamorphic rocks: New York, Springer-Verlag Inc., 220 p.

Young, E. J., and Segerstrom, Kenneth, 1973, A disseminated silver-lead-zinc sulfide occurrence at Hahns Peak, Routt County, Colorado: U.S. Geological Survey Bulletin 1367, 33 p.

APPENDIX A.—PETROCHEMICAL PROCEDURES AND COMMENTS

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ESTIMATES OF RELATIVE VOLUME

Counts of regularly spaced or random points on plane surfaces are used to estimate volumes throughout this report. The plane surfaces range in size from the surface of a single microscopic crystal, through thin sections and rock slabs of various sizes, to 1:24,000 and 1:48,000 maps of the northern Park Range and a 1:500,000 map of Colorado. The volumes of interest range from microscopic to thousands of cubic kilometers. More than 430,000 points were counted along equally spaced parallel traverse lines, rectilinear traverse lines, or random-walk traverse lines, whichever was most appropriate for a particular situation.

Numerous studies have been made of the minimum number of points it is necessary to count in an average thin section to be reasonably sure that the results are indicative of the actual relative volumes, and many of these studies recommend 500 to 1,000 points, depending on the grain size of the rock. One check of this was performed for this report. A uniformly spaced sequential count of minerals in a thin section of gabbro (sample 1685) was run for 2,000 points, and the mineral-count statistics were compiled after each 200 points. When all these percentages were plotted on graphs, it was found that the percentages of all evenly distributed minerals had leveled off at or before 1,200 points. Most thin-section point counts in this report exceed this number; where there were special problems or unusual interest, several times as many points were counted.

Judgment is required to assess the need for a volumetric count on a volume of rock larger than just one thin section. In some cases several thin sections will do. In obviously inhomogeneous rocks there is danger that thin sections will be purposely or inadvertently chosen from the inhomogeneities, leading to concomitant inaccuracies in estimated relative volumes. In these cases, thin sections chosen to show particular rock inhomogeneities exaggerate the abundances of these inhomogeneities. In the worst case, a rock (sample 988 GARN) that had a slab count of 0.27 percent garnet, the thin section chosen to show garnet gave a count of 28.13 percent, a 10,419-percent error on the too-generous side.

PLAGIOCLASE COMPOSITION

One of the most critical petrographic parameters for monitoring changes in rock composition is the anorthite content of plagioclase. More than 2,500 individual plagioclase compositions were determined, and many of these data are summarized in histograms in this report. Most plagioclase compositions were estimated from extinction angles of grains cut parallel to crystallographic direction 100 (Tröger, 1956, p. 111), such "MP" grains being easily recognized by their orientation perpendicular both to the albite- or Carlsbad-twin composition planes and to the chevron-patterned basal cleavages in these twins. This method loses some utility near An_{20} (where the separate twins become indistinguishable at zero extinction angle), but, because most rocks seem to have a natural variation of at least several percent anorthite, this limitation is seldom a serious problem. Some anorthite determinations were made using index oil techniques, direct chemistry, or comparison with normative chemistry, and these were usually found to check within 5 percent An of the average from the MP-section extinction-angle technique.

In rocks of the Park Range, plagioclases range from pure albite through pure anorthite but have different frequency distributions for different populations within this range. Anorthite content in plagioclase in most rocks correlates positively with color index or total mafic mineral content, but this rule is unreliable in detail. The variation in plagioclase composition in a given group of rocks is dependent on the size of the geographic area sampled, on the homogeneity of the geologic unit represented, and, to a small extent, on various sampling artifacts. (See C below.) At various scales of comparison the range in plagioclase compositions is as follows:

A. Between different thin sections from the same hand specimen, vanishingly small. (See fig. 30, sample 975 composite and sample 987 composite.)
B. Between sections from larger ("bread-basket-size") samples, remarkably small in some (see fig. 30, sample 1014 histograms) but greater in others (fig. 30, sample 988 histograms).
C. Within some large outcrops, quite small (fig. 30, sample 1843 and sample 1735–2033 composite

histograms). Sample 1843 is a special study of sampling reproducibility utilizing anorthite determinations. Three samples of type quartz diorite of Gilpin Lake were collected by three different geologists at 2-year intervals from the same 8-acre (3 1/4-hectare) bare rock exposure. Thin sections of each sample contained many suitably oriented plagioclases that had a range of compositions, but the average plagioclase in each sample was within 2 percent An of that in any other sample.

D. Within the same geologic body, possibly small (fig. 30, compare sample 1290 with sample 1283 histogram, and sample 1843 with sample 1107 histogram) but can be large (compare sample 1102 plagioclase in table B6 with sample 1107 histogram in fig. 30; also sample 2036–2040 composite histogram, same figure; also the spread within a small ultramafic body, samples 1052–1927, fig. 22), especially within a very large body, such as the Mount Ethel pluton (Snyder, 1978, table 5) or the Elkhorn Mountain pluton (compare individual gabbros and basalts of Elkhorn Mountain with each other, fig. 17; see distribution within gabbro, fig. 23B).

E. Between adjacent, related geological bodies, unpredictably small (fig. 24*E*, *F*, and *G*) or large (fig. 24*D*, and *E*).

F. Between unrelated geological bodies or formations, small or large, by chance. Where the variation is small between possibly or demonstrably different geological units (such as pod rocks and intrusive quartz monzonites, fig. 30, or olivine gabbros and their ultramafic inclusions, fig. 16*D*), one does well to look for and rely on other criteria for recognition or differentiation.

COMPARISON OF MODAL AND NORMATIVE MINERALOGY

Experience indicates that the present modes and norms (tables B1–B12) are in generally good agreement (compare modal and normative plots on triangular diagram figures 3 and 27) but, because of the impossibility of isolating all the operative variables, few exact comparisons are possible. However, comparisons of actual and theoretical plagioclase composition, amount of quartz or olivine, and a few other parameters give useful data.

Of 44 rocks for which both modal and normative anorthite contents of plagioclase were determined, most are within 3 percent An of a match, and all but one have their modal anorthite within 9 percent An of their normative anorthite. There may be a slight bias favoring a higher An in normative than in modal plagioclase, perhaps because most rocks contain some amphibole, which is not reflected in the normative analysis, and the amphibole may contain some of the anorthite molecule missing from the plagioclase. (For example, tschermakite, which has a composition of $2CaO \cdot 3MgO \cdot 2Al_2O_3 \cdot 6SiO_2 \cdot H_2O$, can be described as compositionally equivalent to two anorthites, one olivine, one hypersthene, and one water.) This must be the explanation of the mismatch (modal An=38.5, normative An=56) in sample 987 (layered amphibolite metasedimentary rock). As this sample has such a narrow modal plagioclase frequency distribution (fig. 30), simple mineralogy (table B6; fig. 6*A*), and the second highest hornblende amount of any analyzed rock, anorthite in the hornblende is the only tenable explanation of the lower-than-expected anorthite in the actual plagioclase. One rock that has a late-alteration zone of anorthite and clinoamphibole after hornblende (figs. 20*G* and *H*) may have frozen an anorthite-containing hornblende in the act of surrendering its anorthite.

Modal and normative quartz match within 4 percent in most of the 39 rocks for which comparable data are available, and only two are mismatched by more than 10 percent quartz. The latter two may reflect sampling problems with heterogeneous rocks (samples 1065 and 715 pod). The occurrence of such problems is surprising, though, as nine thin sections were studied and nearly 16,000 points were counted for these rocks.

There appears to be a definite bias against olivine (only one rock has more modal than normative olivine), perhaps because this mineral has consistently reacted with plagioclase (see previous comments on coronas) in its metamorphic environment subsequent to its magmatic crystallization. Modal olivine averages 10 percent less than normative olivine in Park Range rocks. Samples 1052 and 1927 (figure 19), averaging 33 percent less modal olivine than predicted, have a particularly well-disguised olivine component.

Most analyzed micaceous felsic rocks contain normative corundum (occurs in analyses that have more than enough Al_2O_3 to satisfy alkalies and CaO for feldspars). All felsic rocks that have more than 5 percent biotite or 2 percent muscovite, except one, contain significant normative corundum.

On the assumption that most CO_2 is in calcite, the marbles 989 and 1065 have good modal and normative matches. The 12-percent mismatch for sample 1064 may be partly due to a sampling problem (even though more than 5,000 points were counted in three thin sections) or may be partly due to the presence of carbonates other than calcite.

NOMENCLATURE

Several sets of igneous rock nomenclature are used in this report:

(1) Names for phaneritic rocks are derived from either modal (actual) or normative (ideal) minerals (often both) and are based on the recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks (Streckeisen, 1973, 1976) or on changes in this nomenclature recommended by Lyons (1976). Mineral names are listed in order of decreasing abundance.

(2) Volcanic names are derived from chemical analyses (Rittmann, 1952). Chemical volcanic names that approximate current usage are useful in at least three ways: (a) for identifying glassy or recrystallized rocks that were originally volcanic; (b) for comparing any analyzed rocks with a standard extrusive suite; and (c) for seeing what kind of a lava an analyzed rock would make if it were completely melted.

(3) Common names, those most familiar to local geologists or those used in previous publications, are favored when these differ from the above. Thus "quartz monzonite," the term common in Colorado, is substituted for the plagioclase-rich part of the IUGS granite field (or for the Lyons' (1976) "adamellites").

It is useful to use nomenclatures based on both modal and normative analyses for the following reasons:

(1) Arrived at by totally different routes, each is a check on the sampling and analytical accuracy of the other. Bad mismatches require explanation and (or) further work. Those contrasted in this report are believed to be in reasonably good agreement (to the extent that they are comparable), but the matches are seldom perfect.

(2) Rocks located near classification boundary lines may be on one side modally and the other side normatively, which gives one a better feel for the natural variability of a rock suite. Important classificatory boundaries occur at plagioclase compositions An_5 and An_{50}, at the presence or absence of quartz or subsilicic minerals (such as olivine), at 90 percent total mafic minerals, and at various other arbitrary mineral mixtures as shown on figures 3 and 27.

(3) Working with both whenever possible provides a basis for later inferences about the chemical averages of samples that can only be analyzed normatively. For example, figs. 35 and 36, based on the normative minerals of some volume-weighted or theoretical analyzed families of rocks, may have more utility in conjunction with earlier figures that showed both modes and norms, than if only the modes had been used earlier.

The An_5 nomenclatural boundary is one that could stand some improvement. As things are now in felsic rocks the main nomenclatural breakdowns come by contrasting most plagioclases with potassium feldspar, but if the plagioclase is An_5 or less, it is lumped with potassium feldspar and the rock called an alkali-feldspar syenite or granite. It would make better nomenclatural sense to use the "alkali-feldspar" modifier with any root name (if it fits). For example, sample 1013 is a normative granodiorite (An_6) and a modal quartz diorite (Lyons) (An_{11}), whereas sample 1011 is a normative alkali-feldspar granite (An_5) and a modal quartz diorite (Lyons) (An_{11}), compositionally near to sample 1013. (See figs. 29*B* and *C*.) Should such different sounding normative names hang on such a thin distinction between similar rocks? Similarly, sample 1676 is a modal adamellite (Lyons) (An_8) and a normative alkali-feldspar granite (An_3), and sample 1028 is modally and normatively an alkali-feldspar granite (An_{1-4}) that, if plagioclase is plotted as plagioclase, rests in Lyons' adamellite field. It seems more descriptive to refer to alkali-feldspar adamellites (or quartz monzonites) or to alkali-feldspar granodiorites, for instance, rather than restricting this modifier to the syenites and granites. This change would maintain an appreciation of the plagioclase-potassium feldspar ratio while accurately reflecting the alkali-rich nature of the rock.

REPLICATE CHEMISTRY OF VARIABLE ROCKS

Most of the 104 Park Range chemical analyses utilized in this report (many reported in tables B1, B3, B5, B7, B9, and B11 for the first time) are from uniform medium- to coarse-grained rocks. Others are less uniform, and several duplicate chemical analyses have been run on these to check the uniformity of the rock. These variable Precambrian rocks can be compared with the most uniform Park Range rocks, the fine-grained Tertiary intrusive rocks. Duplicate analyses of hand specimens of three fine-grained Tertiary intrusive rocks (Snyder, 1978, table 5, analyses of samples 19, 22 and 226) show that all major-oxide analyses were duplicated within an average of 0.3 weight percent or 1.5 percent of the value given, whichever is smaller. The greatest discrepancies are in the volatiles H_2O^+, H_2O^-, and CO_2, and in P_2O_5. How does the variation of these duplicate analyses of uniform fine-grained Tertiary rock compare with the variation of duplicate analyses of some coarse Precambrian rocks analyzed from the same hand specimen or small outcrop? Three groups of visually variable rocks have been analyzed for comparative purposes: Ultramafics having irregularly grouped corona structures, anisotropic pod and pisolite rocks, and marbles that may have extreme sedimentary variability.

Chemical variability in these rocks averages at least twice that in the cited Tertiary rocks, as detailed below.

Ultramafics are represented by the Wapiti Ranch lherzolite or dunite and by the Damfino Creek websterite. Wapiti Ranch is represented by sample 1116 (table B3; fig. 19) and by two analyses of sample 116 (Snyder, 1978, table 5), and Damfino Creek is represented by samples 1052 and 1927 (table B3; fig. 19). Representative samples of these two bodies were collected from the same exposures within a few feet of each other. Analyses of all constituents in these two rocks are duplicated within an average of 0.6 weight percent or 3.1 percent of the value given, whichever is smaller. In other words, these ultramafics appear to be about twice as variable as the "control" Tertiary intrusives. The greatest ultramafic variability occurs in Al_2O_3, alkalies, H_2O^-, P_2O_5, and CO_2.

Pisolite rocks are represented by samples 1854 and 12-1-20-5 (table B9; figs. 6*D*, *E*, and *F*) samples collected from nearby, visually similar outcrops near the summit of Farwell Mountain. Here all analyzed constituents were duplicated within an average of 0.1 weight percent or 3.7 percent of the value given (but the most relatively variable constituent, CO_2, differed by 800 percent: 0.01 weight percent versus 0.09 weight percent), again roughly twice as variable as the Tertiary intrusives.

Pod-rock matrix variability should be considered separately from pod variability. Duplicate matrix analyses are available from samples 988 and 1014 (table B11; figs. 9, 11, and 12) from Independence Mountain. Here all constituents were duplicated within an average of 0.8 weight percent or 2.4 percent of the value given, with greatest variability showing for Fe_2O_3, CaO, K_2O, and H_2O. Again, this is about twice (or perhaps not quite twice) as variable as the Tertiary intrusives. However, the 988 and 1014 pod samples are much more variable than their matrices, having some percentage misduplications of 100 percent or greater. It is not clear whether this great variability is a function of different initial pod composition (if, indeed, there ever was an initial pod, such as a cobblestone) or whether it is due to some form of metamorphic segregation. The duplicate analyses of the sample 715 pod samples (from near the sample 988 locality), by contrast, match within an average of 0.04 weight percent or 2.7 percent of the values given, whichever is smaller, a variability more comparable with other Precambrian results. The worst pod replication appears to occur with H_2O, Fe_2O_3, P_2O_5, and CO_2, and the uniformly best replication is for SiO_2.

The vesuvianite marbles from Red Elephant Mountain (samples 1064 and 1065, table B9; fig 6*B*) were the most unpredictably variable of all the analyzed rocks, perhaps because most mineral constituents were colorless or in shades of off-white, so the inhomogeneities were not very visible. These samples have wide percentage differences in all chemical constituents except (ironically) MgO, CaO, H_2O^-, and P_2O_5. Values determined for K_2O were 3.32 and 0.20 weight percent—a misduplication of 1,560 percent—and those for CO_2, were 12.08 and 1.26 weight percent—a misduplication of 859 percent!

It is possible that small samples of the gedrite rock (represented by sample 975 in table B5) would also show large chemical variability owing to the visible garnet inhomogeneities (0–20 percent) in this rock. But the large single sample analyzed for this report was chosen as an average representative. It is believed that replicate analyses from samples of this size would show no more than normal variability.

APPENDIX B—TABULAR CHEMICAL AND PETROGRAPHIC DATA

[All chemical analyses in tables B1 through B17 are reported in weight percent; petrographic analyses are in volume percent, based on a systematic count of points covering each thin section]

TABLE B1.—*Chemistry of mafic and ultramafic rocks from the gabbro of Elkhorn Mountain, northernmost Park Range, Colorado*

[Analysts: Vertie C. Smith (1), June 18, 1974; Elaine L. Brandt (2), Dec. 28, 1977. Al_2O_3 includes Cr_2O_3 (see text). Column 12, average gabbro, is the mean of columns 3 through 11 recalculated to 100 percent minus H_2O^-]

Column No.	1	2	3	4	5	6	7	8	9	10	11	12
Geologic unit and published map reference	Peridotite-Xep-MI-1113		Olivine gabbro-Xeo-MI-1113			Basalt dike-Xeb-MI-1113	Gabbro-Xe-MI-1113				Gabbro-Xe-MI-1113	
Field No.	1428	1412	1606	1410	1411	1985	1501-A	1685	1413	1765	1781	Average gabbro
Laboratory No.	D103311	D103309	D103315	D103307	D103308	D103892	D103312	D103319	D103310	D103887	D103888	
Analyst	(1)	(1)	(1)	(1)	(1)	(2)	(1)	(1)	(1)	(2)	(2)	
1973 IUGS name using modal minerals.	Olivine melanorite	Amphibole olivine melanorite	Pargasite olivine leuconorite	Pargasite olivine leuconorite	Pargasite olivine leuconorite	Dark "basalt" porphyry	Hornblende-biotite norite	Biotite-hornblende gabbro	Hornblende leuconorite	Hornblende-biotite leucogabbro	Biotite diorite	
1973 IUGS name using normative minerals.	Olivine melanorite	Olivine melanorite	Olivine leuconorite	Olivine leuconorite	Olivine gabbro	Olivine norite	Olivine norite	Norite	Norite	Olivine norite	Diorite (noritic)	(Olivine norite)
North latitude	40°58'39.8"	40°58'48.9"	40°48'0.3"	40°58'37.7"	40°58'48.9"	40°57'24.1"	40°55'13.3"	40°56'30.2"	40°58'48.9"	40°59'15.6"	40°59'25.0"	
West longitude	106°51'48.3"	106°51'8.6"	106°51'35.9"	106°51'1.0"	106°51'8.6"	106°58'30.2"	106°55'24.0"	106°53'50.2"	106°51'8.6"	106°57'51.2"	107°2'34.6"	
SiO_2	40.00	40.67	46.79	47.30	48.33	48.52	49.41	49.69	49.89	50.45	53.06	49.38
Al_2O_3	5.86	8.68	21.17	20.86	18.43	16.54	15.97	15.50	16.92	15.90	15.75	17.48
Fe_2O_3	5.10	6.31	1.22	1.07	0.91	2.26	2.42	2.10	2.37	1.74	1.57	1.73
FeO	7.22	8.80	7.18	6.93	6.88	8.64	9.00	9.63	8.44	8.73	8.98	8.28
MgO	30.74	23.83	8.17	8.92	10.48	8.11	7.59	7.49	8.55	8.69	5.70	8.20
CaO	3.49	4.69	1.18	10.56	11.16	10.72	9.60	10.16	9.88	9.34	8.56	10.15
Na_2O	0.50	0.92	2.25	2.44	2.27	2.40	2.81	2.44	2.39	2.50	3.64	2.57
K_2O	0.04	0.07	0.24	0.14	0.14	0.39	0.65	0.68	0.22	0.70	0.70	0.43
H_2O^+	5.88	4.48	0.50	0.84	0.65	0.81	0.46	0.45	0.34	0.55	0.22	0.54
H_2O^-	0.48	0.57	0.08	0.09	0.10	0.04	0.11	0.10	0.11	0.09	0.08	----
TiO_2	0.17	0.29	0.69	0.27	0.24	0.95	1.14	1.10	0.63	0.75	1.13	0.77
P_2O_5	0.02	0.04	0.11	0.02	0.03	0.19	0.35	0.24	0.02	0.18	0.19	0.15
MnO	0.18	0.21	0.13	0.12	0.13	0.19	0.18	0.20	0.18	0.17	0.17	0.16
CO_2	0.08	0.33	0.23	0.37	0.20	0.17	0.13	0.12	0.10	0.01	0.09	0.16
Total	99.76	99.89	99.94	99.64	99.95	99.93	99.82	99.90	99.94	99.80	99.84	100.00

NORMS

[Leaders (---), not present, or not present in significant amounts; xxx, not present because not possible under conditions described below. For method of calculation, see Johannsen (1950, p. 89–90). Before calculation all analyses, except 1428 and 1412, recalculated to 100 percent minus H_2O^-. 1428 and 1412 recalculated to 100 percent minus H_2O^+ and H_2O^- and then Fe_2O_3 converted to equivalent FeO, and ΣFeO used in NORM calculations]

Column No.		1	2	3	4	5	6	7	8	9	10	11	12
Q		---	---	---	---	---	---	---	---	---	---	0.48	---
or		---	.56	1.67	.56	.56	2.23	3.90	3.90	1.11	3.90	3.90	2.78
ab		4.72	8.39	18.87	20.45	19.40	20.45	23.59	20.45	20.45	20.97	30.93	21.50
an		14.74	20.30	47.00	45.89	39.77	33.10	29.20	29.48	34.77	30.32	24.75	34.77
100 an/ab+an		76	71	71	69	67	62	55	59	63	59	44	62
di	Ca	1.39	.81	2.67	1.86	5.92	7.43	6.62	7.66	5.81	6.39	6.85	5.69
	Mg	1.00	.50	1.61	1.10	3.81	4.32	3.71	4.12	3.41	3.71	3.41	3.31
	Fe	.26	.26	.92	.66	1.71	2.77	2.64	3.30	2.11	2.37	3.30	2.11
hy	Mg	6.32	5.82	4.22	5.72	6.12	9.23	9.54	11.74	14.45	13.45	10.84	9.94
	Fe	1.85	2.51	2.24	3.03	2.77	5.80	6.73	9.23	8.84	8.57	10.29	6.20
ol	Mg	52.27	39.40	10.20	10.76	11.33	4.64	3.94	1.97	2.39	3.17	---	4.99
	Fe	16.40	19.36	6.21	6.21	5.60	3.26	3.06	1.63	1.63	2.14	---	3.36
mt		xxx	xxx	1.85	1.62	1.39	3.24	3.47	3.01	3.24	2.55	2.32	2.55
il		.30	.61	1.37	.46	.46	1.82	2.13	1.98	1.22	1.37	2.13	1.52
ap		---	---	.33	---	---	.43	.66	.66	---	.33	.33	.33
cc		.20	.80	.50	.80	.50	.40	.30	.30	.20	---	.20	.40
H_2O^+		xxx	xxx	.50	.84	.65	.81	.46	.45	.34	.55	.22	.54
Total		99.45	99.32	100.16	99.96	99.99	99.93	99.95	99.88	99.97	99.79	99.95	99.99

TABLE B2.—*Petrography of chemically analyzed mafic and ultramafic rocks from the gabbro of Elkhorn Mountain, northernmost Park Range, Colorado*

[Petrographers: (1) George L. Snyder; (2) Peter A. Drobeck]

	Olivine melanorites		Olivine leuconorites			"Basalt" porphyry	Gabbros				Diorite
Field No. --	1428	1412	1606	1410	1411	1985	1501-A	1685	1413	1765	1781
Petrographer	(1)	(1)	(1)	(1,2)	(1,2)	(1)	(1,2)	(1)	(1,2)	(1)	(1)
Thin sections studied --	2	2	2	2	2	1	2	1	2	1	3
Total points counted --	2,340	3,083	2,530	1,808	1,934	1,006	6,892	2,000	1,870	2,016	3,255
Texture ----	Granular, poikilitic.	Coronitic, poikilitic.	Coronitic, poikilitic.	Coronitic, poikilitic.	Coronitic, poikilitic.	Diabasic, porphyritic.	Diabasic ---	Diabasic --	Diabasic --	Diabasic --	Diabasic.
Plagioclase -	12.14 An_{67} altered to sericite-chlorite mixture 6.75, and <0.04 calcite.	15.96 An_{70} altered to 1.82 sericite and 0.13 calcite.	67.07 An_{72} (euhedral) altered to 0.67 sericite, 0.61 calcite, and 0.34 aluminous epidote.	63.10 An_{71} altered to 0.06 clay.	59.71 An_{69} altered to 0.26 clay.	1.9 zoned phenocrysts, 28.3 groundmass lathes (An_{50}).	48.07 An_{56} altered to 0.12 sericite, 0.01 calcite, and <0.02 clay.	48.85 An_{55}	57.05 An_{61} altered to 0.05 clay.	47.6 An_{51}	56.90 An_{38} (strongly zoned).
Potassium feldspar --							0.07 exsolved perthite.	<0.1 exsolved perthite.			2.25 large orthoclases with myrmekitic edges.
Quartz ----							.10				.10
Olivine ----	64.53 altered to 30.21 chlorite, 6.03 magnetite, 0.13 talc.	45.86 altered to 20.95 chlorite, 6.58 magnetite.	9.42 altered to 1.48 magnetite along joints; 1.14 chlorite.	12.39 (caried) altered to 2.93 yellow serpentine, 1.33 green serpentine.	7.29 altered to 1.24 yellow chlorite, 0.10 green chlorite.	Rare(?) reacted remnants.					
Ortho-pyroxene	13.63 large twinned poikilitic, altered to 0.17 chlorite.	10.70 (6.00 large; 4.70 corona cockscombs).	4.64 (1.48 large; 3.16 corona cockscombs altered to 0.54 talc).	15.76 (11.89 large poikilitic grains; includes some clinopyroxene; 3.87 corona cockscombs).	11.12 (6.62 large poikilitic grains; 4.50 corona cockscombs).	55.3 fine-grained groundmass.	15.75	5.25	19.63	4.0	.5

Clinopyroxene		6.16 (6.16 large; <0.03 in coronas).	0.47 large, poikilitic.	(See orthopyroxene)	11.07 (some intertwins with orthopyroxene).	11.6 (0.6 phenocrysts; 11.0 small).	6.39 (1.17 augite; 5.22 pigeonite).	29.55 (mainly pigeonite?).	9.73 (8.76 pigeonite; 0.97 augite).	17.4	31.05
Amphibole	1.88 (0.94 brown hornblende; 0.94 clear corona pargasite).	18.00 (4.44 large brown; 3.28 corona brown; 4.05 large clear; 6.23 clear corona pargasite).	12.67 (8.63 large poikilitic pargasite; 4.04 kelyphitic corona intergrowth with spinel).	7.30 (0.83 large pargasite; 6.47 kelyphitic corona intergrowth with spinel; rare pargasite-carbonate intergrowth).	10.00 (3.67 large pargasite; 6.31 kelyphitic corona intergrowth with spinel).	(See groundmass statements above).	23.69 green hornblende.	5.90 green hornblende altered to 0.40 light green actinolite along joints.	11.34 green hornblende.	26.6 green hornblende.	0.25 green hornblende.
Biotite	0.26	0.13	1.68 (poikilitic)	0.06	<0.05	Rare	2.76	6.25	<0.05	3.7	4.35
Magnetite-ilmenite	0.47 (two oxides)	1.27	0.87 (2 oxides) poikilitic.	1.33	0.62	2.9	2.50 (two oxides)	3.55	2.25	0.5	4.25
Sulfide	0.01 pyrite	0.13 pyrrhotite.					0.02 pyrrhotite.				
Chromite	0.34	1.10									
Spinel		0.62 large	<0.07 large. (Also see amphibole.)	0.06 large. (Also see amphibole.)	0.21 large. (Also see amphibole.)						
Carbonate		0.19	0.13	(See amphibole)	<0.05		0.02		<0.05		
Epidote			2.69 aluminous epidote(?) kelyphitic corona rims.								
Apatite			0.26				0.64	0.65		0.2	
Sphene							<0.05				
Zircon											<0.1

TABLE B3.—*Chemistry of small ultramafic bodies (Xmp and Xep from published maps MI-1112 and MI-1113, respectively), northernmost Park Range, Colorado*

[Analyst, Elaine L. Brandt: (1) Dec. 26, 1972, and (2) Dec. 28, 1977. Al_2O_3 includes Cr_2O_3 (see text). Column 12, average ultramafic rock, is the mean of columns 1 through 11, plus 1428 and 1412 from table B1, as well as two analyses of 116 (same location as 1116) (Snyder, 1978, table 5); all analyses were recalculated to 100 percent minus H_2O^+ and H_2O^-]

Column No.	1	2	3	4	5	6	7	8	9	10	11	12
Field No.	1116	1017	1018	1078	1079	1052	1927	1070	1072	1112	1194	
Laboratory No.	D103056	D103036	D103037	D103050	D103051	D103041	D103891	D103047	D103048	D103055	D103058	
Analyst	(1)	(1)	(1)	(1)	(1)	(1)	(2)	(1)	(1)	(1)	(1)	
1973 IUGS name using modal minerals.	Spinel-bearing pargasite lherzolite.	Amphibole dunite.	Amphibole wehrlite.	Amphibole lherzolite.	Talc-magnetite hornblendite.	Spinel-bearing pargasite websterite.	Spinel-pargasite olivine websterite.	Amphibole olivine websterite.	Edenite(?) olivine clinopyroxenite.	Talc-phlogopite-amphibole rock.	Poikilitic enstatite crystal in peridotite.	Average ultramafic rock
1973 IUGS name using normative minerals	Melatroctolite	Plagioclase-bearing lherzolite	Olivine melagabbro	Olivine melanorite	Olivine melanorite	Olivine gabbro	Olivine gabbro	Olivine melagabbro	Olivine melagabbro	Orthoclase olivine melanorite	Plagioclase olivine orthopyroxenite	(Olivine melanorite)
Body	Wapiti Ranch	Bear Creek		Spring station		Damfino Creek		Three Island Lake		Big Agnes	Sawtooth	
North latitude West longitude	40°42′53.8″ 106°48′59.7″	40°45′35.1″ 106°37′8.0″	40°46′9.2″ 106°37′8.0″	40°30′12.0″ 106°45′55.6″	40°30′15.1″ 106°45′48.1″	40°59′49.7″ 106°41′44.0″	40°59′49.7″ 106°41′44.0″	40°45′12.9″ 106°42′1.2″	40°45′26.4″ 106°42′8.5″	40°49′4.1″ 106°41′28.4″	40°50′34.3″ 106°42′21.7″	
SiO_2	36.50	40.15	44.22	42.49	46.16	45.11	45.13	48.50	48.98	51.10	51.57	45.60
Al_2O_3	4.59	2.66	3.22	6.91	6.81	12.29	12.28	5.32	3.70	5.76	3.08	6.31
Fe_2O_3	12.68	11.63	6.09	5.15	4.42	2.99	2.82	2.96	2.66	1.81	4.12	6.76
FeO	5.94	3.95	6.57	7.04	8.93	6.37	6.41	5.52	5.24	7.05	7.87	6.81
MgO	29.20	27.60	23.71	26.09	19.76	18.67	18.73	20.67	19.98	24.02	28.72	25.83
CaO	2.62	5.24	10.87	6.01	7.42	12.66	12.80	12.86	15.84	2.47	2.54	7.19
Na_2O	.23	.28	.36	.44	.82	.58	.60	.67	.48	.10	.12	.47
K_2O	.02	.05	.07	.09	.09	.09	.10	.20	.13	2.32	.01	.23
H_2O^+	7.09	7.54	4.01	4.13	3.27	.86	.80	2.55	2.10	4.33	1.34	---
H_2O^-	.70	.32	.22	.27	.09	.03	.07	.17	.13	.17	.06	---
TiO_2	.18	.18	.26	.38	.47	.23	.25	.22	.26	.18	.24	.25
P_2O_5	.02	.02	.02	.34	.28	.03	.04	.04	.03	.03	.09	.07
MnO	.24	.22	.22	.24	.24	.16	.16	.17	.16	.20	.27	.22
CO_2	.16	.16	.16	.44	1.18	.08	.17	.17	.35	.23	.07	.26
Total	100.17	100.00	100.00	100.02	99.94	100.15	100.36	100.02	100.04	99.77	100.10	100.00

NORMS

[Leaders (---), not present, or not present in significant amounts. For method of calculation, see Johannsen (1950, p. 89–90). Before calculation all analyses recalculated to 100 percent minus H_2O^+ and H_2O^- and then Fe_2O_3 converted to equivalent FeO, and ΣFeO used in NORM calculations—thereby explaining the low totals]

Column No.	1	2	3	4	5	6	7	8	9	10	11	12
or	---	.56	.56	.56	.56	.56	.56	.56	.56	14.47	---	1.11
ab	2.10	2.62	3.15	3.67	7.34	5.24	5.24	5.77	4.19	.94	1.05	4.19
an	12.52	6.12	7.23	17.52	15.02	30.59	30.59	11.68	7.79	11.40	8.07	14.46
100 an/ab+an	86	70	70	83	67	85	85	67	65	92	88	78
C	---	---	---	---	---	---	---	---	---	1.63	---	---
di Ca	.12	8.71	19.97	3.37	5.57	13.01	13.35	22.06	29.38	---	1.39	7.90
di Mg	.07	5.82	13.45	2.31	3.51	8.83	9.13	15.66	20.98	---	1.00	5.32
di Fe	.04	2.24	5.01	.79	1.71	3.17	3.17	4.48	5.80	---	.26	1.98
hy Mg	2.86	8.03	3.51	15.96	26.60	1.00	.16	11.14	6.12	52.40	55.51	12.95
hy Fe	1.25	3.17	1.32	5.28	12.66	.40	.05	3.17	1.71	8.44	16.49	4.75
01 Mg	53.10	42.56	31.31	34.82	14.56	25.96	26.35	18.36	16.67	7.25	11.29	32.29
01 Fe	25.79	18.23	12.94	12.53	7.64	10.09	10.13	5.81	5.20	1.32	3.67	13.14
il	.30	.30	.46	.76	.91	.46	.46	.46	.46	.30	.46	.46
ap	---	---	---	.99	.66	.33	---	---	---	---	.33	.16
cc	.40	.40	.40	1.00	2.80	.20	.40	.40	.80	.50	.20	.60
Total	98.55	98.76	99.31	99.56	99.54	99.84	99.59	99.55	99.66	98.65	99.60	99.31

TABLE B4.—*Petrography of chemically analyzed rocks from small ultramafic bodies, northernmost Park Range, Colorado*

[Petrographer, George L. Snyder]

Body	Wapiti Ranch, melatroctolite	Bear Creek, amphibole peridotite		Spring station, melanorite		Damfino Creek, spinel-pargasite websterite		Three Island Lake, melagabbro		Big Agnes, soapstone	Sawtooth, poikilitic enstatite
Field No.	1116	1017	1018	1078	1079	1052	1927	1070	1072	1112	1194
Thin sections studied	2	1	2	1	1	2	1	1	1	1	2
Total points counted	2,760	2,763	2,154	2,239	2,311	2,964	2,486	1,784	3,101	1,639	2,186
Texture	Poikilitic, coronitic	Granular, poikilitic	Granular, poikilitic	Poikilitic	Granular	Coronitic, poikilitic	Coronitic, poikilitic	Granular, poikilitic	Granular, poikilitic	Interlocking, poikiloblastic	Interlocking, poikilitic
Plagioclase	1.8 An_{78} (6–8 in second ts) altered to 0.1 isotropic mineral, 0.7 sericite, <0.04 aluminous epidote.					4.5 An_{78} altered to <0.03 sericite.	1.7 An_{78}				
Olivine	73.3 altered to 3.6 brown bowlingite(?), 20.4 yellow chlorite, 16.0 clear chlorite, 14.5 magnetite.	63.4 altered to 48.9 chlorite(?), 11.9 magnetite-hematite.	37.8 altered to 16.3 clear chlorite or brucite, 8.0 hematite, 0.4 yellow chlorite.	35.6 altered to 9.1 clear chlorite(?), 4.9 yellow chlorite, 3.7 magnetite, 0.3 talc.		1.5 altered to 0.2 chlorite, 0.1 magnetite.	5.1 altered to 0.4 magnetite, 0.2 serpentine.	13.7 altered to 6.2 brown serpentine, 1.7 magnetite.	16.8 altered to 6.6 brown serpentine, 2.6 magnetite-hematite.		0.1 unaltered relicts.
Orthopyroxene	6.4 mainly corona cockscombs altered to 1.9 yellow chlorite; <0.04 in large poikilitic grains partly altered to amphibole.			14.5 poikilitic grains altered to 1.2 clear chlorite, 0.3 yellow chlorite, 0.1 tremolite.		20.3 finely twinned and zoned crystals.	10.2 corona cockscombs.	3.5			59.1 mainly single very poikilitic crystal with very thin twins.
Clinopyroxene	5.6 (5.0 as large poikilitic grains altered to 3.2 pargasite, 0.1 yellow chlorite; 0.6 in coronas).	7.0	28.9 (28.7 equidimensional, 0.2 elongate).	4.8 poikilitic grains altered to 0.2 colorless chlorite.		30.7 (24.3 large grains, 0.2 inclusions in amphibole or plagioclase, 6.2 in tight symplectite with spinel).	33.5 (29.0 large grains, 0.2 inclusions in amphibole or plagioclase, 4.2 in symplectite with spinel, one grain symplectite with amphibole).	27.1 (27.0 poikilitic grains; 0.1 inclusions in amphibole).	41.1 large poikilitic grains.		
Amphibole	10.6 colorless pargasite (2.1 in coronas next to clinopyroxene, orthopyroxene, or, rarely, olivine; 2.4 in large grains; 5.9 in symplectite with spinel; 0.2 as inclusions in clinopyroxene).	28.9 poikilitic grains (2 species?).	33.2 (27.3 large poikilitic grains; 5.9 inclusions in clinopyroxene).	40.8 (40.0 small euhedral crystals; 0.5 inclusions in pyroxenes; 0.3 elongate orthoamphibole).	66.4 (65.9 green to olive-green hornblende with 0.5 clear to light-green tremolite-actinolite rims).	31.8 clear pargasite (26.6 large poikilitic crystals; 2.8 open symplectite with spinel; 2.4 inclusions in clinopyroxene).	34.3 clear pargasite (27.4 large poikilitic crystals; 5.0 symplectite with spinel; 1.9 inclusions in clinopyroxene; <0.04 symplectite with clinopyroxene).	55.6 (53.9 in large poikilitic grains; 1.7 inclusions in clinopyroxene).	41.7 green edenite(?) (38.7 large poikilitic grains; 3.0 inclusions in clinopyroxene).	22.5 tremolite (may include some anthophyllite).	26.5 tremolite (may include some pargasite) poikilitic crystals interlocked with poikilitic enstatite but with randomly different orientations.

Biotite				0.1 (very light brown).		<0.04 symplectite with spinel.			0.05	35.8 very light brown phlogopite.	0.5
Talc			<0.05?		20.0 (occurs with, and may include, some carbonate).					37.5 (some pseudomorphs anthophyllite).	
Chlorite				0.9 (some interleaved with biotite; some with pyroxene, chromite and amphibole inclusions).						1.8 (some with peculiar chevron-wrinkled folia).	8.5 (may include brucite).
Magnetite-ilmenite	0.5 (may include pyrrhotite).	0.5	0.1	0.2 (large phenocrysts).	9.7 (0.7 large; 9.0 "dust").			0.1	0.3 (may include pyrrhotite).	1.5 (euhedral and different sizes).	4.9 (much associated with tremolite).
Sulfide						0.3 (pyrrhotite)	0.2 (pyrite?)	<0.06 (hematite?, altered).	?	0.4 (pyrite)	
Chromite	0.3 (brown)			2.1 (brown)							
Spinel	2.6 (2.1 symplectite with pargasite in coronas; 0.5 interstitial, large; <0.04 tiny inclusions in plagioclase).					10.6 (7.2 tight symplectite with clinopyroxene; 2.5 open symplectite with pargasite; 0.9 large interstitial; <0.04 symplectite with biotite).	14.9 (10.2 symplectite with pargasite; 4.1 symplectite with clinopyroxene; 0.6 large interstitial crystals).				
Carbonate	0.2 (half in veins).	0.2	<0.05	1.0 (some in veins).	3.0 (See talc).	0.3 (in clinopyroxene)	0.04		0.05	0.4	0.1
Apatite			<0.05		0.9 (single cluster).						0.3
Sphene										0.1 (with talc-anthophyllite pseudomorphs).	
Zircon(?)										<0.06 (tiny high-index mineral creating halos in phlogopite).	

TABLE B5.—*Chemistry of some igneous and metaigneous rocks, and one amphibole, northernmost Park Range, Colorado*

[Analyst, Elaine L. Brandt: (1) Dec. 26, 1972, and (2) Dec. 28, 1977]

Geologic unit and published map reference	Metavolcanics		Quartz diorite of Gilpin Lake		Porphyry dike	Quartz monzonite of Mount Ethel pluton, Yq MI-1112	Pegmatite		Metavolcanics			Amphibole from 1297
	Xgn MI-1113	Xo MI-1113	Xgl MI-1113	Xgl MI-1113	Yp MI-1113		YXp MI-1113	YXp MI-1113	Xgn MI-1113	Xgn MI-1112	Xgn MI-1113	
Field no.	987	975	1290	1102	1097	1023	985	1011	1013	1297	1028	
Laboratory no.	D103031	D103027	D103059	D103054	D103053	D103039	D103029	D103034	D103035	D103060	D103040	D103886
Analyst	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(2)
1973 IUGS name using modal minerals (Lyons' (1976) recommended corrections in parentheses).	Tonalite (quartz diorite)	Quartz diorite (tonalite)	Granodiorite	Tonalite (quartz diorite)	Granite (adamellite)	Granite (adamellite)	Granite (adamellite)	Tonalite (quartz diorite)	Tonalite (quartz diorite)	Granodiorite	Alkali-feldspar granite, but would be granite (adamellite) if An_4 equal to plagioclase	Ferrohastingsite (See text for optical data.)
1973 IUGS name using normative minerals (Lyons' (1976) recommended corrections in parentheses).	Monzogabbro	Tonalite (quartz diorite)	Granodiorite	Tonalite (quartz diorite)	Granite (adamellite)	Granite (adamellite)	Granite (adamellite)	Tonalite (quartz diorite)	Granodiorite	Granodiorite	Alkali-feldspar granite, but would be granite (adamellite) if An_1 equal to plagioclase	Essexite
Rittmann (1952) volcanic name where appropriate.	Pigeonite-labradorite andesite	Dark dacite			Rhyolite				Light dacite	Rhyodacite near light dacite	Alkali rhyolite	Near leucite melilitite
North latitude	40°59′ 12.74″	40°58′ 42.83″	40°46′ 45.27″	40°47′ 42.21″	40°48′ 17.39″	40°43′ 42.11″	40°58′ 44.96″	40°57′ 3.31″	40°58′ 12.80″	40°43′ 42.32″	40°59′ 13.53″	40°43′ 42.32″
West longitude	106°37′ 23.47″	106°37′ 59.88″	106°48′ 43.53″	106°41′ 20.13″	106°42′ 44.83″	106°36′ 32.55″	106°38′ 53.02″	106°29′ 17.29″	106°27′ 47.11″	106°46′ 14.88″	106°37′ 59.02″	106°46′ 14.88″
SiO_2	52.27	58.60	66.20	71.19	71.79	72.86	73.78	75.30	70.30	76.54	76.72	37.69
Al_2O_3	14.95	16.04	15.88	15.73	14.61	13.42	14.31	14.32	14.64	12.00	12.09	11.45
Fe_2O_3	1.67	3.14	1.38	.31	.78	.91	.25	.07	.70	1.18	.75	7.46
FeO	9.32	7.20	2.28	1.19	1.29	1.45	.74	.10	3.24	1.58	.74	24.66
MgO	6.35	3.82	1.97	.57	.48	.40	.16	.03	1.65	.05	.03	.70
CaO	9.24	4.33	4.44	3.02	1.40	1.16	1.51	.41	.79	1.55	.52	10.38
Na_2O	2.46	3.92	4.38	5.43	3.65	2.64	3.54	4.37	5.51	4.50	3.58	1.44
K_2O	1.15	.40	1.97	.89	4.75	5.82	4.92	4.69	1.49	1.85	4.91	1.83
H_2O^+	1.24	.59	.61	.52	.44	.51	.20	.22	.51	.16	.14	1.44
H_2O^-	.06	.01	.08	.07	.05	.06	.04	.00	.04	.04	.03	.14
TiO_2	.92	.98	.38	.19	.28	.32	.11	.02	.48	.19	.08	1.29
P_2O_5	.14	.42	.13	.06	.08	.07	.02	.01	.11	.02	.01	.03
MnO	.19	.30	.07	.03	.04	.05	.02	.01	.19	.06	.03	.91
CO_2	.01	.07	.06	.55	.03	.01	.10	.01	.00	.01	.01	.01
Cl											.01	
F											.30	.18
Subtotal											99.95	99.61
Less O											.13	.08
Total	99.97	99.82	99.83	99.75	99.67	99.68	99.70	99.56	99.65	99.73	99.82	99.53

NORMS

[For method of calculation, see Johannsen (1950, p. 89–90). Before calculation all analyses recalculated to 100 percent minus H_2O]

Q	1.92	16.76	20.78	30.03	28.55	31.73	31.16	31.17	26.61	39.47	36.85	
or	6.68	2.23	11.69	5.01	28.38	34.50	28.94	27.83	8.85	10.96	29.05	10.85
ab	20.97	33.03	37.23	46.14	30.93	22.54	29.89	37.12	46.77	38.12	30.20	.68
an	26.42	18.08	17.80	11.13	5.92	5.34	6.76	1.95	3.17	7.15	.28	19.50
100 an/ab+an	56	35	32	19	16	19	18	5	6	16	1	97
ne												6.28
C		2.65		1.73	1.29	.80	.78	1.36	2.82		.83	
di Ca	7.78		1.28							.14		12.84
di Mg	3.91		.80							.01		.62
di Fe	3.69		.40							.15		13.77
hy Mg	11.95	9.54	4.12	1.41	1.20	1.00	.40	.07	4.14	.11	.07	
hy Fe	11.08	9.50	2.11	1.71	1.33	1.49	1.00	.12	4.95	1.58	.66	
ol Mg												.79
ol Fe												19.42
mt	2.32	4.63	2.08	.46	1.16	1.32	.37	.09	1.02	1.71	1.09	10.88
il	1.67	1.82	.76	.30	.53	.61	.21	.03	.91	.36	.15	2.46
ap	.33	.99	.33	.14	.20	.13	.05	.03	.26	.05	.02	.07
fr											.62	.37
hl											.02	
cc	.02	.20	.10	1.30	.07	.02	.23	.02		.02	.02	.02
H_2O^+	1.24	.59	.61	.52	.44	.51	.20	.22	.51	.16	.14	1.45
Total	99.98	100.02	100.09	99.88	100.00	99.99	99.99	100.01	100.01	99.99	100.00	100.00

TABLE B6.—*Petrography of some chemically analyzed igneous and metaigneous rocks, northernmost Park Range, Colorado*

[Petrographers: (1) George L. Snyder; (2) Peter A. Drobeck. t.s., thin section]

Geologic unit	Metavolcanics		Quartz diorite of Gilpin Lake		Porphyry dike	Mount Ethel pluton	Pegmatite		Metavolcanics		
Field No. -----	987	975	1290	1102	1097	1023	985	1011	1013	1297	1028
Petrographer --	(1,2)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1,2)	(1)
Thin sections studied.	3	5	2	1	1	1	1	1	1	3	1
Total points counted.	3,334	2,098 t. s.; 3,103 garnet count on slab	1,548	1,692	1,559	1,427	1,409	1,655	1,370	4,120	1,489
Texture (all rocks medium to coarse grained).	Granular, anhedral.	Granular, gneissic, "turkey-track" lineation, anhedral to subhedral.	Granular, interlocking, to gneissic.	Granular, interlocking, anhedral.	Granular, porphyritic, subhedral.	Gneissic, granular to interlocking to porphyritic, subhedral.	Gneissic, poikilitic to granular, anhedral.	Granular to poikilitic, anhedral.	Granular, unoriented micaceous.	Granular, anhedral.	Indistinctly layered, granular, anhedral.
Plagioclase ----	29.6 $An_{38.5}$ altered to 0.1 sericite.	58.0 An_{31} altered to <.05 sericite.	53.8 An_{25} altered to 4.7 sericite.	54.1 An_{16} altered to 1.2 sericite, 0.06 carbonate.	19.2 zoned phenocrysts altered to 1.2 sericite, 1.0 coarse muscovite; 16.3 $An_{15.5}$ groundmass altered to 0.2 sericite, 0.2 coarse muscovite.	24.4 An_{17} altered to 4.1 sericite.	36.9 An_{17} altered to 1.6 sericite.	56.8 An_{11} altered to <0.06 sericite, 0.1 wormy kaolin veins.	48.7 An_{11}	41.07 An_{13}	26.4 An_4
Potassium feldspar.			7.3 microcline		27.0 microcline (16.5 phenocrysts, 10.5 groundmass)	42.9 large microclines	22.4 large but irregular microclines	3.9 large microclines and antiperthite patches in plagioclase		10.56 microcline	33.0 microcline
Quartz -------	9.8	14.1	23.9	34.7	28.8 (16.2 phenocrysts, 12.6 groundmass)	27.8	33.6	36.6	32.5	42.62	37.3
Muscovite ----			<0.06	3.9	1.5 (2/3 phenocrysts).	0.7	1.8 (some near biotite).	2.6 (some in quartz graphic intergrowths).	0.2 (mainly at biotite-biotite contacts).		
Garnet -------		Poikilitic, variable distribution, some t.s. plucking; 0.9 t.s.; 4.95 slab count.							1.2 (thick clear rims; quartz in poikilitic centers).		

Clinoamphibole	56.6 green hornblende.		6.3 green hornblende.	<0.06 (in quartz).		<0.07 (in microcline).				4.89 dark ferrohastingsite.	
Orthoamphibole		13.5 clove brown gedrite altered to 0.05 chlorite.									
Biotite -------	3.8	7.3 altered to <0.05 chlorite.	5.0 altered to 0.3 chlorite.	5.3 altered to 1.0 chlorite, <0.06 sphene.	5.3 phenocryst altered to 0.4 chlorite, 0.1 sphene; 0.5 groundmass altered to 0.1 chlorite, 0.1 sphene.	2.0 altered to 4.06 chlorite, 0.1 sphene.	4.6		17.4		1.9
Chlorite ------		0.1									
Prehnite(?) ----			0.2 (pods in biotite).								
Magnetite-ilmenite -----	<0.06	3.5 magnetite, 1.2 ilmenite.		0.1	0.1 phenocryst, 0.4 groundmass	0.6	0.1	<0.06		0.41	0.3
Sulfide -------		0.4 pyrite		0.1 pyrite(?) all altered to hematite.							
Carbonate ----				1.7	0.1 groundmass		0.2				
Epidote ------			2.4		0.3 groundmass	0.9	0.1 allanite rims.				
Allanite ------		0.1	<0.06	<0.06	0.1 groundmass	0.2 altered to <0.07 chlorite.	0.1			0.15	0.1 (metamict)
Apatite -------	0.2	0.9	0.3	<0.06	0.1 groundmass	0.1	0.2				0.1
Fluorite ------											0.9
Sphene -------			0.5 altered to 0.1 leucoxene.		0.1 phenocryst, 0.2 groundmass.	0.3				0.26 altered to 0.15 leucoxene	
Rutile --------										<0.04 sphene inclusions and single grains.	
Zircon --------	<0.06	<0.05	<0.06	<0.06	<0.06 groundmass	0.1	<0.07	<0.06		0.04	<0.07
Monazite(?) ---									<0.07 (alteration rims).		

TABLE B7.—*Chemistry of the quartz monzonite of Seven Lakes (Snyder, 1980b), northernmost Park Range, Colorado*

[Analysts: Elaine L. Brandt: (1) Dec. 26, 1972, and (2) Dec. 28, 1977; Vertie C. Smith, (3) June 18, 1974. Column 11, average quartz monzonite of Seven Lakes, is the mean of columns 1 through 10 recalculated to 100 percent minus H_2O^-]

Column No.	1	2	3	4	5	6	7	8	9	10	11
Field No.	986	1066	984	1162	1068	1827	991	1525	1067	1676	Average quartz monzonite of Seven Lakes
Laboratory No.	D103030	D103044	D103028	D103057	D103046	D103889	D103033	D103313	D103045	D103318	
Analyst	(1)	(1)	(1)	(1)	(1)	(2)	(1)	(3)	(1)	(3)	
1973 IUGS name using modal minerals (Lyons' (1976) recommended corrections in parentheses)	Granite (adamellite).	Granodiorite	Granite (adamellite).	Granite (adamellite).	Granite (two-feldspar granite).	Granite (adamellite).	Granite (adamellite).	Granite (adamellite).	Granite (adamellite).	Granite (adamellite).	
1973 IUGS name using normative minerals (Lyons' (1976) recommended corrections in parentheses)	Quartz monzonite (quartz-rich monzonite).	Granodiorite	Granite (adamellite).	On boundary between granite (adamellite) and granodiorite.	Granite (adamellite).	Granite (adamellite).	Granite (adamellite).	Granite (adamellite).	Granite (adamellite).	Alkali-feldspar granite, but would be albite granodiorite if An_3 equal to plagioclase	Granite (adamellite).
Location	Line Creek just south of Wyo.	SW. of Big Creek Lakes	NE. of Big Creek Lakes	East of Mica Creek	Type Seven Lakes	Black Mountain	North of Hill Ranch	Farwell Mountain	Summit of Davis Peak	North of Whiskey Park	
North latitude	40°59' 53.61"	40°54' 44.43"	40°56' 20.86"	40°47' 48.45"	40°53' 50.17"	40°56' 43.50"	40°55' 44.40"	40°49' 36.11"	40°55' 12.74"	40°59' 5.45"	
West longitude	106°36' 11.23"	106°37' 37.45"	106°35' 33.98"	106°41' 44.57"	106°40' 56.20"	106°46' 29.71"	106°32' 17.67"	106°49' 24.52"	106°41' 57.99"	106°53' 11.89"	
SiO_2	64.26	67.63	72.37	73.27	73.41	73.71	74.19	74.31	75.27	77.38	72.85
Al_2O_3	16.23	14.52	14.04	14.03	13.04	13.17	14.32	12.67	13.17	12.41	13.79
Fe_2O_3	1.67	1.03	.87	.47	.91	1.06	.44	.95	.79	.48	.87
FeO	3.49	3.80	1.52	1.56	1.60	1.80	.74	1.44	.78	.64	1.74
MgO	1.08	.90	.54	.44	.36	.35	.20	.33	.23	.46	.49
CaO	3.27	2.92	1.87	1.84	1.06	1.23	.96	1.02	.88	.28	1.54
Na_2O	3.67	3.58	3.64	3.76	3.32	3.32	3.43	3.20	3.84	4.52	3.64
K_2O	4.32	3.72	4.08	3.74	5.08	4.59	5.26	5.00	4.38	2.94	4.33
H_2O^+	.41	.55	.25	.21	.35	.22	.22	.32	.18	.21	.29
H_2O^-	.06	.05	.06	.07	.09	.05	.03	.06	.05	.08	
TiO_2	.67	.61	.28	.21	.31	.33	.07	.26	.12	.09	.30
P_2O_5	.21	.23	.07	.06	.07	.08	.02	.05	.03	.01	.08
MnO	.10	.09	.06	.04	.05	.04	.03	.05	.05	.01	.05
CO_2	.01	.07	.01	.01	.01	.02	.03	.02	.01	.01	.02
Cl								.02			
F						.03		.12			.02
Subtotal						100.00		99.82			100.01
Less O						.01		.05			.01
Total	99.45	99.70	99.66	99.71	99.66	99.99	99.66	99.77	99.78	99.52	100.00

NORMS

[For method of calculation, see Johannsen (1950, p. 89–90). Before calculation all analyses recalculated to 100 percent minus H_2O^-]

Column No.	1	2	3	4	5	6	7	8	9	10	11
Q	16.64	23.53	30.33	31.83	31.47	33.26	31.63	34.07	33.87	38.46	30.50
or	25.71	22.04	24.21	22.15	30.11	27.10	31.22	29.66	25.93	17.47	25.60
ab	31.20	30.36	30.93	31.88	28.15	28.05	29.10	26.84	32.56	38.48	30.78
an	14.88	12.63	8.79	8.76	4.78	5.17	4.42	3.73	4.12	1.28	6.81
100 an/ab+an	32	29	22	22	15	16	13	12	11	3	18
C	.10		.43	.61	.36	.87	1.09	.69	.62	1.33	.62
hy Mg	2.71	2.24	1.35	1.09	.89	.87	.50	.82	.57	1.14	1.22
hy Fe	4.14	5.30	1.74	2.24	1.78	1.98	.92	1.53	.69	.79	2.08
mt	2.43	1.50	1.25	.76	1.32	1.53	.65	1.37	1.13	.69	1.25
il	1.28	1.15	.53	.40	.59	.62	.14	.49	.23	.17	.56
ap	.49	.53	.16	.13	.16	.20	.05	.12	.07	.02	.20
fr						.06		.24			.04
hl								.04			
cc	.02	.16	.02	.02	.02	.05	.07	.05	.02	.02	.05
H_2O^+	.41	.55	.25	.21	.35	.22	.22	.32	.18	.21	.29
Total	100.01	100.00	99.99	99.99	99.98	99.98	100.01	99.97	99.99	100.06	100.00

TABLE B8.—*Petrography of chemically analyzed rocks from quartz monzonite of Seven Lakes, northernmost Park Range, Colorado*

[Petrographers: (1) George L. Snyder; (2) Peter A. Drobeck]

Location	Line Creek just south of Wyoming	SW. of Big Creek Lakes	NE. of Big Creek Lakes	East of Mica Creek	Type Seven Lakes	Black Mountain	North of Hill Ranch	Farwell Mountain	Summit of Davis Peak	North of Whiskey Park
Field number	986	1066	984	1162	1068	1827	991	1525	1067	1676
Petrographer	(1)	(1)	(1,2)	(1)	(1,2)	(1)	(1)	(2)	(1)	(2)
Thin sections studied	2	1	2	1	2	2	1	1	2	1
Total points counted	1,323	1,296	3,321	1,671	3,422	1,314	1,603	2,090	1,556	1,840
Texture (all rocks coarse grained)	Granular, gneissic, porphyroblastic.	Gneissic, granular, anhedral.	Gneissic, poikilitic to granular, anhedral.	Granular, interlocking, anhedral.	Gneissic, granular to poikiloblastic, anhedral.	Gneissic, granular to interlocking.	Flaser gneissic, granular (but garnets euhedral).	Gneissic, granular to porphyroblastic, subhedral.	Granular, anhedral.	Granular, interlocking to gneissic.
Plagioclase	4.9 An_{24} altered to 0.1 sericite.	37.6 An_{22} (locally zoned to thin albite rims) altered to 0.7 sericite.	37.2 An_{19} with An_2 rims; altered to 0.1 sericite.	36.3 An_{20} altered to 0.2 sericite.	19.0 $An_{13.5}$ with An_4 rims; altered to 0.1 sericite.	37.0 An_{17} with An_6 rims; altered to 0.2 sericite.	32.3 An_{18} cores with wide An_8 rims (avg: An_{13}) altered to 0.1 sericite, 0.2 coarse muscovite.	27.31 An_{10} altered to 1.0 clay and 0.57 sericite.	37.4 An_{13} altered to 0.1 sericite.	29.4 An_8 altered to 0.05 clay, <0.05 sericite.
Microcline	23.3	15.3	23.1 with plagioclase rims and exsolved blebs.	22.7	42.7	30.7	28.5	31.58 altered to 0.1 clay.	30.7	21.58
Quartz	20.3	27.6	30.6	34.3	27.5	27.0	30.1	33.36	27.6	43.75
Muscovite			<0.06				4.0 (some as oriented swarms in microcline)			2.39
Garnet							<0.6			
Blue-green clinoamphibole	7.5	7.5	<0.06	0.3	2.4 altered to 0.1 chlorite.			0.33	0.1	
Biotite	6.4	9.6 altered to 0.3 chlorite.	7.3 altered to 0.4 chlorite.	6.0	6.7 altered to 0.1 chlorite.	5.1 altered to 0.1 chlorite.	4.4 altered to <0.06 chlorite.	6.31 altered to 0.62 chlorite.	3.2	2.88
Magnetite-ilmenite	0.5	<0.08	0.1		0.1	<0.08	0.1		0.1	
Pyrite	<0.08? (all altered to hematite).	<0.08? (all altered to hematite).						0.05		
Carbonate		0.2								
Epidote	0.1	0.2	1.1	<0.06	0.5		0.6	0.96	0.6	
Allanite	<0.08 (zoned)	0.3 (metamict)	0.2 (metamict)	0.1	0.2 (in epidote)	<0.08		0.5	<0.06	<0.05
Apatite	0.5	0.5	0.1	0.1	0.2	0.1			<0.06	
Fluorite			0.1?		0.1			0.05		
Sphene	0.4	1.2	0.3 (leucoxene cores)	0.1	0.5	<0.08			0.3	
Zircon	0.1	<0.08	<0.06	0.1	0.1	0.1			<0.06	<0.05

TABLE B9.—*Chemistry of some metasedimentary and metavolcanic rocks, northernmost Park Range, Colorado*

[Analysts: Elaine L. Brandt: (1) Dec. 26, 1972, and (2) Dec. 28, 1977; Vertie C. Smith, (3) June 18, 1974.]

Geologic unit and published map reference	Metalimestone			Metashale			Pisolite rocks		Metavolcanics		Quartzite
	Xm			Xs			Xca		Xgn		Xq
	MI-1113			MI-1112	MI-1113	MI-1112			MI-1113		
Field No.	989	1064	1065	1080	1019	1077	1854	12-1-20-5	1006	1657	1643
Laboratory No.	D103032	D103042	D103043	D103052	D103038	D103049	D103890	D103314	D103301	D103317	D103316
Analyst	(1)	(1)	(1)	(1)	(1)	(1)	(2)	(3)	(3)	(3)	(3)
Rittmann (1952) name, where appropriate							Rhyodacite near quartz latite and labradorite rhyodacite	Quartz latite near rhyodacite and labradorite rhyodacite	Quartz latite	Quartz latite	
Location	Independence Mountain	Red Elephant Mountain		Near Chipmunk claim	Hogback E. of Shafer Ranch	E. of Strawberry Park	Farwell Mountain		Independence Mountain	Willow Creek	
North latitude	40°56′ 31.54″	40°52′42.85″		40°31′ 40.34″	40°51′ 37.81″	40°31′ 0.18″	40°49′33.69″		40°57′ 16.60″	40°45′ 16.94″	40°46′ 3.77″
West longitude	106°30′ 5.39″	106°39′37.41″		106°44′ 35.87″	106°32′ 23.92″	106°48′ 42.93″	106°50′36.03″		106°29′ 55.30″	106°53′ 17.17″	106°54′ 12.64″
SiO_2	24.81	42.53	52.77	58.68	59.59	70.90	62.95	63.33	73.20	77.33	87.26
Al_2O_3	6.33	9.51	13.49	19.67	19.35	14.30	17.72	17.48	13.53	12.97	5.05
Fe_2O_3	.96	1.30	1.73	4.01	3.62	.90	.89	.97	.72	1.01	3.90
FeO	2.63	.63	.57	5.44	4.37	4.46	5.01	5.06	2.32	1.80	.41
MgO	2.12	2.02	2.03	1.97	1.88	1.25	1.82	1.81	2.49	1.08	.20
CaO	36.26	27.56	27.40	1.34	1.08	.65	1.60	1.46	.22	.02	.06
Na_2O	.45	.16	.02	2.12	1.67	1.69	3.63	3.32	1.82	.19	.13
K_2O	1.38	3.32	.20	2.33	4.01	3.34	3.60	3.84	3.27	3.27	1.39
H_2O^+	.34	.06	.03	2.72	2.86	1.27	1.52	1.66	1.21	1.43	.49
H_2O^-	.04	.04	.04	.18	.19	.14	.08	.08	.14	.14	.07
TiO_2	.12	.10	.15	.81	.77	.60	.64	.63	.35	.17	.75
P_2O_5	.02	.02	.02	.15	.13	.11	.15	.15	.08	.02	.01
MnO	.26	.20	.10	.22	.10	.10	.08	.08	.12	.04	.01
CO_2	24.15	12.08	1.26	.01	.02	.02	.09	.01	.02	.02	.01
Total	99.87	99.53	99.81	99.65	99.64	99.73	99.78	99.88	99.49	99.49	99.74

NORMS

[For method of calculation, see Johannsen (1950, p. 89-90). Before calculation all analyses recalculated to 100 percent minus H_2O^-]

Q	3.56	9.45	13.52	29.63	28.21	42.54	19.25	20.59	45.02	61.48	81.04
or	8.12	19.76	1.17	13.80	23.82	19.81	21.31	22.76	19.42	19.42	8.29
ab	3.83	1.36	.16	18.04	14.21	14.37	30.78	28.15	15.47	1.63	1.10
an	11.21	15.49	36.21	5.67	4.39	2.36	6.40	6.20	.42		.19
100 an/ab+an	75	92	99.6	24	24	14	17	18	3	0	15
C				11.66	10.72	7.07	5.54	5.61	6.90	9.18	3.26
di Ca	6.65	6.10	5.84								
di Mg	3.54	5.05	5.05								
di Fe	2.90	.29									
wo—(Ca)		12.70	32.55								
hy Mg	1.74			4.93	4.71	3.14	4.56	4.51	6.25	2.71	.50
hy Fe	1.42			5.79	3.97	6.69	7.58	7.47	3.34	2.28	
mt	1.39	1.90	1.71	5.83	5.28	1.30	1.30	1.41	1.06	1.48	
ne			.54								3.91
il	.23	.18	.29	1.53	1.46	1.14	1.22	1.20	.67	.32	.89
ru											.28
ap	.05	.05	.05	.35	.30	.26	.35	.35	.19	.04	.02
cc	55.02	27.61	2.86	.02	.05	.05	.20	.02	.05	(1)	.02
H_2O^+	.34	.06	.03	2.73	2.88	1.28	1.52	1.66	1.22	1.44	.49
Total	100.00	100.00	99.98	99.98	100.00	100.01	100.01	99.93	100.01	[1] 100.00	99.99

[1] Includes 0.02 CO_2 unsatisfied by CaO.

TABLE B10.—*Petrography of some chemically analyzed metasedimentary and metavolcanic rocks, northernmost Park Range, Colorado*

[Petrographers: (1) George L. Snyder; (2) Peter A. Drobeck. t.s., thin section]

	Metalimestone			Metashale			Pisolite rocks		Metavolcanic(?) pod rocks		Quartzite
									(24.8 pct. pods)	(7.1 pct. pods)	
Geologic unit and location	Independence Mountain	Red Elephant Mountain		Near Chipmunk claim	Hogback E. of Shafer Ranch	E. of Strawberry Park	Farwell Mountain		Independence Mountain	Willow Creek	
Field No.	989	1064	1065	1080	1019	1077	1854	12-1-20-5	1006	1657	1643
Petrographer	(1)	(1)	(1)	(1)	(1)	(1)	(1,2)	(2)	(2)	(2)	(2)
Thin sections studied	3	3	4	1	1	1	2	2	2	2	1
Total points counted	4,721	5,204	7,676	1,762	1,696	2,290	7,696	3,486	3,450 t.s.; 13,113 pod count on slab.	3,533 t.s.; 20,761 pod count on slab.	1,483
Texture (all rocks medium to coarse grained).	Granular (carbonate) to interlocking (silicates), anhedral.	Granular, poikiloblastic, subhedral to euhedral (vesuvianite and garnet).		Granular to schistose, retrogressive.	Granular to schistose, retrogressive.	Schistose, granular to poikiloblastic, relict clastic(?) grains.	Schistose, granular, elongate, pisolitic.	Schistose, granular, pisolitic.	Schistose, granular, poikilitic, podiform.	Schistose, granular, podiform.	Layered (relict crossbedding), granular, unoriented, micaceous.
Plagioclase	1.40 (1.37 to 1.45) altered to 1.15 (1.05 to 1.22) fine-grained sericite and epidote.	0.02 (0 to 0.05) altered to <0.02 (0 to <0.05) sericite.		39.3 An_{25} altered to 2.5 sericite.	18.1 An_{24} altered to 0.1 sericite.	12.4, partly round An_{25} grains, partly An_4.	38.43 An_{17}	29.85 An_{18} altered to 0.7 sericite.	18.68 An_{10} altered to 1.05 sericite.		1.3(?), all altered to clay and limonite.
Microcline	10.83 (7.03 to 17.55).	25.12 (15.54 to 34.16).	5.08 (<0.07 to 12.93).		0.5 (pods dilating biotites).	15.7 altered to 6.2 muscovites.			3.25 (0 to 6.5).		
Quartz	3.26 (2.32 to 4.26).	12.32 (8.86 to 15.44).	27.13 (24.29 to 30.63).	22.9	28.3	43.8 (27.3 original round clastic grains, 16.5 secondary serrate fringes on these).	18.85	26.15	45.60	54.89	78.2
Muscovite	0.02 (0 to 0.06)		0.01 (0 to 0.04)	9.2	4.2	15.5	13.72 (concentrated in pisolites).	17.30	7.17	31.10	15.2
Sillimanite				10.6 altered to 9.2 pinite	28.1 (pseudomorphs; all altered to pinite).	8.2 altered to 8.1 pinite.			3.57 altered to 1.31 pinite.	5.70 altered to 0.03 pinite.	
Zeolite(?)						.1					
Garnet		13.63 (7.61 to 17.21).	50.35 (34.90 to 65.95).	1.0	3.5 altered to 0.6 sericite and 1.0 chlorite.	0.17 altered to 0.13 muscovite, <0.04 chlorite.				0.11 (t.s.) 0.6 (slab).	

Vesuvianite -----		0.72 (0 to 1.70).	4.18; 3.88 (0.43 to 6.02) large euhedral grains zoned to 0.01 brown metamict centers; 0.29 (0 to 1.14) aggregates of small subhedral grains.								
Clinopyroxene ---	7.14 (2.15 to 10.56).	6.54 (4.90 to 7.73).	12.13 (6.33 to 17.03).								
Clinoamphibole --	7.90 (4.04 to 13.37) light green plus 1.28 (1.11 to 1.46) clear.										
Biotite ---------				14.3 almost all altered to 13.3 chlorite, 1.0 magnetite.	16.6 altered to 2.3 muscovite, 8.6 chlorite, 0.4 magnetite, and <0.06 sphene	3.5 altered to 0.3 muscovite, 0.8 chlorite.	28.54 altered to 1.2 chlorite.	26.35 altered to 0.05 chlorite.	21.70	8.09 altered to 0.03 chlorite.	
Prehnite(?) ------			0.09 (0 to 0.34) veins.								
Magnetite-ilmenite -------	<0.02			2.0	0.4	0.1					
Sulfide ---------	0.02 (pyrrhotite).	<0.02 (pyrrhotite).		0.05 all altered to hematite.							4.9 all altered to hematite.
Carbonate ------	56.99 (37.05 to 74.81).	38.63 (32.25 to 44.92).	0.92 (0.05 to 2.61).				0.12				
Epidote --------	10.41 (5.72 to 13.37); aluminous.	2.92 (1.39 to 5.29); aluminous.	0.10 (0 to .35); aluminous.		<0.06					0.08	
Allanite --------	0.30 (0.05 to 0.60)	0.08 (0 to 0.23)							<0.03		
Apatite ---------				0.05 altered to <0.06 clay.	0.3	0.3	0.34	0.35			0.1
Sphene ---------	0.40 (0.21 to 0.68)			0.1 altered to 0.05 leucoxene.		0.3 all altered to leucoxene.					
Tourmaline ------										<0.03	
Zircon ----------	<0.02	0.02	0.01	0.05	<0.06	<0.04	<0.1		0.03	<0.03	0.3
Monazite(?) -----				<0.06	<0.06	<0.05 (with alteration rims).					

TABLE B11.—*Chemistry of overall average and selected individual mechanically disaggregated and mathematically reconstituted siliceous-pod rocks, northernmost Park Range, Colorado*

[Individual samples of A, B, and C were prepared mechanically by sawing 1-cubic-foot samples into parallel slabs ½ to 1 inch thick (1¼ to 2½ cm). After mapping each slab on lucite sheets and determining relative proportions of pods and matrix on each sheet, some slabs were broken up with a hammer and chisel, and selected portions of individual pods and pod-free matrix were analyzed chemically]

A.—Chemistry, analyzed by Vertie C. Smith, June 18, 1974, of disaggregated portions of garnet (0.27 percent of rock), siliceous pods (3.20 percent of rock), and matrix (96.53 percent of rock) (percentages determined by 31,268 slab point counts) of sample 988 from placer ditch cut on Independence Mountain at lat 40°56′21.19″ N. and long 106°29′50.26″ W. Column 4A, average 988 siliceous pod, is the mean of columns 2A and 3A recalculated to 100 percent minus H_2O^-. Column 7A, average 988 matrix, is the mean of columns 5A and 6A recalculated to 100 percent minus H_2O^-. Column 8A, reconstituted whole rock 988, consists of 0.27 percent column 1A (recalculated to 100 percent minus H_2O^-), plus 3.20 percent column 4A, plus 96.53 percent column 7A.

Column No.	1A	2A	3A	4A	5A	6A	7A	8A
Lithology and field No.	Garnet	Siliceous pods		Average 988 siliceous pod	Matrix		Average 988 matrix	Reconstituted whole rock 988
	988GARN	988CC′	988B		988M/B	988M1,2		
Laboratory No.	D103298	D103297	D103296		D103299	D103300		
SiO_2	37.37	69.59	73.49	71.95	73.61	75.00	74.75	74.55
Al_2O_3	21.39	17.22	14.66	16.03	13.23	12.42	12.90	13.02
Fe_2O_3	1.33	.16	.09	.13	.33	.43	.38	.38
FeO	27.06	.34	.19	.27	2.13	2.15	2.15	2.16
MgO	3.36	.30	.16	.23	1.57	1.58	1.58	1.54
CaO	1.49	1.19	.71	.96	1.78	1.88	1.84	1.81
Na_2O	.03	2.98	2.13	2.57	2.78	2.76	2.79	2.78
K_2O	.16	7.00	7.78	7.43	3.14	2.35	2.76	2.90
H_2O^+	.32	.48	.21	.35	.57	.60	.59	.58
H_2O^-	.03	.08	.06		.14	.20		
TiO_2	.01	.03	.02	.03	.18	.17	.18	.18
P_2O_5	.01	.01	.02	.02	.02	.02	.02	.02
MnO	7.28	.02	.01	.02	.05	.05	.05	.07
CO_2		(1)	.02	.01	.01	.01	.01	.01
Total	99.84	99.40	99.55	100.00	99.54	99.62	100.00	100.00

B.—Overall pod-rock chemical averages, and individual chemistry, analyzed by Elaine L. Brandt, August 8, 1971, of disaggregated portions of siliceous-pods (23.72 percent) and matrix (76.28 percent) (percentages determined by 5,717 slab point counts) of sample 715 from placer ditch cut on Independence Mountain (less than 100 yards, 91 m, from sample 988) at lat 40°56′23.76″ N. and long 106°29′49.73″ W. Column 1B, average pod rock, is the chemical means of columns 8A, 8B, and 8C in this table, as well as analyzed pod-rock samples 1006 and 1657 from table B9. Column 2B, average pod-pisolite rock, is the chemical mean of all the analyzed pod rocks of 1B plus analyzed pisolite-rock samples 1854 and 12-1-20-5 from table B9. Column 6B, average 715 siliceous pod, is the mean of columns 3B, 4B, and 5B recalculated to 100 percent minus H_2O^-. Column 8B, reconstituted whole rock 715, consists of 23.72 percent column 6B plus 76.28 percent column 7B.

Column No.	1B	2B	3B	4B	5B	6B	7B	8B
Lithology and field No.	Average pod rock	Average pod-pisolite rock	Siliceous pods			Average 715 siliceous pod	Matrix	Reconstituted whole rock 715
			715B	715A	715C		715MA	
Laboratory No.			D102925	D102924	D102926		D102923	
SiO_2	76.30	72.59	75.82	76.08	76.57	76.48	75.94	76.38
Al_2O_3	12.98	14.31	15.75	15.51	15.25	15.57	12.55	13.32
Fe_2O_3	.60	.70	.45	.46	.45	.46	.74	.68
FeO	1.57	2.57	.23	.22	.19	.21	1.37	1.10
MgO	1.40	1.52	.59	.57	.54	.57	1.81	1.52
CaO	.58	.85	.00	.00	.00	.00	.89	.68
Na_2O	2.10	2.49	.17	.17	.17	.17	2.44	1.91
K_2O	3.24	3.38	4.59	4.62	4.53	4.60	2.40	2.93
H_2O^+	.94	1.13	1.85	1.87	1.82	1.86	1.11	1.29
H_2O^-			.12	.09	.10		.17	
TiO_2	.18	.31	.05	.05	.04	.05	.15	.13
P_2O_5	.03	.06	.00	.00	.00	.00	.00	.00
MnO	.06	.06	.01	.02	.01	.01	.05	.04
CO_2	.02	.03	.02	.01	.02	.02	.02	.02
Total	100.00	100.00	99.65	99.67	99.69	100.00	99.64	100.00

[1] Insufficient sample for analysis.

TABLE B11.—*Chemistry of overall average and selected individual mechanically disaggregated and mathematically reconstituted siliceous-pod rocks, northernmost Park Range, Colorado*—Continued

C.—Chemistry, analyzed by Vertie C. Smith, June 18, 1974, of disaggregated portions of siliceous pods (2.88 percent of rock) and matrix (97.12 percent of rock) (percentages determined by 21,076 slab point counts) of sample 1014 from slumped crop on top of Independence Mountain at lat 40°58′37.55″ N. and long 106°28′52.31″ W. Column 4C, average 1014 siliceous pod, is the mean of columns 1C, 2C, and 3C recalculated to 100 percent minus H_2O^-. Column 7C, average 1014 matrix, is the mean of columns 5C and 6C recalculated to 100 percent minus H_2O^-. Column 8C, reconstituted whole rock 1014, consists of 2.88 percent column 4C plus 97.12 percent column 7C.

Column No.	1C	2C	3C	4C	5C	6C	7C	8C
Lithology and field No.	Siliceous pods			Average 1014 siliceous pod	Matrix		Average 1014 matrix	Reconstituted whole rock 1014
	1014IJ	1014A	1014E		1014M89	1014M1516		
Laboratory No.	D103304	D103302	D103303		D103306	D103305		
SiO_2	79.19	80.07	81.78	80.78	78.36	78.86	79.02	79.07
Al_2O_3	14.54	14.35	13.94	14.36	11.89	11.62	11.81	11.88
Fe_2O_3	.54	.48	.40	.47	.21	.19	.20	.21
FeO	.19	.18	.18	.18	.45	.48	.47	.46
MgO	.29	.28	.21	.26	.32	.31	.32	.32
CaO	.00	.00	.00	.00	.18	.16	.17	.17
Na_2O	.40	.39	.28	.36	3.88	3.83	3.87	3.77
K_2O	3.11	2.64	1.90	2.56	3.97	3.70	3.85	3.81
H_2O^+	1.16	.93	.68	.93	.18	.12	.15	.17
H_2O^-	.10	.09	.07		.06	.05		
TiO_2	.07	.07	.05	.06	.09	.09	.09	.09
P_2O_5	.01	.02	.01	.01	.02	.02	.02	.02
MnO	.02	.02	.02	.02	.02	.02	.02	.02
CO_2	.01	.00	.01	.01	.01	.01	.01	.01
Total	99.63	99.52	99.53	100.00	99.64	99.46	100.00	100.00

NORMS

[For method of calculation, see Johannsen, 1950]

Field No. and equivalent column No. above	Avg. 988 siliceous pod 4A	Average 988 matrix 7A	Whole rock 988 8A	Avg. 715 siliceous pod 6B	715 matrix 7B	Whole rock 715 8B	Avg. 1014 siliceous pod 4C	Average 1014 matrix 7C	Whole rock 1014 8C	Average pod rock 1B	Avg. pod-pisolite rock 2B
Rittmann (1952) name	Rhyolite	Quartz latite	Quartz latite	Quartz latite	Rhyodacite	Quartz latite	Quartz latite	Soda-rhyolite	Rhyolite	Quartz latite	Quartz latite
Q	26.08	40.20	39.63	57.04	47.72	49.78	68.50	40.78	41.57	47.54	39.63
or	43.91	16.31	17.14	27.16	14.25	17.31	15.14	22.76	22.54	19.14	19.98
ab	21.76	23.59	23.49	1.47	20.40	16.15	3.04	32.72	31.88	17.72	21.08
an	4.56	8.93	8.79		4.32	3.28		.64	.61	2.56	3.64
100 an/ab+an	17	27	27	0	17	17	0	2	2	13	15
C	2.08	2.05	2.10	10.31	4.46	5.80	11.00	1.05	1.44	5.09	5.22
hy Mg	.57	3.93	3.83	1.42	4.53	3.79	.64	.79	.79	3.47	3.77
hy Fe	.38	3.43	3.50		1.75	1.33		.58	.57	2.19	3.73
mt	.19	.56	.53	.60	1.09	.97	.49	.30	.30	.88	1.02
he				.03			.13				
il	.06	.33	.33	.09	.29	.24	.11	.17	.17	.35	.59
ap	.05	.05	.05	.02			[2].01	.05	.05	.07	.14
cc	.02	.02	.02	[2].02	.05	.04	[2].01	.02	.02	.04	.06
H_2O^+	.35	.59	.58	1.86	1.12	1.29	.93	.15	.17	.94	1.13
Total	100.01	99.99	99.99	100.00	99.98	99.98	100.00	100.01	100.01	99.99	99.99

[2] Uncompensated CO_2 or P_2O_5 (no CaO for these).

TABLE B12.—*Petrography of chemically analyzed siliceous pods and matrices of selected pod rocks from Independence Mountain, northernmost Park Range, Colorado*

[Petrographers: (1) George L. Snyder; (2) Peter A. Drobeck]

Field No. and rock type	988 pods	988 matrix	715 pods	715 matrix	1014 pods	1014 matrix
Petrographer	(1,2)	(1,2)	(2)	(2)	(1,2)	(1,2)
Thin sections studied	5 (two are 1½×3 in.; 3.8×7.6 cm)	7 (two are 1½×3 in.; 3.8×7.6 cm)	5	2	6 (4 are 1½×3 in.; 3.8×7.6 cm)	8 (6 are 1½×3 in.; 3.8×7.6 cm)
Total points counted	2,324	11,269	8,128	1,991	3,930	11,935
Texture (all rocks coarse grained)	Granular, zoned, poikiloblastic (garnet, microcline, plagioclase, muscovite)	Schistose, granular	Granular to interlocking, zoned, poikiloblastic (muscovite and quartz with splayed sillimanite sheaves)	Schistose, granular	Granular, zoned, poikiloblastic (muscovite and quartz with splayed sillimanite sheaves)	Gneissic, granular
Plagioclase	12.00 (3.19 to 26.81) altered to 1.86 (0 to 7.71) clay, 1.32 (<0.24 to 3.36) sericite	26.72 (22.11 to 29.97) (0.02 as perthite in microcline) An$_{19}$ altered to 1.66 (0 to 7.19) clay, 1.46 (0.11 to 3.13) sericite	0.08 (0 to 0.26) altered to 0.01 (0 to 0.04) clay	19.71 (10.82 to 28.6) An$_9$ altered to 2.65 (0 to 5.3) clay, 2.5 (2.0 to 3.0) sericite	1.52 (0 to 3.89)	27.05 (21.10 to 30.78) (0.16 as perthite in microcline) An$_7$ altered to 0.01 (0 to 0.08) sericite
Microcline	25.26 (0.24 to 53.68) altered to 0.04 (0 to 0.21) sericite	12.35 (8.11 to 18.75) altered to 0.02 (0 to 0.16) sericite		2.95 (0.2 to 5.68) altered to 1.95 (0 to 3.89) clay	1.03 (0 to 2.02)	24.80 (17.11 to 28.84) (<0.01 as antiperthite in plagioclase)
Quartz	30.96 (14.35 to 43.80)	44.31 (38.86 to 53.72)	39.53 (26.76 to 45.45)	51.09 (43.40 to 58.82)	62.86 (54.84 to 69.13)	43.53 (36.38 to 58.13)
Muscovite	2.71 (0 to 5.71)	1.63 (0.43 to 3.37)	14.95 (8.0 to 19.81)	12.3 (8.8 to 20.3)	18.41 (8.42 to 27.24)	1.76 (0.83 to 2.77)
Sillimanite		0.01 (0 to 0.05) all altered to pinite	43.50 (31.53 to 55.51) altered to 43.07 (30.72 to 55.51) pinite	1.89 (0 to 3.78) all altered to pinite	16.12 (9.30 to 27.43) altered to 0.23 (0 to 0.60) pinite	0.03 (0 to 0.16) altered to 0.01 (0 to 0.08) pinite
Garnet	28.13 (0 to 45.64; NOTE: slab count is 0.27) altered to 1.10 (0 to 3.65) green chlorite, 2.09 (0 to 4.83) green biotite			<0.07 (0 to <0.11)		
Biotite	0.58 (0 to 1.35) altered to 0.04 (0 to 0.21) fringe muscovite, 0.11 (0 to 0.34) chlorite	14.89 (10.27 to 17.16) altered to 0.34 (0 to 1.68) fringe muscovite, 0.04 (0 to 0.31) chlorite	1.68 (1.04 to 2.69)	11.90 (10.29 to 13.5) altered to 0.81 (0.21 to 1.4) chlorite	0.02 (0 to 0.11)	2.76 (2.33 to 3.39)

Magnetite-ilmenite ---------			0.03 (0 to 0.1)			
Pyrite ------------	<0.04 (0 to <0.19) all altered to hematite	<0.1 (0 to <0.06) all altered to hematite	0.09 (0 to 0.2) altered to 0.06 (0 to 0.2) hematite	0.05 (0 to 0.1) altered to <0.05 hematite	0.02 (0 to 0.13) altered to <0.02 hematite	
Epidote -----------	0.07 (0 to 0.34)	0.04 (0 to 0.17)				
Allanite -----------		00.1 (0 to 0.06)	0.03 (0 to 0.1)			<0.01 (0 to <0.09)
Apatite -----------		0.01 (0 to 0.06)	<0.03 (0 to <0.1)	<0.05 (0 to <0.1)		
Zircon ------------	<0.04 (0 to <0.17)	0.02 (<0.05 to 0.11)	0.11 (0 to 0.3)	0.1 (0 to 0.2)	0.02 (0 to 0.11)	0.07 (0 to 0.15)

TABLE B13.—*Volume-weighted average Precambrian crustal chemistry at successive times between 1.8 and 1.4 b.y., northern Park Range, Colorado*

[Relative volumes of crustal units estimated from a regular rectilinear point count of 1:48,000 maps for mapped units, and a separate count of outcrops along traverses for unmapped units (totaling 35,299 points or equivalent observations): 1.8-b.y. country rocks (1), 50.35 percent; 1.8-b.y. mafic-ultramafic intrusives (2), 6.50 percent; 1.7-b.y. felsic intrusives (4), 29.94 percent; 1.4-b.y. felsic intrusives (6), 13.21 percent. Details of volume-weighted analytical input to each of these units given in footnotes]

Column number	1	2	3	4	5	6	7
Geologic unit	1.8-b.y. average metavolcanic and metasedimentary country rock	1.8-b.y. average mafic to ultramafic intrusive rock	Average composition after (2) (88.56 pct. (1) plus 11.44 pct. (2))	1.7-b.y. average felsic intrusive rock	Average composition after (4) (65.49 pct. (3) plus 34.51 pct. (4))	1.4-b.y. average felsic intrusive rock	Average composition after (6) (86.79 pct. (5) plus 13.21 pct. (6))
1973 IUGS name using normative minerals (Lyons' (1976) recommended changes in parentheses)	Granodiorite	Olivine norite	Quartz monzodiorite near quartz monzogabbro	Granite (adamellite)	Granodiorite	Granite (adamellite)	Granodiorite
SiO_2	60.72	50.40	59.53	69.05	62.82	71.30	63.94
Al_2O_3	15.22	16.00	15.31	15.16	15.26	14.44	15.15
Fe_2O_3	1.83	2.04	1.85	1.13	1.60	1.13	1.54
FeO	5.61	8.81	5.98	1.98	4.60	1.40	4.18
MgO	3.55	8.23	4.09	.96	3.01	.59	2.69
CaO	5.59	9.51	6.04	2.40	4.78	1.68	4.37
Na_2O	2.73	2.66	2.72	3.58	3.02	3.43	3.07
K_2O	2.51	.59	2.29	4.59	3.08	4.98	3.33
H_2O^+	.95	.43	.89	.49	.75	.43	.71
TiO_2	.75	.88	.77	.36	.63	.37	.60
P_2O_5	.16	.18	.16	.11	.14	.10	.14
MnO	.14	.18	.15	.06	.12	.05	.11
CO_2	.24	.09	.22	.10	.18	.02	.16
Cl	.00		.00	.01	.00	.01	.00
F	.01		.01	.04	.02	.13	.03
Subtotal	100.01		100.01	100.02	100.01	100.06	100.02
Less O	.01		.01	.02	.01	.06	.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

NORMS

[For method of calculation, see Johannsen (1950, p. 89-90). Before calculation all analyses recalculated to 100 percent minus H_2O^-]

Rittmann (1952) name	Dark rhyodacite or dark labradorite rhyodacite	Pigeonite basalt	Dark labradorite rhyodacite	Rhyolite or quartz latite	Rhyodacite	Rhyolite	Dark quartz latite
Q	16.28		14.28	23.98	17.44	28.50	18.74
or	14.86	3.45	13.52	27.10	18.20	29.44	19.70
ab	23.07	22.54	23.02	30.09	25.53	28.94	25.95
an	21.86	29.95	22.81	10.07	19.00	5.70	17.72
100 an/ab+an	49	57	50	25	43	16	41
C				.64		1.34	
di Ca	1.36	6.46	1.96		.95		.74
di Mg	.70	3.73	1.05		.50		.39
di Fe	.62	2.43	.84		.42		.33
hy Mg	8.12	12.40	9.12	2.40	7.00	1.48	6.30
hy Fe	7.16	8.09	7.33	2.22	5.88	1.09	5.30
ol Mg		3.07					
ol Fe		2.20					
mt	2.66	2.94	2.69	1.62	2.32	1.64	2.22
il	1.43	1.93	1.46	.68	1.20	.70	1.14
ap	.39	.43	.39	.26	.34	.25	.34
fr				.13	.03	.51	.07
hl				.02		.01	
cc	.54	.20	.50	.24	.41	.05	.36
H_2O^+	.95	.43	.89	.49	.75	.43	.71
Total	100.00	100.25	99.86	99.94	99.97	100.08	100.01

TABLE B13.—*Volume-weighted average Precambrian crustal chemistry*—Continued

ANALYTICAL INPUT

[All analyses recalculated to 100 percent minus H_2O^-]

(1) 1.8-b.y. average metavolcanic and metasedimentary country rock (42 different rock analyses used, as indicated below):
- 43.68 percent unmapped layered amphibolite in country rock; average of three analyses: field no. 987, table B5, this report; nos. 52 and 124, Segerstrom and Young (1972, table 1, p. 10);
- 37.38 percent unmapped felsic gneiss in country rock; average of eight analyses: field nos. 1013, 1297, and 1028, table B5, this report; nos. 227, 21, 129, 3, and 78, Segerstrom and Young (1972, table 1, p. 10);
- 11.59 percent mapped pelitic schist layers in country rocks; average of five analyses: field nos. 1080, 1019, and 1077, table B9, this report; nos. 110 and 1, Segerstrom and Young (1972, table 1, p. 10);
- 3.24 percent unmapped pegmatites in country rock; average of two analyses, field nos. 985 and 1011, table B5, this report;
- 2.36 percent mapped siliceous pod-rocks in country rock; average of five whole-rock analyses as given in table B11, column 1B, this report;
- 0.52 percent mapped normal marble and calc-silicate rock; one analysis, field no. 987, table B5, this report;
- 0.38 percent unmapped pelitic schist layers in country rock; same five-analysis average as used for mapped pelitic schist layers above;
- 0.32 percent unmapped calc-silicate pods in country rock; one analysis, field no. 987, table B5;
- 0.21 percent unmapped hornblendite pods in country rock; fifteen-analysis peridotite average as given in table B3, column 12, this report;
- 0.21 percent mapped conglomerate, agglomerate, and pisolite-rocks; average of two pisolite-rock analyses, field nos. 1854, 12-1-20-5, table B9, this report;
- 0.05 percent mapped orthoamphibole rock, field no. 975, table B5, this report;
- 0.05 percent mapped quartzite, field no. 1643, table B9, this report;
- 0.01 percent vesuvianite marble, average of field nos. 1064 and 1065, table B9, this report.

(2) 1.8-b.y. average mafic to ultramafic intrusive rock (24 different rock analyses used, as indicated below):
- 60.23 percent mapped gabbro; average of four analyses: field nos. 1501-A, 1685, 1413, and 1765, table B1, this report;
- 32.84 percent mapped diorite; average of two analyses: field nos. 1765, and 1781, table B1, this report;
  - *Note 1*—analysis 1765 included in both the gabbro and diorite averages above because this rock is almost exactly on the boundary between gabbro and diorite, both petrographically and geographically;
  - *Note 2*—3.15 percent of the rocks mapped as gabbro or diorite are miscellaneous small mafic intrusives outside of the Elkhorn Mountain and Farwell Mountain plutons;
- 4.27 percent mapped olivine gabbro; average of three analyses: field nos. 1606, 1410, and 1411, table B1, this report;
- 2.13 percent mapped peridotite and related rocks; average of fifteen analyses as given in column 12, table B3, this report;
- 0.53 percent mapped basalt dikes, field no. 1985, table B1, this report.

(4) 1.7-b.y. average felsic intrusive rock (27 different rock analyses used, as indicated below):
- 54.01 percent mapped coarse-grained massive gneisses of the Buffalo Pass pluton; average of three analyses: field nos. 544, 555 and 554, Snyder, 1978, table 5;
- 38.06 percent mapped quartz monzonite of Seven Lakes; average of 11 analyses: all those in table B7, this report, and Segerstrom and Young, (1972, no. 95, table 1, p. 10);
- 4.09 percent mapped sillimanite-pelite inclusion-rich phase of the Buffalo Pass pluton; not analyzed directly; average of five siliceous-pod rock analyses substituted here, as given in column 1B, table B11, this report;
- 1.64 percent mapped quartz diorite of Gilpin Lake; average of four analyses: field nos. 1290 and 1102, table B5, this report, and nos. 96 and 228, Segerstrom and Young (1972, table 1, p. 10);
- 1.45 percent mapped pegmatites distant from Mount Ethel pluton; average of field nos. 985 and 1011, table B5, this report;
- 0.75 percent mapped fine-grained rocks of the Buffalo Pass pluton; average of nos. 550 and 553, Snyder, 1978, table 5.

(6) 1.4-b.y. average felsic intrusive rock (21 different rock analyses used, as indicated below):
- 74.25 percent mapped quartz monzonite of Roxy Ann Lake in Mount Ethel pluton; average of five analyses: field no. 1023, table B5, this report, and nos. 527, 523, 526, and 347, Snyder, 1978, table 5;
- 19.67 percent mapped quartz monzonite porphyry of Rocky Peak in Mount Ethel pluton; average of four analyses: nos. 437, 157, 525, and 520, Snyder, 1978, table 5;
- 3.80 percent mapped granite of the Mount Ethel pluton; average of nos. 521 and 522, Snyder, 1978, table 5;
- 0.66 percent mapped porphyry dikes in vicinity of Mount Ethel pluton; average of three analyses: nos. 549, 524, and 545, Snyder, 1978, table 5;
- 0.57 percent mapped porphyry dikes north of 40°45′ N. Lat. (north of Mount Ethel pluton); average of three analyses, field no. 1097, table B5, this report, and nos. 13B and 132, Segerstrom and Young (1972, table 5, p. 10). *Note* that the latter two analyses are from rocks that were mapped by Segerstrom and Young as Tertiary dikes but which are considered by Snyder to be Precambrian;
- 0.52 percent mapped leucogranite dikes of the Mount Ethel pluton, no. 528, Snyder, 1978, table 5;
- 0.44 percent mapped pegmatites close to the Mount Ethel pluton; average of field nos. 985 and 1011, table B5, this report;
- 0.09 percent mapped granodiorite inclusions in Mount Ethel pluton, no. 551, Snyder, 1978, table 5.

TABLE B14.—*Recent estimates of the composition of the Earth's mantle*

[All compositions recalculated to 100 percent on a volatile-free basis. Fe_2O_3/FeO of columns 5, 6, and 9 adjusted to equal average Fe_2O_3/FeO of other columns]

Column No.	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	42.2	42.89	44.5	44.6	44.61	44.7	45.1	45.2	45.9	46.2	47.3	44.8
Al_2O_3	4.1	7.00	2.4	2.7	2.46	3.7	4.6	4.1	2.2	4.6	3.2	3.7
Cr_2O_3		.18	.4	.3	.42	.5	.3	.3	.4	.1	.18	.28
Fe_2O_3	1.9	.36	1.4	1.4	1.38	1.35	.3	2.0	1.15	1.0	4.9	1.6
FeO	10.9	8.98	7.0	6.6	6.77	6.65	7.6	7.9	5.65	9.1	5.2	7.5
MgO	36.2	35.10	41.2	41.4	40.90	39.5	38.1	36.6	41.9	32.9	33.9	38.0
CaO	3.0	4.37	2.4	2.2	2.42	2.7	3.1	2.3	1.7	5.3	4.5	3.1
Na_2O	.8	.45	.18	.23	.29	.23	.4	.6	.2	.3	.32	.36
K_2O	.14	.003	.03	.03	.09	.06	.02	.02	.16	.07	.04	.06
TiO_2	.5	.33	.06	.1	.16	.2	.2	.5	.3	.3	.20	.26
P_2O_5	.06				.06	.04	.02	.1	.02		.01	.03
MnO	.2	.14	.12	.14	.18	.1	.1	.2	.1	.2	.13	.15
NiO		.20	.3	.3	.26	.3	.2	.2	.3		.10	.20
Total	100.0	100.00	100.0	100.0	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0

COLUMN DESCRIPTIONS:

1. Limiting composition of upper mantle based on 20-percent oceanic tholeiite (Engel and others, 1965, p. 721, table 2) and 80-percent average dunite (Nockolds, 1954, p. 1023). The other limiting composition suggested would be oceanic tholeiite (Engel and others, 1965) with 49.9 percent SiO_2 and 7.7 percent MgO.
2. Average undepleted upper mantle composition under Kilbourne Hole, N. Mex., based on an ultramafic nodule model (Carter, 1970, p. 2021, 2032).
3. Mean of 92 spinel-peridotite nodules in alkali basalts (as summarized in Ringwood, 1975, p. 108).
4. Average undepleted upper mantle from selected ultrabasic rocks and nodules (as summarized in Harris, 1967, p. 307, table 1).
5. Primitive mantle based on model using mainly 384 analyzed spinel lherzolites (Maaløe and Aoki, 1977, p. 165, table 2, no. 6).
6. Average of three high-temperature intrusive peridotites from Cornwall, England; Venezuela; and St. Paul's Rocks (Atlantic Ocean) (as summarized in Ringwood, 1975, p. 87).
7. Average mantle pyrolite (average of various models) (Ringwood, 1975, p. 188, table 5–2, no. 8).
8. Undepleted oceanic mantle based on model with 22.3-percent adjusted oceanic basalt and 77.7-percent adjusted deep-sea serpentinite (Nicholls, 1967, p. 303, table 9, column 1).
9. Average of fifteen garnet-peridotite xenoliths from South African diamond pipes (as summarized in Ringwood, 1975, p. 103).
10. Peridotitic komatiites from South Africa and Australia (as summarized in Ringwood, 1975, p. 187).
11. South African primitive mantle, average of peridotitic komatiite (Viljoen and Viljoen, 1969, p. 92, table 1, no. 9), and average bulk composition of layered ultramafic bodies (Viljoen and Viljoen, 1970, p. 676, 677, 683).
12. Average mantle, average of columns 1 through 11. Note that Sun (1982, p. 180) derives a mantle TiO_2 value of 0.16–0.21 by taking the MgO content of the mantle to be 38% on a plot of spinifex-textured peridotitic komatiites and high-magnesian basalts.

TABLE B15.—*Selected estimates of the composition of the Earth's crust*

	Precambrian shield				Continental crust				Entire lithosphere			
Column No.	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	66.4	66.7	69.0	67.4	57.9	59.4	61.9	59.7	55.2	59.3	60.3	58.3
Al_2O_3	15.5	15.0	14.5	15.0	15.2	15.5	15.6	15.4	15.3	15.9	15.5	15.6
Fe_2O_3	1.8	1.4	1.4	1.5	2.3	2.3	2.6	2.4	2.8	2.5	3.2	2.8
FeO	2.8	2.8	2.9	2.8	5.5	5.0	3.9	4.8	5.8	4.5	3.8	4.7
MgO	2.0	2.3	1.7	2.0	5.3	4.2	3.1	4.2	5.2	4.0	3.5	4.2
CaO	3.8	4.2	3.1	3.7	7.1	6.6	5.7	6.5	8.8	7.2	5.2	7.1
Na_2O	3.5	3.6	3.2	3.4	3.0	3.1	3.1	3.1	2.9	3.0	3.8	3.2
K_2O	3.3	3.2	3.6	3.4	2.1	2.3	2.9	2.4	1.9	2.4	3.2	2.5
TiO_2	.6	.5	.6	.6	1.2	1.2	.8	1.1	1.6	.9	1.1	1.2
P_2O_5	.2	.2	.2	.2	.3	.2	.3	.3	.3	.2	.3	.3
MnO	.1	.1		.1	.2	.1	.1	.1	.2	.1	.1	.1
Total	100.0	100.0	100.2	100.1	100.1	99.9	100.0	100.0	100.0	100.0	100.0	100.0

COLUMN DESCRIPTIONS:

1. Continental shield crystalline surface rocks (Poldervaart, 1955, p. 127).
2. Canadian Precambrian shield (Shaw and others, 1967, p. 848).
3. Fennoscandian shield, average of Finnish Precambrian shield (Sederholm, 1925) and Norwegian Precambrian (Barth, 1961).
4. Average Precambrian shield (average of columns 1, 2, and 3).
5. U.S. Continental crust, based on geophysical thicknesses and Nockolds' average igneous rocks (Pakiser and Robinson, 1966, p. 624).
6. Continental crust, equal to 30 percent young fold belts plus 70 percent continental shield (Poldervaart, 1955, p. 134, table 20).
7. Continental crust (Ronov and Yaroshevsky, 1969, p. 48 and 53).
8. Average continental crust (mean of columns 5, 6, anf 7).
9. Lithosphere (Poldervaart, 1955, p. 133, table 20).
10. Entire lithosphere (Ronov and Yaroshevsky, 1969, p. 53).
11. Lithosphere (Clarke, and Washington, 1924, p. 32; Parker, 1967, p. D3).
12. Average lithosphere (mean of columns 9, 10, and 11).

TABLE B16.—*Chemical constraints on the derivation of Earth's crust from Earth's mantle—a comparison of seven possible chemical models*

[Required mantle thicknesses are calculated for three limiting stages of each model. The second and third limiting stages are appropriate only if the prior K_2O constraints can be satisfied first. Similarly, the third Al_2O_3-limiting stage is appropriate only if the second Na_2O constraint can be satisfied next. Calculated thicknesses based on the derivation from tabular layers of infinite extent. Adjustment for spherical shells would increase the size of all mantle thickness numbers. The chemical constraints illustrated are immutable, and would differ only in details of application for any other reasonable models]

"A" columns: Successive chemical stages in the evolution of depleted residuum during the derivation of average Park Range Precambrian and average Colorado Precambrian from average Park Range ultramafic rock.

1A. Volatile-free average Park Range ultramafic rock (table B3, col. 12), with Fe_2O_3/FeO adjusted to average mantle ratio.
2A. Volatile-free weighted average Park Range Precambrian rock (table B13, col. 7).
3A. Composition of K_2O-limited depleted residuum of 1A (assuming that slightly more than 5.95 percent of 2A removed from 1A).
4A. Composition of Na_2O-limited depleted residuum of 1A (assuming that slightly less than 16.13 percent of 2A removed from 1A); includes -0.41 percent K_2O.
5A. Composition of Al_2O_3-limited depleted residuum of 1A (assuming that slightly more than 41.23 percent of 2A removed from 1A); includes -1.33 percent Na_2O and -2.03 percent K_2O.
6A. Volatile-free weighted average Colorado Precambrian rock (applying Park Range chemistry to Colorado map units of Tweto, 1976a).
7A. Composition of K_2O-limited depleted residuum of 1A (assuming that slightly more than 5.26 percent of 6A removed from 1A).
8A. Composition of Na_2O-limited depleted residuum of 1A (assuming that slightly more than 17.24 percent of 6A removed from 1A); includes -0.54 percent K_2O.
9A. Composition of Al_2O_3-limited depleted residuum of 1A (assuming that slightly less than 41.18 percent of 6A removed from 1A); includes -1.19 percent Na_2O and -2.34 percent of K_2O.

	1A	2A	3A	4A	5A	6A	7A	8A	9A
SiO_2	46.0	64.5	44.8	42.3	32.0	66.9	44.8	41.4	30.3
Al_2O_3	6.3	15.3	5.7	4.6		15.3	5.8	4.4	
Fe_2O_3	2.2	1.55	2.2	2.3	2.6	1.5	2.2	2.3	2.6
FeO	11.0	4.2	11.4	12.3	15.3	3.4	11.4	12.5	15.8
MgO	26.0	2.7	27.5	30.3	41.0	2.0	27.3	30.8	41.4
CaO	7.2	4.4	7.4	7.7	8.9	3.5	7.4	7.9	9.5
Na_2O	.5	3.1	.34			2.9	.37		
K_2O	.2	3.4				3.8			
TiO_2	.3	.61	.28	.24	.08	.5	.29	.25	.15
P_2O_5	.1	.14	.10	.10	.07	.1	.10	.10	.10
MnO	.2	.16	.20	.20	.21	.1	.21	.22	.26
Total	100.0	100.06	99.92	100.04	100.16	100.0	99.87	99.87	100.11
Thickness of 1A required to supply 22.5 km (14 mi) of 2A or 6A[1]			378 km 235 mi	139 km 87 mi	55 km 34 mi		428 km 266 mi	131 km 81 mi	55 km 34 mi

"B" columns: Successive chemical stages in the evolution of depleted residuum during the derivation of average Park Range Precambrian and average Colorado Precambrian from the average of selected Park Range peridotites closest to average mantle.

1B. Volatile-free average of the four Park Range peridotites (1428, 1412, 1017, and 1078) nearest to average mantle in composition, with Fe_2O_3/FeO adjusted to average mantle ratio.
2B. Volatile-free weighted average Park Range Precambrian rock (table B13, col. 7).
3B. Composition of K_2O-limited depleted residuum of 1B (assuming that slightly more than 2.08 percent of 2B removed from 1B).
4B. Composition of Na_2O-limited depleted residuum of 1B (assuming that slightly less than 18.39 percent of 2B removed from 1B); includes -0.67 percent K_2O.
5B. Composition of Al_2O_3-limited depleted residuum of 1B (assuming that slightly more than 41.88 percent of 2B removed from 1B); includes -1.26 percent Na_2O and -2.31 percent K_2O.
6B. Volatile-free weighted average Colorado Precambrian rock (applying Park Range chemistry to Colorado map units of Tweto, 1976a).
7B. Composition of K_2O-limited depleted residuum of 1B (assuming that slightly more than 1.84 percent of 6B removed from 1B).
8B. Composition of Na_2O-limited depleted residuum of 1B (assuming that slightly less than 19.66 percent of 6B removed from 1B); includes -0.85 percent K_2O.
9B. Composition of Al_2O_3-limited depleted residuum of 1B (assuming that slightly more than 41.83 percent of 6B removed from 1B); includes -1.10 percent Na_2O and -2.62 percent of K_2O.

	1B	2B	3B	4B	5B	6B	7B	8B	9B
SiO_2	43.8	64.5	43.4	38.9	27.9	66.9	43.4	37.9	26.2
Al_2O_3	6.4	15.3	6.2	4.4		15.3	6.2	4.2	
Fe_2O_3	2.4	1.55	2.4	2.6	2.9	1.5	2.4	2.6	2.9
FeO	11.9	4.2	12.1	13.6	16.9	3.4	12.1	13.9	17.4
MgO	29.0	2.7	29.6	34.7	46.3	2.0	29.5	35.3	46.7
CaO	5.2	4.4	5.2	5.4	5.6	3.5	5.2	5.6	6.2
Na_2O	.57	3.1	.52			2.9	.53		
K_2O	.07	3.4				3.8			
TiO_2	.27	.61	.27	.19	.02	.5	.26	.21	.10
P_2O_5	.11	.14	.11	.11	.08	.1	.11	.11	.11
MnO	.23	.16	.23	.24	.27	.1	.23	.26	.31
Total	99.95	100.06	100.03	100.14	99.97	100.0	99.93	100.08	99.92
Thickness of 1B required to supply 22.5 km (14 mi) of 2B or 6B[1]			1080 km 672 mi	122 km 76 mi	54 km 33 mi		1221 km 760 mi	114 km 71 mi	54 km 33 mi

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[1] Average thickness of Colorado crust taken as 45 km (Cordell, 1978, figs. 2 and 5; data after L. C. Pakiser, W. H. Jackson and others; see also Prodehl, 1979, p. 2); of Precambrian shield or continental crust, as 35 km (see discussions in Poldervaart, 1955; Parker, 1967; Ronov and Yaroshevsky, 1969; Jacobs, 1971; and Press, 1971); of lithosphere, as 17 km (see discussions in Mason, 1958; Ronov and Yaroshevsky, 1969; and Haddon and Bullen, 1969 (in Jacobs, 1971, p. 76)). Taking half of these thicknesses as the amount of crustal composition that must be fractionated from the mantle satisfies one of the following two assumptions: that the crust either (1) consists of equal sial over sima, or (2) is gradational in composition from the surface to the mantle. Other models will be simple factors of the data supplied on the basis of these dual assumptions.

TABLE B16.—*Chemical constraints on the derivation of Earth's crust from Earth's mantle*—Continued

"C" columns: Successive chemical stages in the evolution of depleted residuum during the derivation of average Precambrian shield, average continental crust, and average lithosphere from average mantle.

1C. Volatile-free average mantle (table B14, col. 12).
2C. Volatile-free average Precambrian shield (table B15, col. 4).
3C. Composition of K_2O-limited depleted residuum of 1C (assuming that slightly more than 1.76 percent of 2C removed from 1C).
4C. Composition of Na_2O-limited depleted residuum of 1C (assuming that slightly less than 10.59 percent of 2C removed from 1C); includes -0.34 percent K_2O.
5C. Composition of Al_2O_3 (and P_2O_5)-limited depleted residuum of 1C (assuming that slightly less than 24.67 percent of 2C removed from 1C); includes -0.03 percent P_2O_5, -0.64 percent Na_2O, and -1.04 percent K_2O.
6C. Volatile-free average continental crust (table B15, col. 8).
7C. Composition of K_2O-limited depleted residuum of 1C (assuming that 2.5 percent of 6C removed from 1C).
8C. Composition of Na_2O (and P_2O_5)-limited depleted residuum of 1C (assuming that slightly more than 11.61 percent of 6C removed from 1C); includes -0.25 percent K_2O.
9C. Composition of Al_2O_3 (and TiO_2)-limited depleted residuum of 1C (assuming that slightly less than 24.03 percent of 6C removed from 1C); includes -0.05 percent P_2O_5, -0.50 percent Na_2O, and -0.68 percent K_2O.
10C. Volatile-free average lithosphere (table B15, col. 12).
11C. Composition of K_2O-limited depleted residuum of 1C (assuming that 2.4 percent of 10C removed from 1C).
12C. Composition of Na_2O (and P_2O_5)-limited depleted residuum of 1C (assuming that 11.25 percent of 10C removed from 1C); includes -0.25 percent K_2O.
13C. Composition of Al_2O_3 (and TiO_2)-limited depleted residuum of 1C (assuming that slightly less than 23.72 percent of 10C removed from 1C); includes -0.03 percent TiO_2, -0.05 percent P_2O_5, -0.52 percent Na_2O, and -0.69 percent K_2O.

	1C	2C	3C	4C	5C	6C	7C	8C	9C	10C	11C	12C	13C
SiO_2	44.8	67.4	44.4	42.0	36.8	59.7	44.4	42.7	39.57	58.3	44.4	43.0	40.1
Al_2O_3	3.7	15.0	3.5	2.4		15.4	3.4	2.15		15.6	3.4	2.2	
Fe_2O_3	1.6	1.5	1.60	1.60	1.61	2.4	1.58	1.49	1.33	2.8	1.6	1.4	1.2
FeO	7.5	2.8	7.6	8.0	8.9	4.8	7.6	7.8	8.25	4.7	7.6	7.8	8.3
Cr_2O_3	.28		.28	.31	.37		.29	.32	.36		.29	.31	.36
MgO	38.0	2.0	38.6	42.1	48.9	4.2	38.8	42.3	48.06	4.2	38.8	42.2	47.8
NiO	.20		.20	.22	.26		.21	.23	.26		.20	.22	.26
CaO	3.1	3.7	3.1	3.0	2.9	6.5	3.0	2.65	2.00	7.1	3.0	2.6	1.84
Na_2O	.36	3.4	.31			3.1	.29			3.2	.29		
K_2O	.06	3.4				2.4				2.5			
TiO_2	.26	.6	.25	.22	.14	1.1	.24	.15		1.2	.24	.14	
P_2O_5	.03	.2	.03	.01		.3	.02			.3	.02		
MnO	.15	.1	.15	.16	.17	.1	.15	.16	.17	.1	.15	.16	.16
Total	100.0	100.1	100.02	100.02	100.05	100.0	99.98	99.95	100.00	100.0	99.99	100.03	100.02
Thickness of 1C required to supply 17.5 km (11 mi) of 2C or 6C[1], or 8.5 km (5.75 mi) of 10C[1]			992 km 618 mi	165 km 103 mi	71 km 44 mi		700 km 436 mi	151 km 94 mi	73 km 45 mi		354 km 240 mi	76 km 51 mi	36 km 24 mi

NORMS

Normative column numbers correspond to chemical column numbers; compositions without norms are too undersaturated in SiO_2 to supply balanced normative silicates. For method of calculation, see Johannsen (1950, p. 89–92).

	1A	2A and 2B	3A	4A	6A and 6B	7A	8A	1B	3B	4B	7B
IUGS normative name	Olivine melanorite	Granodiorite	Olivine melagabbro	Olivine melagabbro	On boundary between granodiorite and granite (Lyons' adamellite)	Olivine melanorite	Olivine melagabbro	Olivine melanorite	Olivine melanorite	Melatroctolite	Olivine melanorite
Q		18.55			23.33						
or	1.17	19.87			22.43			0.41			
ab	4.25	26.22	2.88		24.54	3.15		4.82	4.40		4.46
an	14.35	17.86	14.10	12.43	16.72	14.16	12.20	14.71	14.60	11.93	14.55
100 an/ab+an	77	41	83	100	41	82	100	75	77	100	77
C					.30						
di Ca	8.65	1.30	9.13	10.51		9.15	10.85	4.32	4.52	2.15	4.39
di Mg	6.15	.68	6.51	7.53		6.52	7.76	3.09	3.23	1.55	3.13
di Fe	1.74	.58	1.81	2.04		1.82	2.13	.84	.88	.41	.87
hy Mg	16.22	6.06	13.46	4.06	4.98	13.11		12.17	10.89		11.25
hy Fe	4.58	5.17	3.75	1.11	4.37	3.67		3.35	2.98		3.10
cs							.17			2.93	
ol Mg	29.68		33.94	44.82		33.88	48.30	39.90	41.70	59.48	41.39
ol Fe	9.22		10.41	13.46		10.45	14.61	12.08	12.56	17.35	12.56
mt	3.19	2.25	3.24	3.36	2.18	3.19	3.33	3.47	3.52	3.75	3.47
il	.56	1.15	.53	.46	.94	.55	.47	.52	.52	.36	.49
ap	.23	.32	.23	.23	.23	.23	.23	.25	.25	.25	.25
Total	99.99	100.01	99.99	100.01	100.02	99.88	99.87	99.93	100.05	100.16	99.91

	1C	2C	3C	4C	6C	7C	8C	10C	11C	12C	13C
IUGS normative name	Olivine melanorite	Granodiorite	Olivine melanorite	Lherzolite	Quartz monzodiorite	Olivine melanorite	Lherzolite	Quartz monzodiorite	Olivine melanorite	Lherzolite	Dunite
Q		23.20			12.78			10.16			
or	.36	20.09			14.19			14.75			
ab	3.04	28.73	2.62		26.22	2.46		27.05	2.46		
an	8.32	15.63	8.15	6.54	21.03	7.98	5.87	20.83	7.98	6.01	
100 an/ab+an	73	35	76	100	45	76	100	44	76	100	
di Ca	2.87	.59	2.94	3.46	3.87	2.82	3.04	5.19	2.82	2.88	.34
di Mg	2.26	.35	2.31	2.73	2.42	2.22	2.40	3.37	2.22	2.27	.27
di Fe	.29	.21	.30	.35	1.21	.29	.30	1.46	.29	.29	.03
hy Mg	16.81	4.63	15.74	6.33	8.04	16.09	10.00	7.09	16.31	11.28	
hy Fe	2.20	2.89	2.07	.81	4.00	2.11	1.27	3.06	2.14	1.44	
cs											2.57
ol Mg	52.95		54.70	67.11		54.87	65.12		54.71	64.13	83.21
ol Fe	7.66		7.92	9.48		7.92	9.05		7.87	8.98	11.31
mt	2.32	2.18	2.32	2.32	3.47	2.29	2.15	4.05	2.32	2.04	1.74
il	.49	1.14	.47	.41	2.08	.46	.29	2.28	.46	.26	
ap	.07	.46	.07	.02	.69	.05		.69	.05		
Total	100.04	100.10	100.01	100.01	100.00	99.99	99.96	99.98	100.06	100.03	100.01

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[1] Average thickness of Colorado crust taken as 45 km (Cordell, 1978, figs. 2 and 5; data after L. C. Pakiser, W. H. Jackson and others; see also Prodehl, 1979, p. 2); of Precambrian shield or continental crust, as 35 km (see discussions in Poldervaart, 1955; Parker, 1967; Ronov and Yaroshevsky, 1969; Jacobs, 1971; and Press, 1971); of lithosphere, as 17 km (see discussions in Mason, 1958; Ronov and Yaroshevsky, 1969; and Haddon and Bullen, 1969 (in Jacobs, 1971, p. 76)). Taking half of these thicknesses as the amount of crustal composition that must be fractionated from the mantle satisfies one of the following two assumptions: that the crust either (1) consists of equal sial over sima, or (2) is gradational in composition from the surface to the mantle. Other models will be simple factors of the data supplied on the basis of these dual assumptions.

TABLE B17.—*Electron-probe analyses of mafic mineral separates from peridotite sample 1927*

[Italicized numbers are not direct measurements but are calculated values that are used in the totals. Numbers in parentheses show total number of observations averaged for each constituent. ΣFeO, total iron expressed as FeO. Analytical measurements February 1978 by George L. Snyder, supervised by Glen A. Izett and George A. Desborough. Details explained in numbered footnotes]

Major oxides	Pargasite		Clinopyroxene		Spinel in symplectite[1]	Ortho-pyroxene	Olivine
	In large grains	In symplectite[1]	In large grains	In symplectite[1]			
SiO_2 -------	44.74 (39)	44.78 (12)	53.52 (19)	54.63 (14)	5.80 (33)	53.62 (32)	38.64 (24)
Al_2O_3 ------	13.01 (39)	14.25 (12)	3.91 (19)	2.90 (14)	62.94 (33)	2.26 (32)	.08 (24)
Fe_2O_3 ------	[2]*1.83*	[2]*1.96*	[3]*1.31*	[3]*1.30*	[4]*6.26*	[5]*1.47*	[6]*1.49*
FeO -------	[2]*5.51*	[2]*5.89*	[3]*3.34*	[3]*3.33*	[4]*16.04*	[5]*11.89*	[6]*20.14*
ΣFeO ------	7.16 (39)	7.65 (12)	4.52 (19)	4.50 (14)	21.68 (33)	13.21 (32)	21.48 (24)
MgO ------	15.08 (24)	13.30 (4)	14.98 (10)	14.37 (6)	13.04 (26)	27.48 (24)	34.16 (14)
CaO -------	12.67 (15)	12.78 (8)	25.04 (9)	24.03 (8)	.31 (7)	.32 (8)	.09 (10)
Na_2O ------	1.64 (15)	1.71 (8)	.08 (9)	.12 (8)	.01 (7)	.01 (8)	.02 (10)
K_2O -------	.46 (39)	.40 (12)	.24 (19)	.24 (14)	.01 (33)	.01 (32)	.01 (24)
[7]H_2O^+ ------	*2.45*	*2.45*					
TiO_2 -------	.49 (15)	.24 (8)	.17 (9)	.14 (8)	.16 (7)	.10 (8)	.16 (10)
MnO ------	.10 (24)	.04 (4)	.16 (10)	.13 (6)	.19 (26)	.25 (24)	.26 (14)
Total ----	97.98	97.80	102.75	101.19	104.76	97.41	95.05

Above analyses recalculated to 100 percent

Major oxides	Pargasite			Clinopyroxene			Spinel in symplectite[1, 10]	Ortho-pyroxene	Olivine
	In large grains	In symplectite[1]	Avg.[8]	In large grains	In symplectite[1]	Avg.[9]			
SiO_2 -------	45.67	45.78	45.68	52.08	53.98	53.01	5.54	55.04	40.66
Al_2O_3 ------	13.28	14.57	13.54	3.81	2.87	3.34	60.07	2.32	.08
Fe_2O_3 ------	1.87	2.00	1.90	1.27	1.28	1.28	5.98	1.51	1.57
FeO -------	5.62	6.02	5.70	3.25	3.29	3.27	15.31	12.21	21.19
MgO ------	15.39	13.60	15.03	14.58	14.20	14.39	12.45	28.21	35.94
CaO -------	12.93	13.07	12.96	24.37	23.75	24.06	.30	.33	.09
Na_2O ------	1.67	1.75	1.69	.08	.12	.10	.01	.01	.02
K_2O -------	.47	.41	.46	.23	.24	.24	.01	.01	.01
[7]H_2O^+ ------	2.50	2.50	2.50						
TiO_2 -------	.50	.25	.45	.17	.14	.16	.15	.10	.17
MnO ------	.10	.04	.09	.16	.13	.15	.18	.26	.27
Total ----	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[1] Symplectites consist of spinel with either pargasite or clinopyroxene.

[2] Pargasite Fe_2O_3 taken as 23 percent of ΣFeO (the average shown by analyzed ultramafic pargasites 5 and 6 of Deer and others, 1963, p. 286–287). Fe_2O_3 and FeO used in totals.

[3] Clinopyroxene Fe_2O_3 taken as 26 percent of ΣFeO (the average shown by analyzed mafic and ultramafic augites 3, 6, and 7 of Deer and others, 1963, p. 114–115). Fe_2O_3 and FeO used in totals.

[4] Spinel Fe_2O_3 taken as 26 percent of ΣFeO (the average shown by analyzed spinels from low-silica rocks 4, 5, and 6 of Deer and others, 1962b, p. 64). Fe_2O_3 and FeO used in totals; $\Sigma Fe_2O_3=24.10$.

[5] Orthopyroxene Fe_2O_3 taken as 10 percent of ΣFeO (the average shown by analyzed mafic and ultramafic bronzites 6, 7, and 9 of Deer and others, 1963, p. 17). Fe_2O_3 and FeO used in totals.

[6] Olivine Fe_2O_3 taken as 3 percent of ΣFeO (the average shown by analyzed mafic olivines 11 and 12 of Deer and others, 1962a, p. 12, which have about the same total iron content as our samples). Fe_2O_3 and FeO used in totals.

[7] 2.50 percent H_2O^+ is the amount of water expected in the pargasite if the average 0.83 percent H_2O^+ in the analyzed rock is all contained in the average 33.14 percent pargasite. Note that 2.45 percent H_2O^+ is added in to the upper totals in order that H_2O^+ in the recalculated lower totals will approximate 2.50 percent.

[8] Average pargasite is weighted with four parts of large-grain pargasite to one part pargasite in symplectite with spinel. The two are in reasonably good agreement except for Al_2O_3, MgO, and TiO_2.

[9] Average clinopyroxene is one part large-grain clinopyroxene to one part clinopyroxene in symplectite with spinel. The two are in reasonably good agreement except for SiO_2 and Al_2O_3.

[10] The presence of excess SiO_2 in spinel is an unsolved problem; the low alkalies attest that it is not due to beam scatter.

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