Intrusive Rocks Northeast of Steamboat Springs, Park Range, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1041

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By GEORGE L. SNYDER
with a section on GEOCHRONOLOGY
By CARL E. HEDGE

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Delineation of intrusive rock types in a previously unstudied area of Colorado and comparison with related rocks elsewhere in Colorado and Wyoming

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INTRUSIVE ROCKS NORTHEAST OF STEAMBOAT SPRINGS, PARK RANGE, COLORADO

By GEORGE L. SNYDER

ABSTRACT

Major Precambrian and minor Tertiary intrusive rocks northeast of Steamboat Springs in the Park Range between 40°30′ and 40°45′ N. lat. are described and compared with related rocks elsewhere in Colorado and Wyoming. The Precambrian intrusives were emplaced in a sequence of high-grade interlayered felsic gneisses, amphibolites, and pelitic schists of sedimentary and volcanic origin. These rocks are cut by a major northeast-trending Precambrian shear zone where mainly left lateral movement of ½ to 1 mile is certain. Cumulative movement of many miles is possible. The Precambrian intrusives consist of a batholith, the Mount Ethel pluton, a smaller Buffalo Pass pluton, and small dikes or lenses of fine-grained porphyry, pegmatites, and ultramafics.

The Mount Ethel pluton is an oval shaped body 7 miles wide by about 40 miles long (shown by geophysical data to extend beneath younger sediments in North Park). Outer batholithic contacts are sharp and dip steeply outward at about 85°. Five mappable internal variants consist, in order of decreasing age, of granodiorite, quartz monzonite porphyry of Rocky Peak, quartz monzonite of Roxy Ann Lake, granite and quartz monzonite, and leucogranite. Internal contacts between these plutonic variants are sharp, and evidence of liquid-solid relationships abounds; despite this, all rocks except the granodiorite contribute to an Rb-Sr whole-rock isochron indicating emplacement about 1.4 b.y. (billion years) ago. The most important variants volumetrically are: the quartz monzonite porphyry of Rocky Peak, which forms an irregular 2-mile-thick carapace or mapped band around the west edge of the pluton and is lithologically similar to nearby Sherman Granite, and the quartz monzonite of Roxy Ann Lake, which forms most of the rest of the pluton and is lithologically similar to Silver Plume Granite. An apparent Sherman–Silver Plume dichotomy with similar rock types and similar relative ages is noted throughout Colorado plutons of that age.

The Buffalo Pass pluton consists of the quartz monzonite and granodiorite augen gneiss of Buffalo Mountain and equigranular quartz monzonite gneiss. Internal contacts are not exposed. These rocks contribute to an Rb-Sr whole-rock isochron indicating syntectonic emplacement 1.7–1.8 b.y. ago, essentially the same as the metamorphism of the felsic gneiss wallrocks in the area of this report, and of rocks of Boulder Creek age elsewhere in Colorado.

The fine-grained porphyry dikes cut the Buffalo Pass pluton, the ultramafics, and some pegmatites. The dikes are within the age range of the Mount Ethel pluton and are older than the mylonite and shear zones. They occur in both an older northwest-trending and a somewhat younger northeast-trending set but do not appear to change compositionally from one set to the other. Regional considerations indicate that they were emplaced between about 1.1 and 1.5 b.y. ago, a time when intermediate to mafic dikes were commonly emplaced throughout Colorado, Wyoming, and southwestern Montana.

The pegmatite and ultramafic bodies are not dated directly, but clustering of many pegmatites outside the contacts of the Mount Ethel pluton may indicate a genetic relation of the pegmatites to the Mount Ethel rocks.

Fluorite is a common accessory mineral in the rocks of the Mount Ethel pluton; it has not been observed in this area in the petrographically similar rocks of the Buffalo Pass pluton. Fluorite was precipitated most abundantly from the Precambrian magma that formed the quartz monzonite of Roxy Ann Lake. In 70 percent of these rocks fluorite is observed in amounts as great as 2 percent and is successively less abundant in both older and younger plutonic phases. Textural evidence indicates that, although most fluorite is intergrown with and contemporaneous with other magmatic minerals, some fluorite is associated with alteration minerals in a manner demonstrating its mobility since its initial deposition. Five areas of economic or potentially economic Tertiary fluorite veins in the North Park area occur in rocks equivalent to the quartz monzonite of Roxy Ann Lake, the unit containing the most interstitial Precambrian fluorite. It seems possible that Tertiary solutions may have redistributed Precambrian fluorite into joints or breccia systems open in the Tertiary, and, if so, the mapped faults and mapped areas of most abundant interstitial fluorite may serve as guides to new economic vein deposits.

Twenty-eight chemical, modal, and spectrographic analyses of 24 Park Range igneous rocks are compared with each other as well as with 185 analyses of Colorado igneous rocks of similar age from other sources. The comparison indicates that the Park Range igneous rocks are typical of others of the same age, that Colorado rocks of different ages overlap in composition, but that rocks low in normative orthoclase may be restricted to the 1.7-b.y. rocks; whereas Tertiary rocks are comparatively high in alkalis and low in silica. The sequence of intrusion of the Precambrian plutonic rocks, from mafic to silicic compositions, is similar to that predicted by experimental feldspar-quartz-water systems. The sequence may have resulted from magmatic differentiation at a minimum depth of 11 miles and at temperatures of 705°–740°C. However, disproportionately large volumes of the most differentiated rocks at the level of present erosion indicate that differentiation from more mafic rocks by any mechanism must have taken place at deeper levels and that subsequent upward transportation and differential concentration of silicic derivatives took place.

There are two types of fine-grained or glassy Miocene or Pliocene intrusives in the area studied in this report: a dark olivine porphyry and a lighter colored intermediate rock whose mutual contacts are not exposed. In this region dark basalts have been previously shown, asserted, or assumed to be younger than light-colored rocks that have been called trachytes or rhyolites. A review of the field, chemical, and temporal data, however, indicates that this is an oversimplification. Basaltic rocks have been erupted at several times in the Tertiary in conjunction with other rocks of mafic, intermediate, silicic, and subsilicic compositions. Available K-Ar dates in this area suggest that rocks of the compositional range olivine basalt through andesite and trachyte to rhyolite are all 10–11 million years old.

INTRODUCTION AND ACKNOWLEDGMENTS

The area of this report in the Park Range of Colorado lies along the Continental Divide from Buffalo Pass north into the southern half of the Mount Zirkel Wilderness (figs. 1, 2). The terrain is one of rugged mountains that have more than a mile of vertical relief. Drainage is by the headwaters of the Elk and Yampa Rivers on the west and by the North Platte River on the east. The area was covered by an icecap in the Pleistocene Epoch (Atwood, 1937). Vegetation ranges from prairie grassland at the lowest elevations through discontinuous successive zones of scrub oak, aspen, lodgepole pine, and spruce to alpine meadows above timberline.

Credit for the geologic mapping is given in figure 3. Snyder was in charge of the field mapping and field interpretation. Credit for the chemical, modal and semiquantitative spectrographic analyses is given in table 5. Carl E. Hedge was in charge of performing the radiometric measurements and interpretations. Zell E. Peterman gave assistance with a computer program for calculating the norms from the chemical analyses.

GENERAL GEOLOGY

The Park Range owes its topography and relief to tectonic uplift and to resistance to erosion of Precambrian crystalline rocks, mainly metavolcanic and metasedimentary felsic gneisses, amphibolites, and mica schists, and intrusive into them, quartz monzonites and granites with which this report is mainly concerned. The sillimanite-grade metamorphic rocks have been extensively folded and faulted during many episodes of deformation, but few of the structures have been accurately delineated or appraised, owing to the lack of detailed mapping and the paucity of regionally traceable stratigraphic units. In the central part of the area the intrusive rocks form an exposed pluton 7 miles wide and more than 17 miles long, whose major axis lies in a northeasterly direction, and several smaller bodies. The crystalline rocks are overlain by rare Paleozoic, extensive Mesozoic, and scattered Cenozoic continental and marine sediments, as well as by Pleistocene tills and outwash deposits (fig. 3).

All the bedrock units have been broken by faults. The Precambrian rocks in the southern part of the area have been mylonitized locally and displaced regionally along a pervasive series of northeast-trending shear zones (figs. 2, 3). The relative offset along various shears of this zone is mainly left lateral with minor right lateral movement as shown by drag of the contacts of two pelitic schist units and one quartz monzonite body and as shown by the offset of lithologic units including a series of vertical porphyry dikes perpendicular to the shear zone (porphyry dikes shown diagrammatically in fig. 9, not shown in fig. 3). The nonsymmetrical nature of the drag of the contacts of the pelitic schist of Soda Mountain demonstrates that movement on the different mylonite planes was episodic rather than simultaneous. For example, the extreme nonsymmetrical drag southwest of Soda Mountain shows that the south contact of the schist of Soda Mountain was not moving as a unit with the north contact. The south contact appears to have been drag folded in response to movements along the nearest shear zone southeast of the schist; whereas the north contact was dragged in response to earlier or later movements along the shear zones parallel to and intersecting the north contact. If all the drag has taken place without significant differential stretching of the folded units, the minimum amount of shearing movement needed to cause the dragged contacts would be roughly equal to the sum of the lengths of the short sides of the drag folds. Differential stretching might be counteracted by continuous sliding on fault planes without further drag. However, it is not possible to assess the relative importance of these opposite effects. Notwithstanding, it is interesting to compare the apparent displacement for different units, as in the following table:

Unit	Amount of apparent displacement	
	Left lateral (miles)	Right lateral (miles)
Porphyry dikes	0.4	0
Quartz monzonite augen gneiss of Buffalo Mountain	1.5	0.4
Schist and gneiss of Lake Dinosaur	4.2	0
Schist of Soda Mountain	8.7	1.9
Total[1]	14.8	2.3

[1] 12.5 miles effectively left lateral.

In this table the amount of displacement given for the vertical porphyry dikes and for the quartz monzonite augen gneiss of Buffalo Mountain is the amount of documentable apparent offset measurable along a fault plane; this must be a minimum as other offsets indicated by sheared porphyry dike inclusions within mylonite have not been estimated. In contrast, the amount of displacement given for the granodiorite and diorite and for the schist of Soda Mountain is mainly the sum of the lengths of the short limbs of their dragged contacts. Two factors are evident: (1) there is a positional or geographic effect — most of the minor right lateral sense of movement has taken place in the

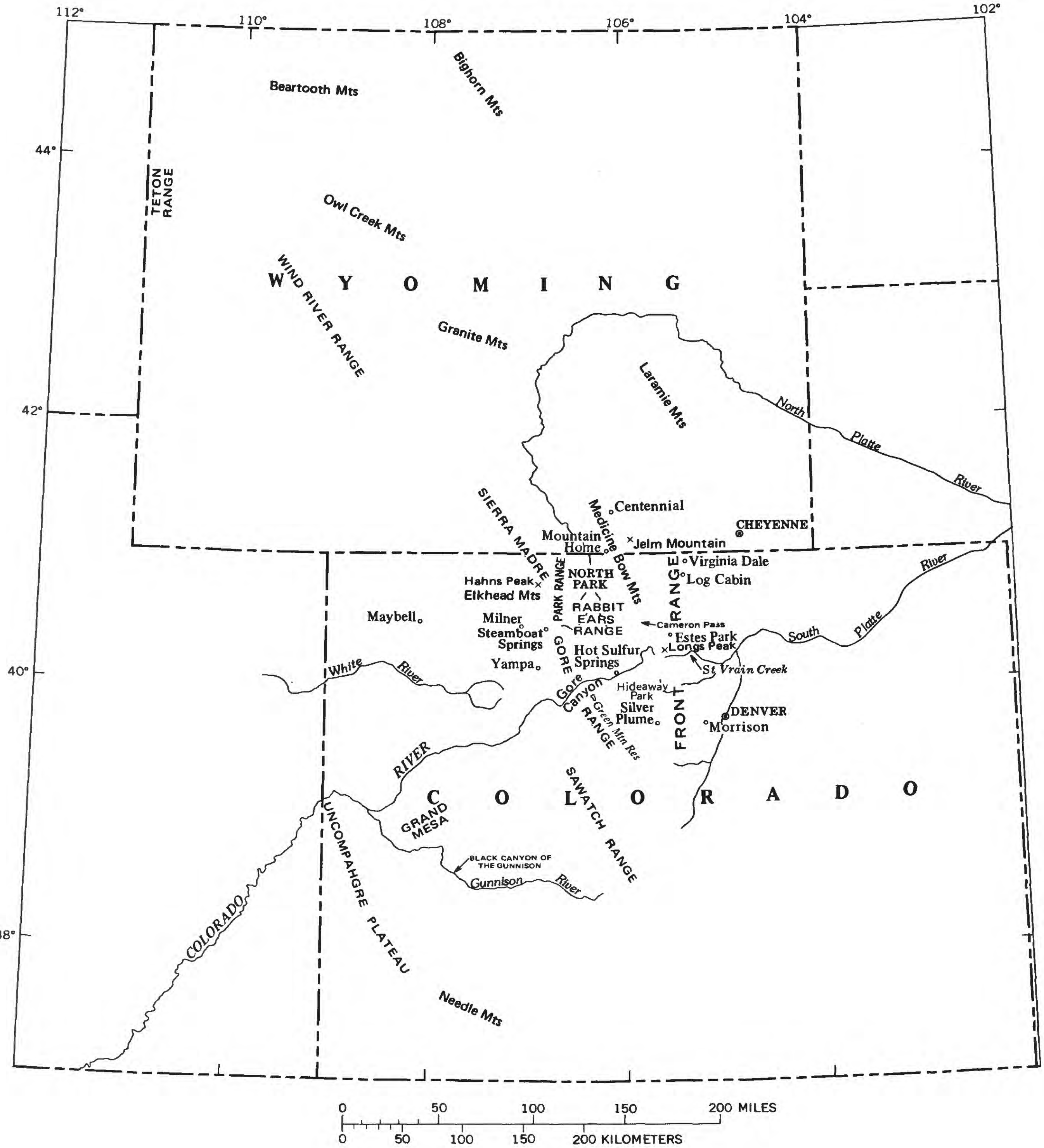


FIGURE 1. — Localities mentioned in text.

east-central and northeastern part of the zone; and (2) there may also be a time effect inasmuch as the porphyry dikes, which are the youngest because they cut the quartz monzonite augen gneiss of Buffalo Mountain and the schist of Soda Mountain, have been displaced least; the augen gneiss, which cuts the granodiorite and diorite and schist of Soda Mountain, is displaced more; and the latter two units are displaced most. The porph-

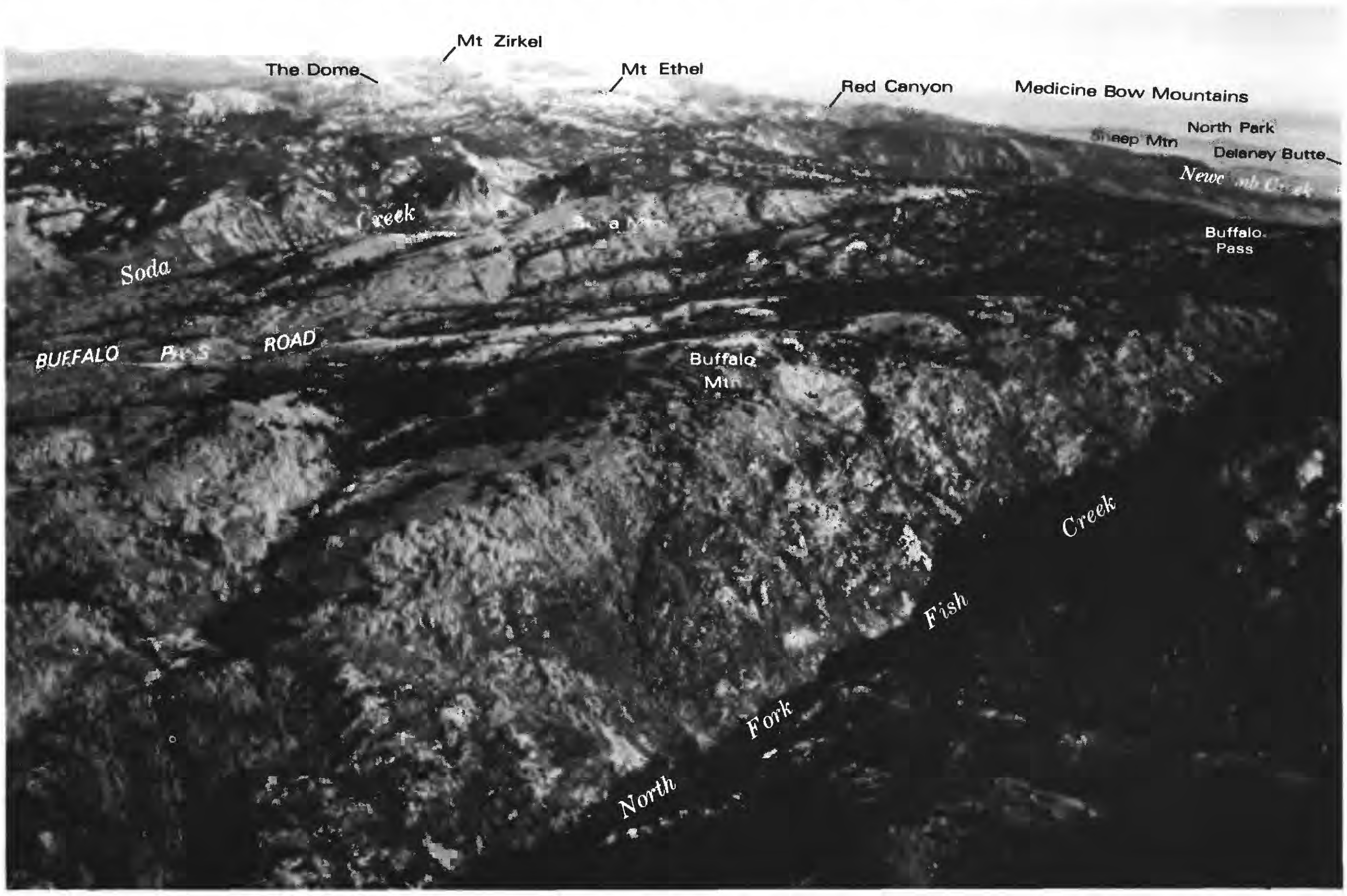


FIGURE 2. — View north-northeast from North Fork of Fish Creek to Mount Zirkel Wilderness. From foreground to middle distance the northeastward-striking alinement of the topography is controlled partly by northeastward-striking gneisses and schists and partly by northeastward-striking mylonites of the Soda Creek–Fish Creek mylonite zone. Rocks exposed in this zone are felsic gneisses, amphibolites, and mylonites along the north wall of the North Fork of Fish Creek, older sheared quartz monzonite of Buffalo Mountain complexly interlayered with other rocks on the plateau above Fish Creek, and pelitic schist on Soda Mountain. The rocks exposed beyond Soda Mountain to the snowy peaks of the Mount Zirkel Wilderness in the distance and also on Sheep Mountain are mainly unsheared granite and quartz monzonite of the younger Mount Ethel pluton.

yry dikes may in fact occupy extensional joints formed either actually or latently along planes about perpendicular to the fault movement direction during early shear movements. At any rate, the apparent cumulative effect of all the offsets in the Precambrian rocks is about 12.5 miles in a left lateral sense.

Faulting was renewed in this area at the close of the Mesozoic, was continued through the Eocene, and was renewed yet again at the end of the Miocene. All Mesozoic and Eocene formations are found faulted against the Precambrian generally along steep to shallow east-dipping thrusts on the west side of the Park Range and along steep west-dipping reverse faults on the east side of the range. Near the heads of Soda Creek and Newcomb Creek, north and northeast of Buffalo Pass, Mesozoic fault movement characterized by brecciation has taken place along the old Precambrian mylonite zones previously described. Breccia is also present along other faults cutting only Precambrian rocks and may represent post-Mesozoic movement, but this is difficult to prove in the absence of transected Mesozoic rocks in contact with the faults. (Farther south brecciation related to northeast-trending shear zones has been related to late Precambrian time (Tweto and Sims, 1963, p. 991, 1006).) Many nonfaulted contacts between lowermost Paleozoic or Triassic rocks and Precambrian rocks exist, and several large and small synclines of mantling sediments are present within the area of Precambrian rocks forming the Park Range; the largest one extends from Big Creek to Hinman Park. Post-Miocene faults are documented in the southwest, northwest, and northeast corners of the area. In the southwest and northwest the Browns Park Formation has been offset as much as 1,000 feet; in the northeast post-Miocene fluorite veins (Steven, 1957, p. 337; 1960, p. 376, 397; Hail, 1965, p. 118) have been emplaced along some of the youngest faults. The northeastern fault that is shown extending east out of the area south of Roaring Fork is probably continuous with the post-Miocene Spring Creek fault of Kinney (Behrendt and others, 1969, p. 1525, figs. 1, 2; Behrendt and Popenoe, 1969, fig. 2). In addition, abundant conglomerates and unconformities in the Mesozoic and Tertiary stratigraphic section show that the Park Range was a positive area subject to repeated upwarpings during the Mesozoic and Tertiary. Other times of faulting for which there is no direct evidence here have been documented just outside of this area.

PRECAMBRIAN INTRUSIVE ROCKS

The Precambrian intrusive rocks in this part of the Park Range fall naturally into five or more variants of one large complex body and four groups of smaller bodies. Textures of the more felsic representatives tend to be hypidiomorphic-granular or gneissic-granular, whereas many of the more mafic rocks are diabasic; rocks of any composition may be porphyritic (table 6). The rock groups are described below in order of their areal importance because it is not possible to be certain of the exact time relations either among all the groups or among all the variants within each group. After the section on radiometric ages, the present state of geochronologic knowledge, including both critical field relations and new radiometric data, is summarized.

A complex, elongate batholith, here called the Mount Ethel pluton, dominates the area of exposed Precambrian rocks; it extends from the west flank of the range north of Copper Ridge northeasterly for 15–19 miles and disappears beneath the Mesozoic and Tertiary rocks of North Park. It reappears in North Park on Delaney Butte and Sheep Mountain (fig. 2) (Hail, 1965, pls. 2, 3). A similar appearing granitic intrusive has been mapped in detail by Steven (1954, 1957, 1960) beyond the northeast corner of North Park in the Medicine Bow Mountains. On the basis of geophysical measurements, Behrendt, Popenoe, and Mattick (1969, p. 1523) speculated that the Mount Ethel pluton "probably extends northeast beneath the North Park basin and connects with granitic rocks in the Medicine Bow Range." If this is true, the Mount Ethel pluton would be 6–7 miles wide by about 40 miles long. This report will be concerned mainly with the segment within the Park Range.

The four groups of smaller Precambrian intrusive bodies are as follows:

1. A small pluton extending about 10 miles through Buffalo Mountain across Buffalo Pass to the east margin of the range, here called the Buffalo Pass pluton, and numerous tiny separate intrusives most of which are within 2 miles of the Buffalo Pass pluton.
2. Fine-grained porphyry dikes, too small to be resolved in figure 3, but located diagrammatically in figure 9.
3. Pegmatites, coarse-grained granitic intrusives, also shown in figure 9.
4. Medium- to coarse-grained mafic and ultramafic intrusive bodies, several of which are shown in figure 9.

Uppermost Miocene or Pliocene (post-Browns Park) intrusive rocks occur locally as thin dikes or sills only in the northwest quarter of this area but are not mapped separately for this report. These rocks are all fine grained, locally glassy or porphyritic, and intermediate in composition (tables 4, 5, 6). All are on the eastern fringe of, and should be considered part of, the Elkhead Mountain eruptive field (fig. 15).

MOUNT ETHEL PLUTON

Rocks of the Mount Ethel pluton are remarkably homogeneous and generally sparsely jointed, and form prominent ledges, canyon walls or cirque headwalls (fig. 4) where the topography is steep, or form large rounded bosses or tors where the terrain is gentler. Quartz, pink and white feldspar, and biotite are visible in all hand specimens, and hornblende and muscovite were observed locally. Except for isolated flat-topped nunataks (a good example is shown in fig. 5*B*), all the area within the Mount Ethel pluton has been glaciated, and the plutonic rocks have contributed numerous large joint-block erratics to the glacial tills lying beyond the boundaries of the pluton itself.

The outer contact of the pluton against its country rocks generally is planar or slightly curved and dips outward at 80°–90°. Complex convolutions or reentrants are present locally, as along the southeast side of the pluton from the head of Soda Creek to the head of Newcomb Creek. Many excellent exposures demonstrate the persistence of this steep dip along many miles of contact and in varied topography (fig. 5). Where the contact is convoluted, however, it is irregularly oriented and shows inclusion or apophysis walls dipping from 0°–90° or changing from one to the other within a few hundred feet. Flow structures within the pluton are generally fairly steep but are less prominent in the center of the pluton than near the contact.

On the basis of magnetic and gravity anomalies and gradients over the Mount Ethel pluton along the Continental Divide, Behrendt, Popenoe, and Mattick (1969, p. 1532, 1533, fig. 6) have postulated a thick platelike pluton whose contacts dip gently outward. This structural interpretation is not supported by the field facts. Figure 3 shows the line of their profile *A–A'*. This profile crosses the northern contact east of Pristine Lake where their interpretive cross section shows a

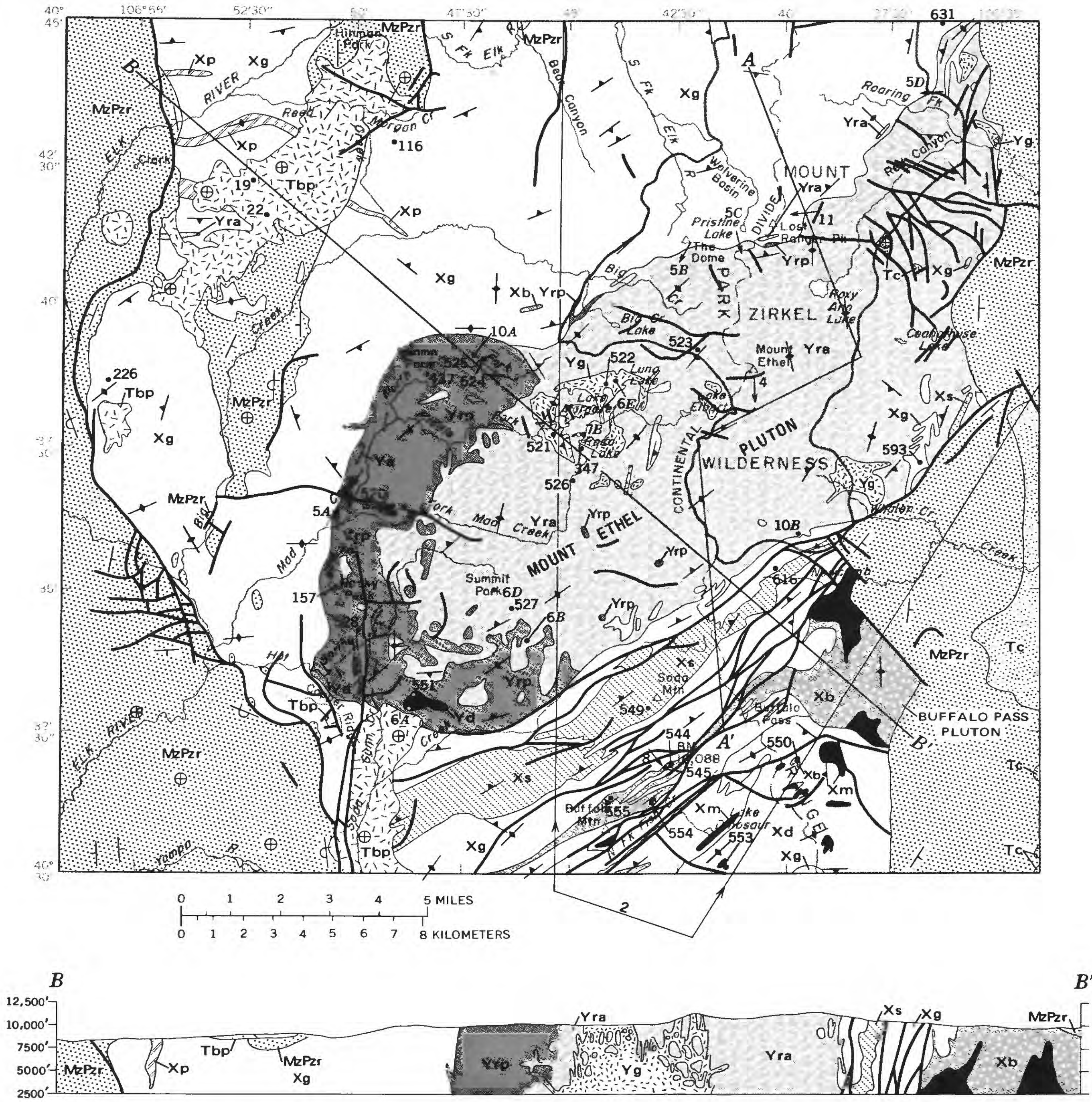
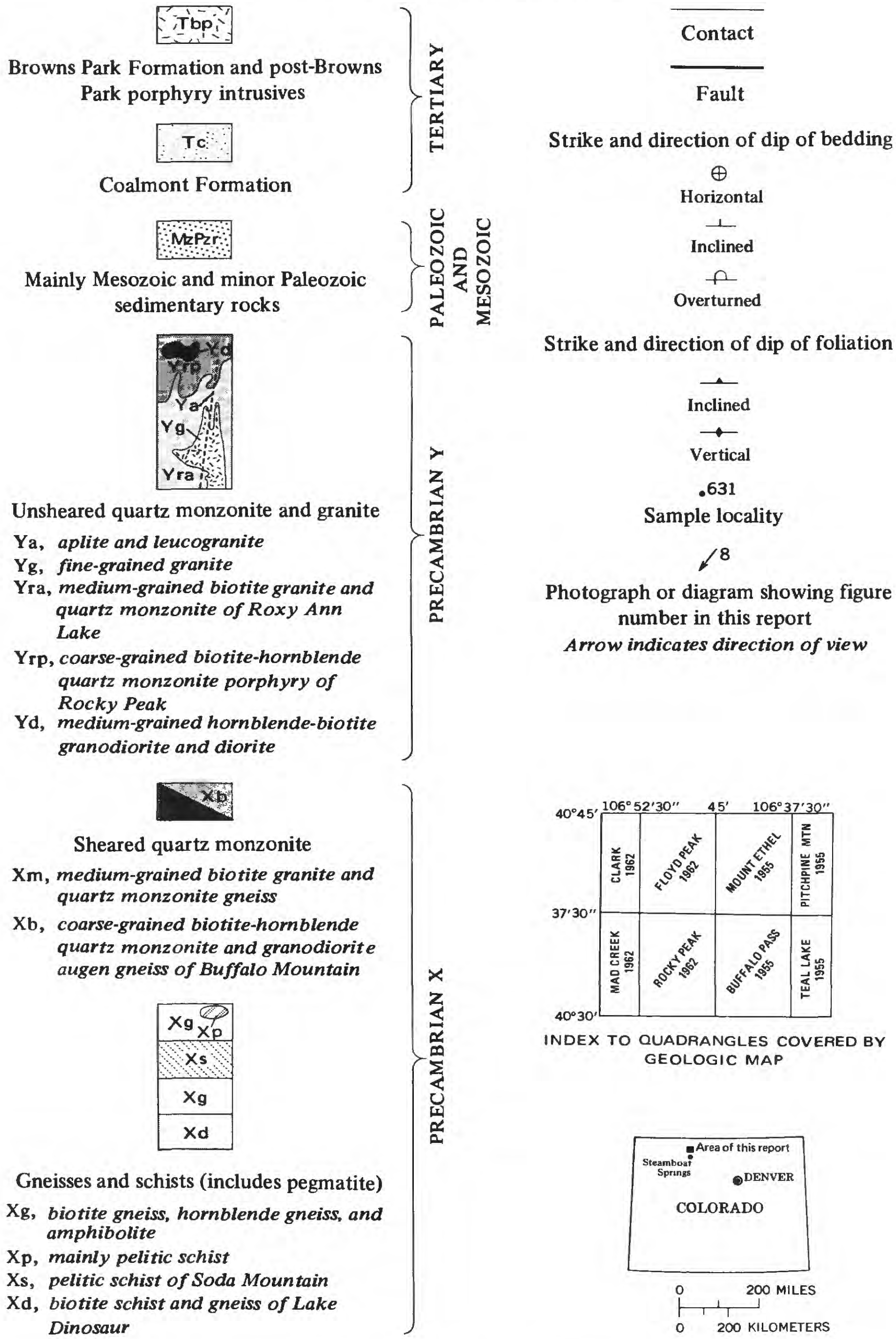


FIGURE 3. — Geologic map and section of part of the northern Park Range, Colorado. Section *A—A′* is the line of profile used by Behrendt, Popenoe, and Mattick (1969, pl. 1). Geology is mainly by George L. Snyder, 1965–67 and 1975, Warren B. Hamilton, 1965, Fredric Hoffman, 1966, and Ronald L. Bonewitz, 1967. Mesozoic and younger geology along the east margin of the map is mainly from W. J. Hail, Jr. (1965, 1968).

contact dipping 35° outward for about 1 mile and then 80° outward for about 2 miles; the profile crosses the southern contact northeast of Soda Mountain where they show a contact dipping 10° outward for about 1 mile and then 70° outward for another 1½ miles. The upper shallow-dipping part of the postulated contact probably is incorrect for the following reasons:

1. The profile, intended to be nearly perpendicular to the map trace of the contact, makes an angle of 35° with the trace of the northern contact;

EXPLANATION



2. The southern contact is intensely convoluted where the profile crosses it; large inclusions of country rock lie just inside the contact and large granitic apophyses occur just outside of it;
3. Within a distance of half a mile outside the northern contact very large pegmatites constitute as much as half the volume of the amphibolitic country rock (figs. 5C, 11);
4. The southern end of the profile crosses a completely different body of granitic rocks, which may expand tremendously in volume within a few miles beneath the surface.

All the above observations were not known to Behrendt, Popenoe, and Mattick, and so a new interpretation of the geophysical data can now be made.

Five mappable variants occur within the Mount

FIGURE 4.—View south from summit of Mount Ethel showing typical granite and quartz monzonite exposed in cirque headwall in center of Mount Ethel pluton. Scale shown by man (arrow).

Ethel pluton. All of these variants possess knife-sharp contacts against other internal variants of the pluton. Invariably, these contacts give clear, unambiguous evidence that one variant originally was solid and one liquid and that one was older and one younger. Furthermore, these relations are consistent from area to area. Figure 6 shows typical observed internal contact relations. Despite these clear liquid-solid relationships and the time span implied for the cooling of at least five magmatic variants, no thin, chilled contact margins of one variant against another have been observed (but see the discussion on p. 13), and contact hornfelses are very rare. Apparently, the temperature of the entire region was elevated throughout the intrusion of the Mount Ethel pluton. Reaction rims exist around granitic inclusions but are rare. Local margins of hornblende- or biotite-rich rock at the edges of inclusions indicate that felsic constituents have been selectively removed and added to the magma in contact with the inclusion. The rarity of these margins may indicate that either most inclusions did not form reaction rims or they were not being selectively dissolved at this level of the magma chamber. Flow structures, alined platy feldspar phenocrysts or tabular inclusions, are prominent in some variants of the Mount Ethel pluton and are rare in others (fig. 7). The time trend of composition is from mafic to felsic. The five variants, in order of age from oldest to youngest, are granodiorite and diorite, quartz monzonite porphyry of Rocky Peak, quartz monzonite of Roxy Ann Lake, granite and quartz monzonite, and leucogranite. They are described in this order.

GRANODIORITE AND DIORITE

The granodiorite and diorite unit, the oldest recognized variant of the Mount Ethel pluton, consists of uniform tough dark-gray medium-grained subdiabasic hornblende-biotite granodiorite and diorite. The rocks of this unit always occur as inclusions in younger units, never demonstrably in their original position of solidification and never in contact with the metamorphic country rocks. The granodiorite inclusions are contained in or cut by the quartz monzonite porphyry of Rocky Peak, the biotite granite and quartz monzonite of Roxy Ann Lake, and the aplite and leucogranite in the southwest corner of the pluton and are contained in a small stock of fine-grained granite in the northeast corner of the pluton. The one inclusion large enough to show in figure 3 occurs in the Gunn Creek drainage in the southwest corner of the pluton and is completely surrounded by quartz monzonite porphyry of Rocky Peak. This inclusion measures about one-third of a mile wide by 1 mile long, and it is cut by a few narrow dikes of the quartz monzonite porphyry of Rocky Peak (fig. 6*A*) and the granite and quartz monzonite of Roxy Ann Lake. An irregular zone, as much as 1 mile wide, of the quartz monzonite porphyry of Rocky Peak around this large inclusion has a higher proportion of hornblende than is normal for the porphyry elsewhere.

QUARTZ MONZONITE PORPHYRY OF ROCKY PEAK

The quartz monzonite porphyry of Rocky Peak consists of uniform, red and reddish-gray, medium- to coarse-grained granular biotite-hornblende quartz monzonite containing tabular euhedral microcline phenocrysts as much as several inches long (fig. 7*A*). It is exposed in boss and tor topography and locally weathers to granule-covered grüs knobs. This porphyry forms the southwest, west, and, locally, the north contact of the Mount Ethel pluton and is distributed as an irregular 2-mile-thick carapace on the west end of the pluton. The quartz monzonite porphyry is included in and intruded by dikes and complex apophyses of the quartz monzonite of Roxy Ann Lake (figs. 6*B*, 6*E*) and by dikes of leucogranite and fine-grained granite. The contact between the quartz monzonite porphyry of Rocky Peak and the granite and quartz monzonite of Roxy Ann Lake is particularly irregular with apophyses of the latter being found in the former as much as 1 mile from the main contact and with inclusions of the former found as much as 3 miles into the latter. The quartz monzonite porphyry of Rocky Peak rarely comes

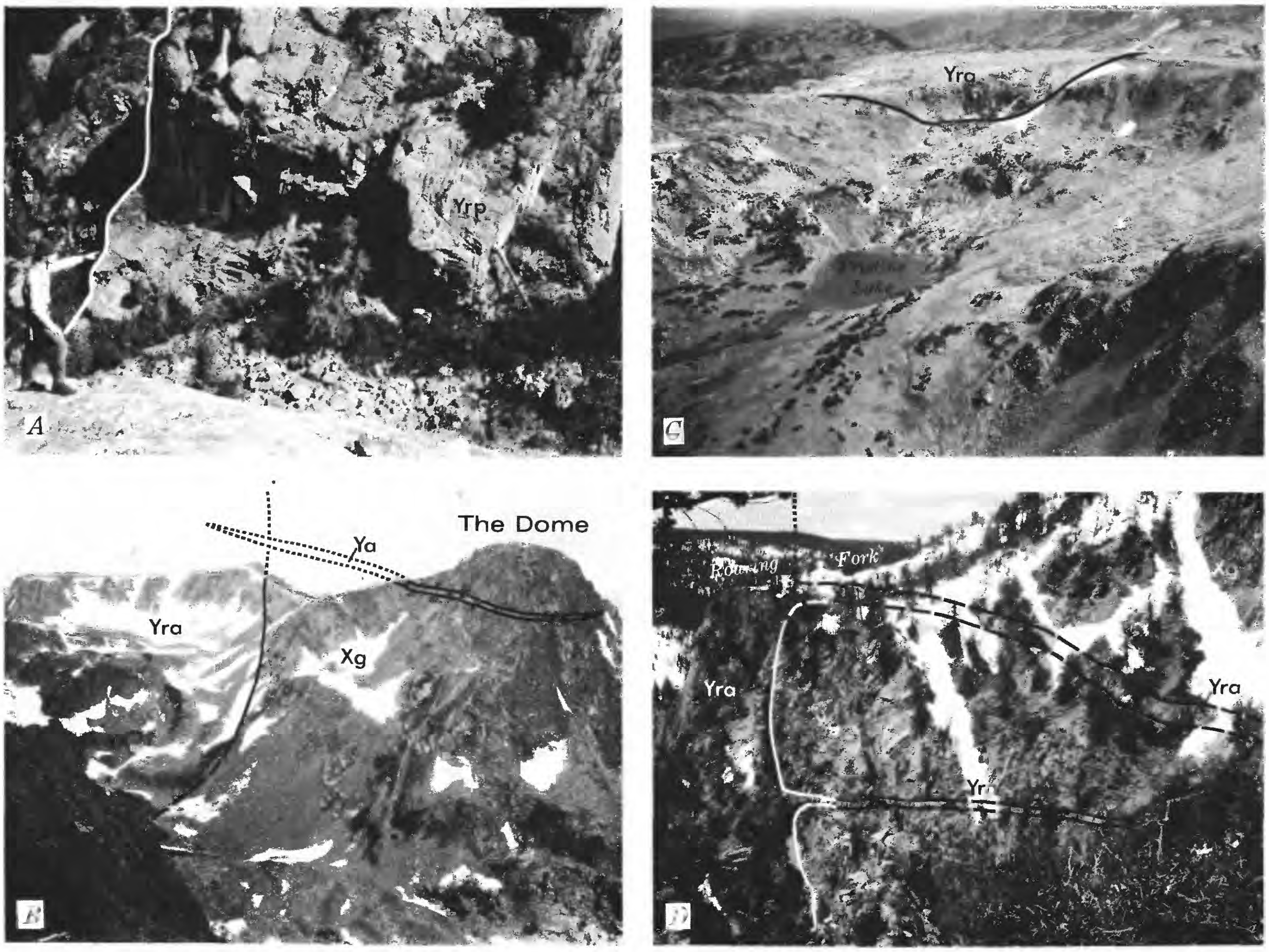


FIGURE 5.—Orientation of the contact between the Mount Ethel pluton and its country rocks.

A. Geologist pointing to contact between quartz monzonite porphyry of Rocky Peak (Yrp) and interlayered amphibolite and felsic biotite gneiss (Xg) north of the South Fork of Mad Creek just east of where it joins Mad Creek. Contact, at extended finger, is nearly vertical or steeply outward dipping (85° in nearby stream exposure). Country rocks to left of finger dip shallower than contact. Quartz monzonite porphyry to right of finger is relatively homogeneous but has flow structure parallel to the contact and is *not* composed of alternating mafic and felsic layers as it might appear from the drip stains on the vertical cliffs.

B. Contact between layered amphibolite (Xg) and quartz monzonite of Roxy Ann Lake (Yra) exposed on the southeast side of The Dome. Contact dips about 80° outward. An aplitic apophysis (Ya) high on The Dome cuts the amphibolite layering at a shallow angle.

C. Looking south from the head of Wolverine Basin across interlayered amphibolite (Xg) and pegmatite to a contact with quartz monzonite of Roxy Ann Lake (Yra) that just cuts into the head of the glacial cirque above Pristine Lake. Trace of the contact across the cirque headwall is indicative of its steep dip. White outcrops to left of Pristine Lake are pegmatite.

D. Looking west at contact between quartz monzonite of Roxy Ann Lake (Yra) and hornblende gneiss (Xg) on the north side of Roaring Fork of Red Canyon. Contact, which is here about perpendicular to the layering of the hornblende gneiss (not prominent in photograph), dips 85° outward. Two nearly horizontal quartz monzonite apophyses (Yra) cut the hornblende gneiss.

in contact with the fine-grained granite found mainly west of Luna Lake. However, it is possible that some of the smaller detached dikes mapped as the Roxy Ann Lake unit are really misidentified fine-grained granite. Because of the abundance of microcline phenocrysts and the contrast in size between them and their groundmass, flow structures, generally nearly vertical, are prominent everywhere within the quartz monzonite of Rocky Peak (figs. 5*A*, 6*A*, 6*B*, 6*C*, 7*A*). Although most of the few granodiorite inclusions are in the quartz monzonite porphyry of Rocky Peak, the latter unit contains very few inclusions of metamorphic country rock

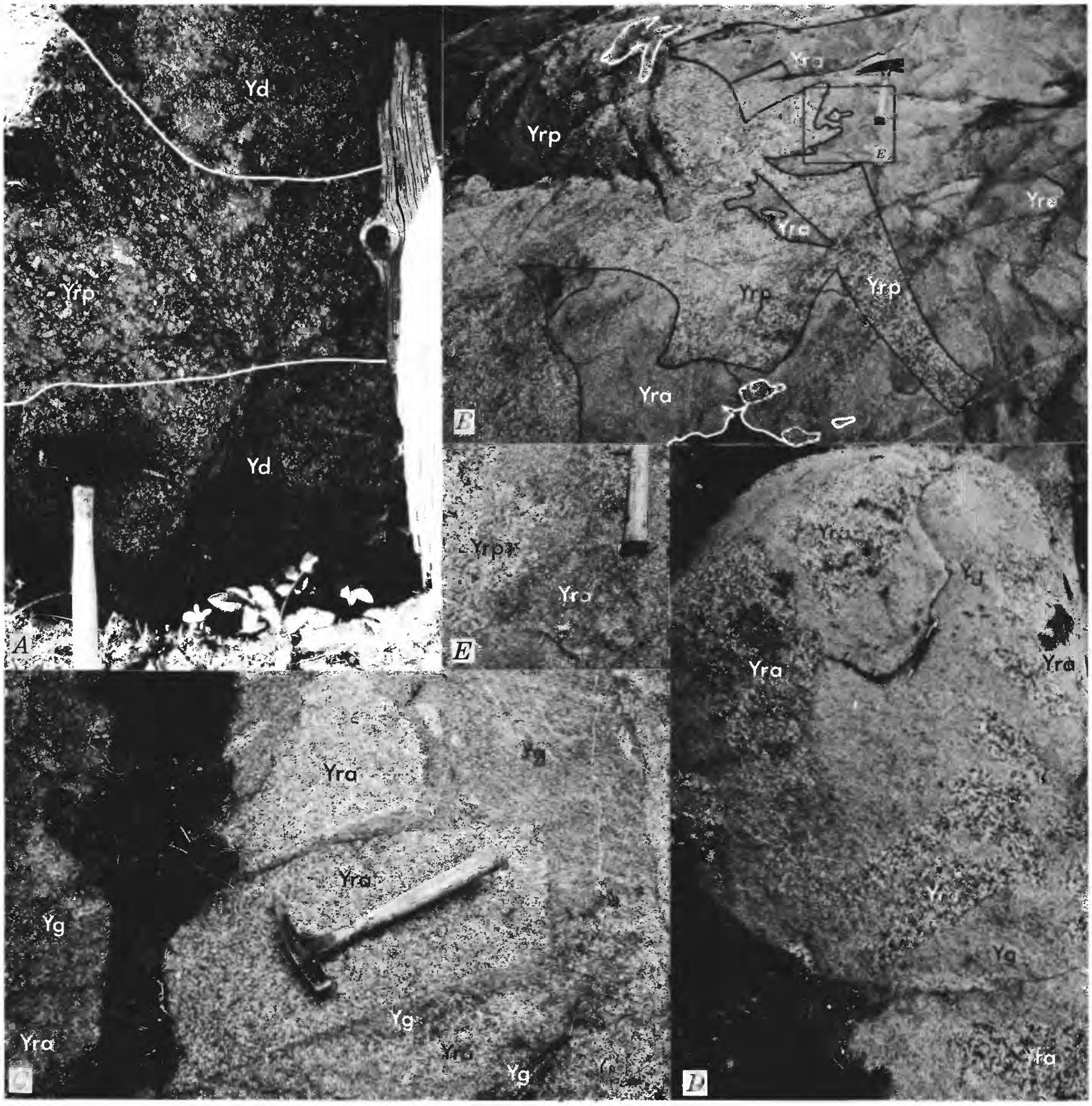


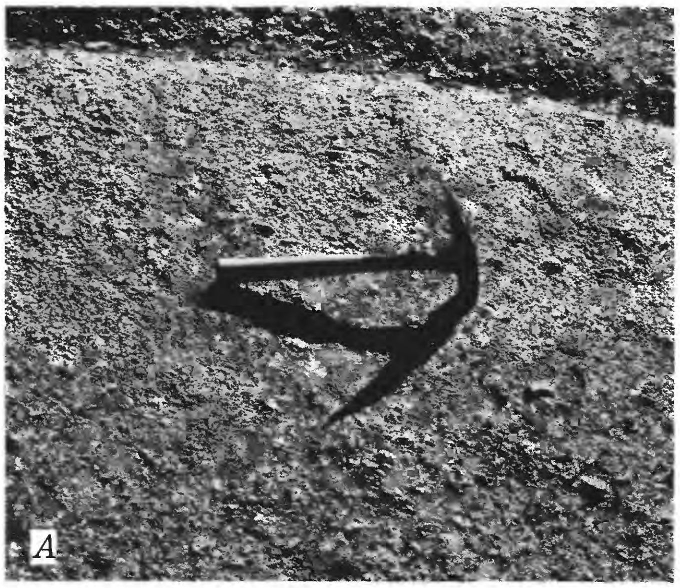
FIGURE 6. — Contact relationships within the Mount Ethel pluton.

A. Dike of quartz monzonite porphyry of Rocky Peak (Yrp) cutting tonalite along the western contact of the granodiorite (Yd) in the north fork of Gunn Creek. Large, fluidally arranged microcline phenocrysts in quartz monzonite porphyry are parallel to dike contacts.

B,E. Irregular contact at 9,400-foot elevation in the east fork of Gunn Creek where fine-grained quartz monzonite of Roxy Ann Lake (Yra) intrudes coarse-grained quartz monzonite porphyry of Rocky Peak (Yrp). Prominent foliation of quartz monzonite porphyry (Yrp) is truncated at contact and quartz monzonite of Roxy Ann Lake (Yra) contains local large microcline xenocrysts.

C. Closeup of dike contact at 10,040-foot elevation on west side of Summit Park near head of Hot Spring Creek. Very fine grained granite dike (Yg) intrudes fine-grained quartz monzonite of Roxy Ann Lake (Yra).

D. Inclusion swarm of medium-grained quartz monzonite of Roxy Ann Lake (Yra) in fine-grained granite body (Yg) from 10,500-foot elevation half a mile northwest of the west end of Luna Lake.



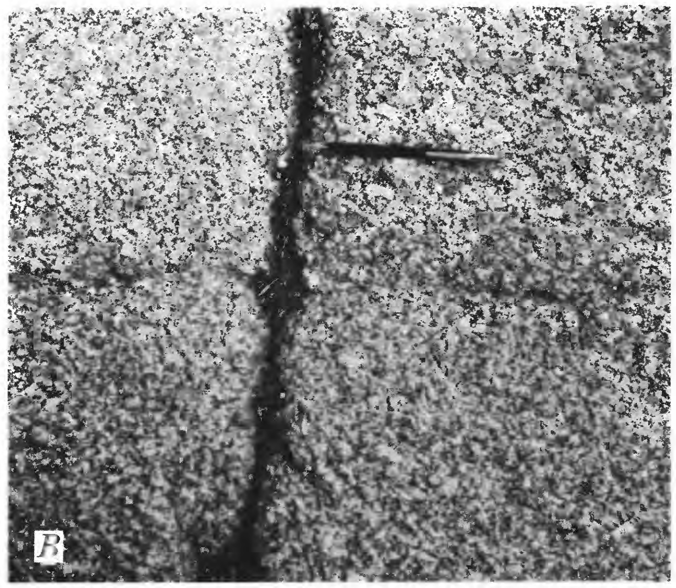


FIGURE 7. — Igneous flow structure in Mount Ethel plutonic rocks.

A. Typically excellent flow structure in quartz monzonite porphyry of Rocky Peak near outer contact of pluton three-fourths of a mile north-northwest of Rocky Peak. Foliation plane, shown by large microcline phenocrysts raised above the general rock surface by weathering, is parallel to plane of hammer (as well as parallel to contact plane not shown).

B. Flow structure in quartz monzonite of Roxy Ann Lake in outcrop at 10,480-foot elevation on ridge east of Rosa Lake in the southwest corner of the Mount Ethel quadrangle. Foliation as shown by orientation of sparse large feldspar crystals is parallel to pencil. Although this foliation example is exceptionally good for the quartz monzonite of Roxy Ann Lake, it is still distinctly less pronounced than that typical for the quartz monzonite porphyry of Rocky Peak.

and only a few dikes of the quartz monzonite porphyry penetrate country rock. This contrasts with the Roxy Ann Lake unit and may indicate that, while the latter was emplaced largely by piecemeal stoping of relatively small blocks, the porphyry was emplaced largely by block-caving or cauldron subsidence of relatively large blocks.

QUARTZ MONZONITE OF ROXY ANN LAKE

The quartz monzonite of Roxy Ann Lake is the most extensive variant of the Mount Ethel pluton and occupies nearly the entire width of the pluton throughout much of its length. This variant is intruded by numerous dikes and small plutons of fine-grained granite and by rare dikes of leucogranite. The rocks are gray to reddish-gray, fine-, medium-, and coarse-grained granular biotite granite and quartz monzonite with rare to very rare tabular euhedral phenocrysts of microcline as much as twice the size of the groundmass minerals. Because of the scarcity of large phenocrysts, flow foliation is generally difficult to discern, but in the best exposures (for example, fig. 7*B*) vertical flow foliation is visible. The quartz monzonite of Roxy Ann Lake commonly is exposed in fresh roches moutonnees. In Red Canyon, however, where the rocks have been broken by Tertiary faults and have been extensively mineralized and altered, hematitic grüssy badland cliffs predominate. The grain size of the quartz monzonite of Roxy Ann Lake increases gradually from west to east in the western one-fourth or one-third of its area and then is fairly uniform throughout the rest of the pluton. Apophyses of this quartz monzonite unit cutting the western carapace of the quartz monzonite porphyry of Rocky Peak are generally fine grained; the west-central area of this unit (from Soda Creek to the South, Middle, and North Forks of Mad Creek) is generally medium grained, whereas north of Luna Lake and east of the Continental Divide the unit tends to be coarser grained. Compare rocks of the unit in figures 6*B*, 6*C*, and 6*E* from the western part of the area with those in figure 7*B* from somewhat farther east and, in turn, with rocks in figure 6*D* still farther east. This decrease in grain size westward may result from cooling by the large masses of porphyry and gneiss included within the western part of the quartz monzonite unit. There are a few areas both east and west of the Continental Divide near the southern margin of the pluton where the quartz monzonite of Roxy Ann Lake may be a multiple or composite unit. Here, several outcrops display sharp contacts between a coarse-grained and a medium-grained variant, and it is possible that another small pluton exists here, perhaps equivalent to the fine-grained granite. However, it has not been possible to map such a pluton.

FINE-GRAINED GRANITE

Pinkish-white to pinkish-gray fine-grained granite forms many dikes and small plutons in the area between Lake Margaret and Luna Lake, in the Whalen Creek area, and in the northeast corner of the Mount Ethel pluton. As was mentioned previously, some of the rocks of this unit may be mistakenly mapped as quartz monzonite of Roxy Ann Lake. The cluster of dikes and small plutons in the Lake Margaret–Luna Lake area suggests that the present level of erosion may be just above the top of a single roughly cylindrical stock about 3 miles in diameter (fig. 3, sec. *A–A'*). This granite is the youngest widespread variant of the Mount Ethel pluton and is cut only by rare dikes of leucogranite.

LEUCOGRANITE

Pink aplite and fine-grained leucogranite form the youngest, but areally minor, variant of the Mount Ethel pluton. This variant is best developed as a series of north-trending dikes as much as several tens of yards wide and 1 mile long in the southwestern corner of the pluton. A few other dikes of it occur along the northwest margin and in the eastern part of the pluton.

BUFFALO PASS PLUTON

The Buffalo Pass and smaller related plutons consist of two mappable variants: The areally most important one is well exposed on and near Buffalo Mountain (figs. 2, 8) and will henceforth be referred to as the quartz monzonite and granodiorite augen gneiss of Buffalo Mountain; the other is a medium-grained equigranular quartz monzonite gneiss present in some of the less well exposed parts of the Buffalo Pass pluton and in most of the smaller plutons, especially those intruding the biotite schist and gneiss of Lake Dinosaur.

The field relations are suggestive but not conclusive concerning both internal and external age relations of the Buffalo Pass pluton. The augen gneiss of Buffalo Mountain and its accompanying equigranular quartz monzonite gneiss crop out close to each other in several areas, mainly in forested grüssy areas at low altitudes, but have not been seen in contact in outcrop or in glacial boulders. So far as is known no rocks of the Buffalo Pass pluton contact any rocks of the Mount Ethel pluton. Therefore, any tentative field conclusions as to the internal or external relative ages of the variants of the Buffalo Pass pluton must rely on indirect evidence. The several varieties of such evidence follow.

1. The quartz monzonite and granodiorite augen gneiss of Buffalo Mountain is compositionally very similar to the quartz monzonite porphyry of Rocky Peak; the equigranular quartz monzonite variant of the Buffalo Pass pluton is compositionally very similar to the quartz monzonite of Roxy Ann Lake. The main difference in hand specimens between these formations is textural, not compositional. The different variants of the Mount Ethel pluton have cooled from an undisturbed melt; they have relict igneous textures and flow structures (fig. 7) and euhedral phenocrysts. The different variants of the Buffalo Pass and smaller related plutons, however, completed their crystallization in a tectonic and high-grade metamorphic environment; they have gneissic textures with anhedral augen.

2. The fine-grained porphyry dikes at first glance appear to be the youngest Precambrian rocks. Some of these rocks, which will be described in more detail in the next section, cut most of the major Precambrian units including the Mount Ethel pluton (fig. 10*A*) and the Buffalo Pass pluton (fig. 8). But incontrovertible evidence has been discovered (fig. 10*B*) that some porphyry dikes are older than some Mount Ethel rocks. The northerly orientation of the Newcomb Creek porphyry dike cut by the quartz monzonite of Roxy Ann Lake is similar to the north-northwesterly orientation of the whole porphyry dike series within the Soda Creek–Fish Creek mylonite zone, several of which cut the augen gneiss of Buffalo Mountain (figs. 8, 9). If all dikes of similar orientation in this area were intruded at the same time, the largest part of the Mount Ethel pluton would clearly be younger than the largest part of the Buffalo Pass pluton. In this connection it is interesting that Steven (1957, 1960) in the Northgate area (northeast of the area in this report) mapped north-northwesterly trending dacite porphyry dikes short segments of which are "found in xenoliths in the intrusive quartz monzonite stock" (probably equivalent to the quartz monzonite of Roxy Ann Lake) and "are definitely older than the enclosing granitic rock" (Steven, 1957, p. M364, pl. 48; 1960, p. 333, pl. 12). It is even more interesting that the radiometric ages to be described later are significantly older for the Buffalo Pass pluton than for the Mount Ethel pluton.

FIGURE 8.—Quartz monzonite and granodiorite augen gneiss of Buffalo Mountain cut by a dark fine-grained quartz latite dike. West (right) contact of 5-foot-wide dike dips 65° W. in foreground; east contact of dike exposed in next outcrop on strike uphill. Dike can be traced with minor offsets 2,000 feet up this hill and down the other side to one of the main Fish Creek mylonite zones where it is truncated and disappears. Behind camera, dike can be traced 1,000 feet with minor offsets to another mylonite zone in a fork of Soda Creek where it is offset 1,200 feet in a left lateral direction. Vehicle in background is parked on Buffalo Pass road near BM 10088.

QUARTZ MONZONITE AND GRANODIORITE AUGEN GNEISS OF BUFFALO MOUNTAIN

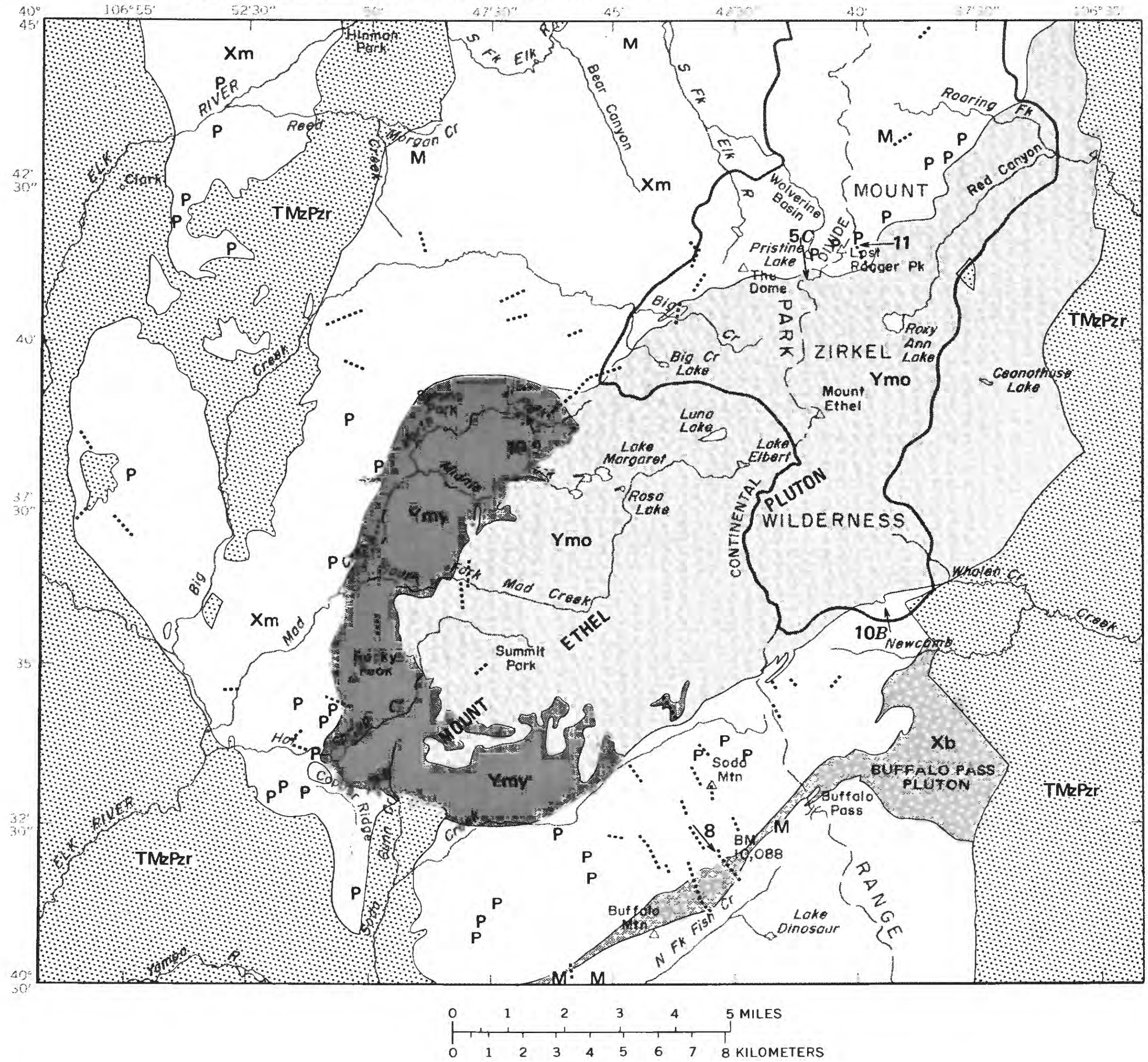
The largest unit of the Buffalo Pass and related plutons is the quartz monzonite augen gneiss of Buffalo Mountain, a unit consisting of uniform, red and reddish-gray, medium- to coarse-grained biotite quartz monzonite containing anhedral microcline augen as much as several inches long. Its texture is gneissic granular indicating that it has been extensively sheared and recrystallized during and after its emplacement; subsequently, several portions of the unit west of Buffalo Pass have also been severely mylonitized or crushed without recrystallization. The rock is quite distinct from the interlayered felsic biotite gneiss and amphibolite country rock, but, where its microcline augen are small, it may resemble the accompanying equigranular quartz monzonite. The map pattern of the unit clearly indicates an intrusive origin, particularly on and east of Buffalo Mountain where the unit splits into three or more layers interleaved with the felsic biotite gneiss and amphibolite country rock and east of Buffalo Pass where the unit truncates the boundary between the biotite schist and gneiss of Lake Dinosaur and the biotite gneiss, hornblende gneiss, and amphibolite.

EQUIGRANULAR QUARTZ MONZONITE GNEISS

Accompanying the quartz monzonite and granodiorite augen gneiss of Buffalo Mountain in the Buffalo Pass and related plutons is a gray medium-grained equigranular biotite granite and quartz monzonite gneiss. Although the augen gneiss seems to occur as larger bodies and the equigranular gneiss as smaller ones, the two are closely associated in several areas. Unfortunately, in all these areas exposures are so poor that it is not known whether their contacts are gradational or abrupt.

FINE-GRAINED PORPHYRY DIKES

Although the bodies of this unit are too small to be shown to scale on the geologic map of figure 3, their positions and orientations have been diagrammed in figure 9. The rocks consist of light-gray to dark-gray to black, fine-grained, hypabyssal, near-vertical dikes with sparse hornblende or feldspar phenocrysts, usually flow alined with the margins of the dikes. Hand specimens show little metamorphic recrystallization. The dikes are usually planar and range from a few feet to several tens of feet wide and several hundred feet to 1 mile long. One dike (table 5, sample 549), on the south side near the top of Soda Mountain, measures 300 feet wide by 1,000 feet long and is coarser grained than normal and diabasic in texture. Because some of the fine-grained porphyry dikes cut the quartz monzonite of Roxy Ann Lake (fig. 9) and others are cut by it (fig. 10*B*), either two ages of quartz monzonite of Roxy Ann Lake or two ages of porphyry dikes exist. Because the quartz monzonite of Roxy Ann Lake is a much more homogeneous rock unit than the porphyry dikes and is areally self contained, it seems more likely that there are two ages of porphyry dikes even though these cannot yet be distinguished. Figure 9 provides some slight additional justification for this position. Two groups of porphyry dikes may be discernible on the basis of their geographic position and orientation. One group located within or near the Soda Creek–Fish Creek mylonite zone is oriented mainly northwesterly. One of these is clearly intruded by the quartz monzonite of Roxy Ann Lake of the Mount Ethel pluton (fig. 10*B*) and others are believed to be. Several of the dikes are offset by the mylonite zones. (See the table on p. 2.) The other group of dikes, less areally localized than the previous group, nevertheless, appears mainly in the northwest half of the map and is concentrated near the northwest corner of the Mount Ethel pluton. The trends of the dikes of the latter group range from north through northeast to east. Several of these clearly cut the quartz monzonite porphyry of Rocky Peak (fig. 10*A*), and the quartz



EXPLANATION

TMzPzr	Tertiary porphyry intrusives and Tertiary, Mesozoic, and Paleozoic sedimentary rocks
Ymy	Younger Precambrian Y rocks of Mount Ethel pluton
Ymo	Older Precambrian Y rocks of Mount Ethel pluton
Xb	Precambrian X rocks of Buffalo Pass pluton
Xm	Precambrian X metamorphic wallrocks

——— Contact

········ Strike of thin, nearly vertical, fine-grained porphyry dikes

P Pegmatite

M Small ultramafic intrusive

↖10A Locality of a figure indicated by its number—Arrow indicates direction of view

FIGURE 9.—Simplified geologic map of part of the northern Park Range showing location and orientation of near-vertical fine-grained porphyry dikes and location of some pegmatites and ultramafic intrusives.

monzonite of Roxy Ann Lake and others are believed to do so.

How fine-grained dikes could be intruded both before and after the emplacement of a coarse-grained batholith poses a problem. The older northwest-trending dikes resemble the younger northeast-trending dikes in degree of crystallinity; therefore, the plutonic magma could not have metamorphosed the northwest dikes significantly or they would appear different from the younger dikes; this is consistent with the minimal effect that the plutonic magma had on its country rocks (p. 8). The older dikes are thin and uniformly fine grained, perhaps owing to cold wallrocks or rapid loss of volatiles at the time of intrusion. Then the region became warm enough, and cooled slowly enough, to allow five successive plutonic phases to form coarse-grained rock without obvious chilled zones. (Four of these phases were intruded at the same level in the crust.) Furthermore, most superheat (if any), heat of crystallization, heat of solidification, or heat of cooling must have been dissipated upward into rocks now removed instead of outward into rocks now exposed. Then, the area cooled and was intruded by the younger porphyry dikes whose crystallization was also inhibited. All this must have required a neat balance in regional temperature levels or volatile control.

PEGMATITES

Large to small bodies of very coarsely crystalline white oligoclase-microcline-quartz pegmatite occur throughout the Precambrian rocks but are especially common locally adjacent to the contacts of the Mount Ethel pluton. Most of the pegmatites are unzoned, but a few contain large books of muscovite or biotite that may be in zones. Pegmatites are concentrated along the northeasternmost contact of the Mount Ethel pluton (figs. 5, 11), on and north of Copper Ridge, and in and near the schist of Soda Mountain (fig. 9). Possibly, these pegmatites are all older than any rocks of the Mount Ethel pluton, but the few presumably cross cutting contacts are not well exposed and the concentration near the pluton remains suggestive of a relationship with the pluton. Possibly, these pegmatites are older than, but were precursors of, the Mount Ethel magma. At Northgate northeast of North Park, replacement pegmatite is contemporaneous with or younger than quartz monzonite gneiss (Steven, 1957, p. 350), but, though abundant adjacent to intrusive quartz monzonite (Mount Ethel equivalent), it is shown as older than the intrusive quartz monzonite (Steven, 1957, pl. 48). Within the Mount Ethel pluton only a few pegmatites cut units as young as the fine-grained granite. At least one internal pegmatite has been truncated by granite and quartz monzonite of Roxy Ann Lake at a quartz monzonite porphyry of Rocky Peak contact. Internal pegmatites are volumetrically minis-

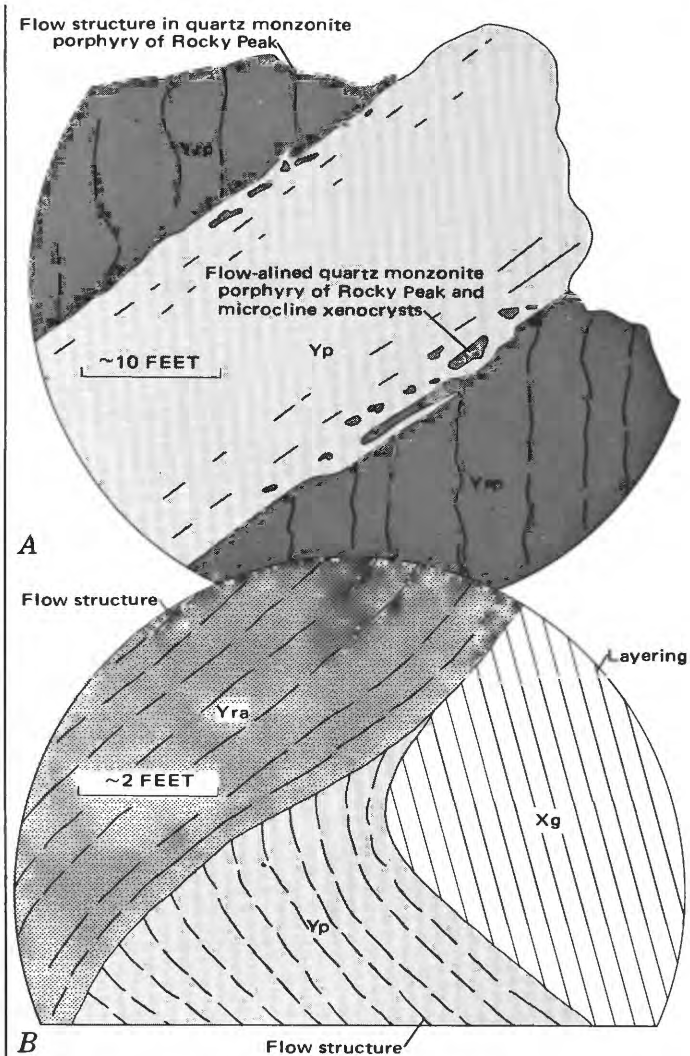


FIGURE 10. — Relations between Mount Ethel plutonic variants and fine-grained porphyry dikes.

A. Sketch of relations shown in cliff exposure of fine-grained trachyandesite dike (Yp) cutting and including quartz monzonite porphyry of Rocky Peak (Yrp) at about 9,650-foot elevation just north of horse trail east of Swamp Park. Xenocrysts of microcline derived from adjacent quartz monzonite prominent in dike near its contact. Sketch drawn partly from field notes.

B. Sketch of relations shown in cliff exposure of quartz monzonite of Roxy Ann Lake (Yra), fine-grained porphyry dike (Yp), and felsic biotite gneiss (Xg) on north side of Newcomb Creek. Note that, while flow structure and contact of porphyry dike clearly crosscut layering of gneiss, flow structure and contact of quartz monzonite equally clearly crosscut both of these. Sketch drawn from field notes.

FIGURE 11. — Giant pegmatites in northeast face of Lost Ranger Peak near contact of Mount Ethel pluton. White cliffs, ledges, and talus in distance are complexly shaped pegmatites in dark amphibolite sequence of uniform dip. Frost-wedged boulders in foreground are quartz monzonite of Roxy Ann Lake; contact of Mount Ethel pluton passes between clumps of brush in left middle distance.

cule and, although they imply that pegmatites formed over a long time, they probably do not contribute much to the understanding of source and time of origin of most pegmatites.

SMALL MAFIC AND ULTRAMAFIC INTRUSIVES

Numerous small mafic and ultramafic intrusives occur throughout the metavolcanics and metasedimentary rocks. Most of these intrusives are amphibolitic, similar to the metavolcanic amphibolites in both appearance and mineralogy, and they are thouroughly metamorphosed so that no trace of either original mineralogy or original texture is preserved. The bodies are mainly a few tens or hundreds of feet in diameter, and no attempt has been made to map them separately. Possibly, most represent feeder dikes for the now-metamorphosed lava flows they occur with, but some, perhaps many, may represent postdepositional premetamorphic intrusive sequences. A few of the mafic and ultramafic intrusives, by virtue of either a preserved original texture or an unusual lithology, are worth further mention.

Medium- to coarse-grained speckled hypersthene metagabbro with relict igneous texture forms a prominent series of ledges above 10,200 feet elevation on the north end of the long ridge between the head of the South Fork of the Elk River and Bear Canyon in the northwest corner of the Mount Ethel quadrangle. The contact with the surrounding meta-amphibolites was not observed. The most noticeable feature of the rock is the clear diabasic texture.

Nodules of medium- to coarse-grained dark dunite in a bright hematite-red soil cap the east side of the 9,035-foot knoll south of the head of Morgan Creek. As no large outcrops are present anywhere in the vicinity, the dunite fragments must be weathering from a subcrop. This dunite locality is nearly on strike with the previously mentioned hypersthene metagabbro, and the two rocks may be genetically as well as spatially related. In the field float fragments are dark grayish brown with light-green to white raised lumps (coronas) scattered sporadically over their surfaces. The rock may be of some economic interest since it contains a trace of platinum and palladium. (See table 5, sample 116.)

A chromite-containing pargasite (?) peridotite occupies several small knolls on the ridge top near triangulation station "Spring" north of Fish Creek in the southeast corner of the Rocky Peak quadrangle. The contacts of this body are not exposed.

Fine-grained porphyry dikes (some of which have been shown to overlap the Mount Ethel pluton in age) cut two of the ultramafic bodies, the chromite-bearing peridotite near triangulation station "Spring" and a diopside hornblendite near the head of the Roaring Fork of Red Canyon.

Hail (1968, p. 7) reported a dike of black hornblendite cutting quartz monzonite about 15 miles south of the southeast corner of the area of this report. This quartz monzonite is probably like the Buffalo Pass type of this report.

Thus, tenuous arguments could be raised to demonstrate that the small mafic and ultramafic intrusives were between the Buffalo Pass pluton and the Mount Ethel pluton in age, but much more work needs to be done before the position in time of the small mafic and ultramafic intrusives is accurately known.

GEOCHRONOLOGY

By Carl E. Hedge

As part of this study, the Mount Ethel and Buffalo Pass plutons and one of the metamorphic wallrock units were dated by whole-rock Rb-Sr methods. The same analytical procedures were used as those described by Peterman, Hedge, and Braddock (1968) and Peterman, Doe, and Bartel (in U.S. Geological Survey, 1967, p. B181--B186).

Rb-Sr analytical data for the Mount Ethel pluton are presented in table 1 and shown on an isochron plot in figure 12. The Rb-Sr ratios of the subunits of the Mount Ethel pluton increase with silica content. The ratios of quartz monzonite porphyry of Rocky Peak, the quartz monzonite of Roxy Ann Lake, and the fine-grained granite define a single line on the isochron plot. This colinearity indicates that these three subunits were all emplaced within a short period of geologic time — probably less than 10 or 20 million years (m.y.). Because of its extremely high Rb^{87}/Sr^{86}, the leucogranite sample (528) is not plotted in figure 12. The sample gives an apparent age of 1,370± 40 m.y., which is somewhat younger than the other subunits of the Mount Ethel pluton. The significance of this age difference is questionable, however, because this sample is slightly weathered. Incipient weathering also may be the reason that some of the other samples deviate from the isochron slightly more than expected only from analytical uncertainty.

Assigning the Mount Ethel pluton to the time interval of 1,370 to 1,470 m.y. makes it part of a major period of plutonism widely recognized throughout the Precambrian of Colorado from the Front Range to extreme

TABLE 1. — *Rb-Sr data for Mount Ethel pluton*

Sample No.	Rb ppm	Sr_t ppm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
Quartz monzonite porphyry of Rocky Peak				
520	[1]138	[1]307	1.300	0.7295
525	122	382	.928	.7211
Quartz monzonite of Roxy Ann Lake				
523	[1]184	[1]196	2.734	0.7570
526	176	263	1.940	.7416
527	171	283	1.759	.7393
Granite and quartz monzonite				
521	263	124	6.211	0.8273
522	271	100	7.976	.8724
Leucogranite				
528	[1]211	[1]20.8	31.08	1.3008

[1] Concentrations are by X-ray fluorescence; others are by isotope dilution.

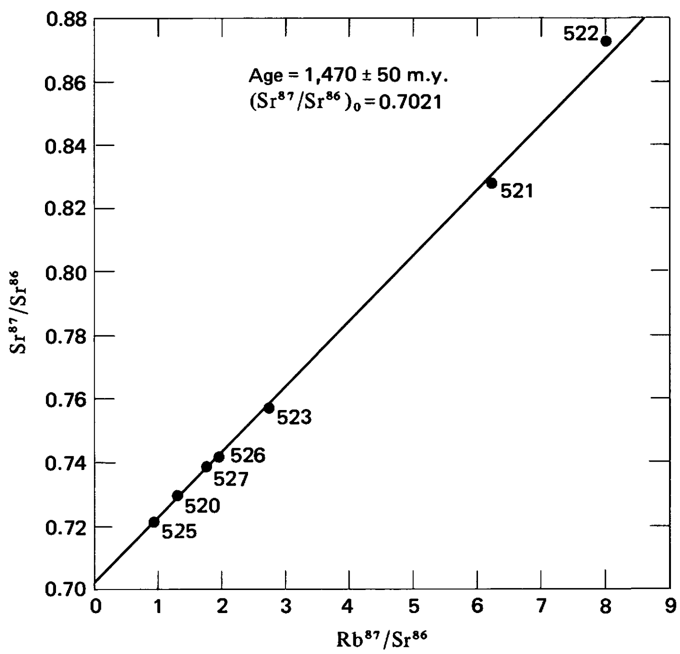


FIGURE 12. — Rb-Sr isochron plot for samples of the Mount Ethel pluton. Sample 528 is not plotted — see text.

western Colorado. (See Peterman and Hedge, 1967, and Hedge and others, 1968.) The age of the Mount Ethel pluton is not significantly different from that of the Sherman Granite or Silver Plume Granite of the northern Front Range to which it has distinct lithological similarities.

The Buffalo Pass pluton gives an age of 1,800±100 m.y. (table 2, fig. 13). Again the two subunits are contemporaneous within analytical uncertainty, and again time-equivalent similar rocks are present in the Precambrian of much of Colorado. In the Front Range rocks of 1,700–1,800 m.y. age are gneissic granodiorite (Boulder Creek Granodiorite) and associated quartz monzonite (Peterman and Hedge, 1967). Augen gneisses about 1,750 m.y. age are common in the southern Front Range and in the Mosquito Range (Hutchinson and Hedge, 1967).

Three samples of feldspathic biotite gneiss were analyzed to determine the age of the metamorphic

TABLE 2. — *Rb-Sr data for Buffalo Pass pluton*

Sample No.	Rb ppm	Sr_t ppm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
Quartz monzonite and granodiorite augen gneiss of Buffalo Mountain				
544	[1]114	[1]429	0.771	0.7214
554	[1]97.4	[1]475	.594	.7163
555	[1]89.9	[1]416	.626	.7179
Quartz monzonite gneiss				
550	142	272	1.518	0.7413
553	125	136	2.689	.7694

[1] Concentrations are by X-ray fluorescence; others are by isotope dilution.

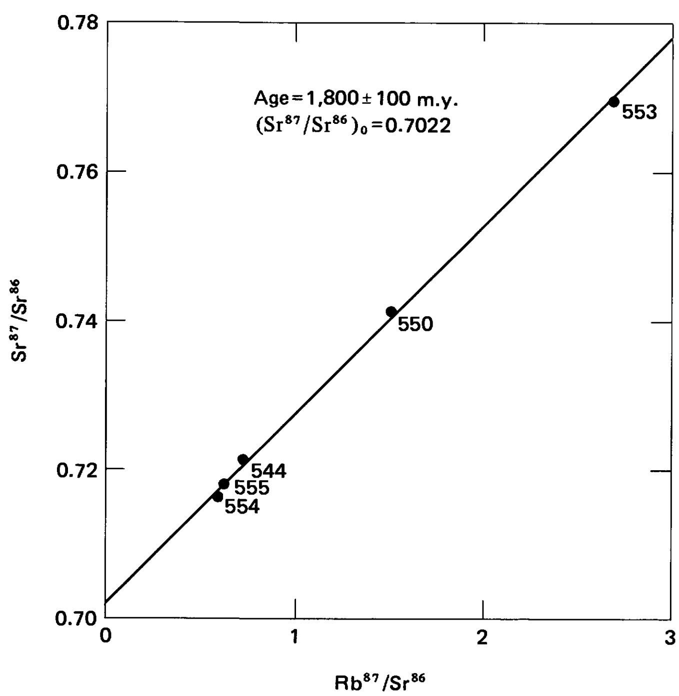


FIGURE 13. — Rb-Sr isochron plot for samples of the Buffalo Pass pluton.

TABLE 3. — *Rb-Sr data for feldspathic biotite gneiss samples*

Sample No.	Rb ppm	Sr_t ppm	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
631	88.0	76.6	3.347	0.7806
593	122	107	3.316	.7790
616	86.7	192	1.313	.7316

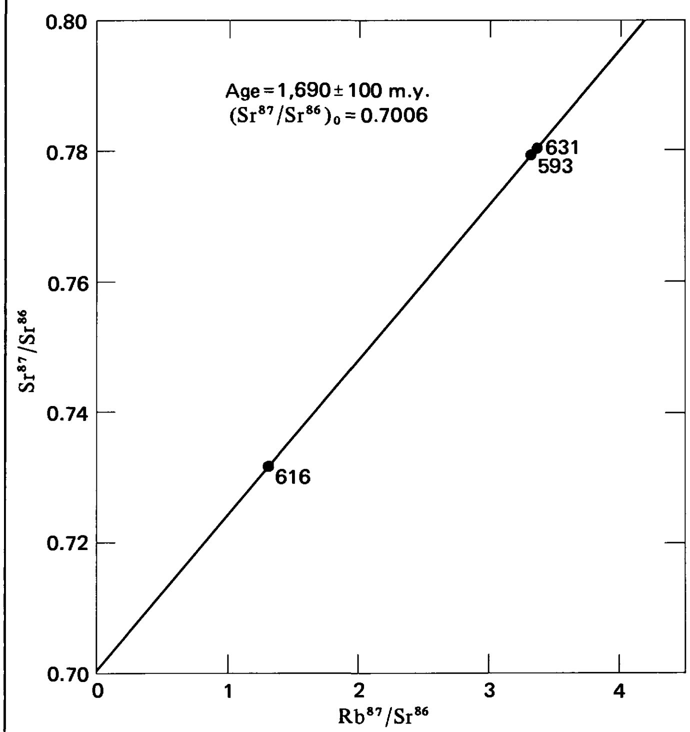


FIGURE 14. — Rb-Sr isochron plot for samples of the feldspathic biotite gneiss.

rocks into which the plutons were intruded (table 3, fig. 14, petrography in table 5). They give an age of 1,690±100 m.y. Since the gneisses must be older than the Buffalo Pass pluton which intrudes them and their analytical uncertainties clearly overlap, the only meaningful age assignment is that both units are approximately 1,700–1,800 m.y. old. Rocks significantly older than 1,800 m.y. have not been found in Colorado, but Hills, Gast, Houston, and Swainbank (1968) delineated a boundary in the Medicine Bow Mountains of southern Wyoming between the 1,700- to 1,800-m.y.-old basement typical of Colorado and the approximately 2,500-m.y.-old basement which appears to occur over most of Wyoming. This age province boundary has not been found in the Park Range, but it must lie to the north of the area of this study.

PETROGRAPHY AND CHEMISTRY OF INTRUSIVE ROCKS

Data on the mineralogy and petography (tables 4, 5) and chemistry (tables 5, 6) are available for most intrusive rocks discussed in this report. These data can be studied, averaged, and combined in many ways. Certain combinations, involving known or potential genetic groupings of the rocks, are worthy of further emphasis. The emphasis will be on whether the petrographic and chemical data contribute to the understanding of the known or potential genetic groupings of the rocks, and the genetic groupings that will be discussed further are as follows (generally from youngest to oldest, or from smallest to largest):

1. Tertiary intrusives (are there two kinds?);
2. Tertiary dikes versus Precambrian dikes;
3. Northwest versus northeast porphyry dikes;
4. Pegmatites (are they related to a particular magma series?);
5. Mount Ethel and Buffalo Pass plutons, similarities and differences, including (a) accessory fluorite, (b) economic implications;
6. Correlation of Park Range rocks with other igneous rocks of Colorado and Wyoming, including (a) Sherman–Silver Plume dichotomy, (b) mafic dikes.

TERTIARY INTRUSIVES

Early workers in the Elkhead Mountains along the west side of the Park Range were convinced that there were two series of post-Cretaceous eruptives: an early light-colored acid porphyry and a late dark basalt. Later work in this and adjacent areas has proved that there is more than one age of basalt and that there is really a continuum of compositions from basalt to rhyolite rather than a strictly bimodal assemblage. However, the variation of magma composition with time is as yet incompletely understood, and more data are needed. Within the area of the present report two compositionally distinctive Tertiary intrusive rocks are present, but their relative ages are not known. Also, the spread in their compositions is less than half as great as the compositional spread of the continuum as a whole (fig. 15). Analyzed examples of these two rocks are provided in table 5: sample 22 is from a light-colored Rittmann trachyandesite sill, and sample 19 is from its feeder dike, from within the area shown as Browns Park Formation and post-Browns Park porphyry intrusives in figure 3 east of Clark; sample 226 is from an olivine-containing Rittmann dark latite dike, one of a series cutting Mesozoic sedimentary rocks and Precambrian crystalline rocks south of Clark.

Since the late 19th century, geologic explorers have generally recognized two series of Tertiary igneous rocks in the Elkhead region west of the northern Park Range: light rocks frequently called trachytes or rhyolite porphyries, and dark basalts. Generally, the

TABLE 4. — *Petrographic summary of primary constituents of metamorphic and igneous rocks of Park Range northeast of Steamboat Springs, Colorado*

[Key to constituent abundance: *A*, abundant in all rocks observed; A, abundant in most rocks observed; a, abundant in a few rocks, not observed in most; *C*, common in small amounts in all rocks observed; C, common in small amounts in most rocks observed; c, present in small amounts in a few rocks, not observed in most rocks; . . ., not observed. Tabulation based on study of 540 thin sections]

Metamorphic and igneous rocks	Constituents: Plagioclase	Potassium feldspar	Quartz	Muscovite	Sillimanite	Christobalite	Olivine	Ortnopyroxene	Clinopyroxene	Orthoamphibole	Clinoamphibole	Garnet	Biotite	Chlorite	Magnetite-ilmenite	Pyrite	Sphene	Epidote	Allanite	Zircon	Fluorite	Carbonate	Spinel	Chromite	Tourmaline	Glass	Apatite	Andalusite	Monazite
Tertiary intrusives	*A*	c	C	...	...	c	a	c	A	...	C	...	c	c	C	...	...	c	...	...	c	c	...	...	...	a	c	...	...
Fine-grained porphyry dikes	*A*	a	A	c	...	...	...	...	...	...	C	...	A	...	C	c	C	C	C	c	c	c	...	...	...	...	C	...	...
Pegmatite	*A*	*A*	*A*	C	c	...	...	...	...	...	c	c	C	...	c	...	...	c	c	c	...	...	...	...	...	...	c	...	...
Mount Ethel pluton:																													
Leucogranite	*A*	*A*	*A*	C	...	...	...	...	...	...	...	...	*C*	...	*C*	c	c	c	c	...	c	...	...	...	...	...	c	...	...
Granite and quartz monzonite	*A*	A	*A*	C	...	...	...	...	...	...	c	...	*A*	...	C	c	c	C	C	C	c	...	...	...	...	...	C	...	...
Quartz monzonite of Roxy Ann Lake	*A*	A	A	C	...	...	...	...	...	...	c	...	*A*	...	C	c	C	C	C	C	C	c	...	...	...	...	C	...	...
Quartz monzonite porphyry of Rocky Peak	*A*	A	*A*	c	...	...	...	...	...	...	c	...	*A*	c	C	c	C	C	C	C	c	c	...	...	...	...	C	...	...
Granodiorite	*A*	A	A	...	...	...	...	...	...	...	*A*	...	*A*	...	*C*	c	C	A	C	C	...	...	...	...	c	...	C	...	...
Buffalo Pass pluton:																													
Quartz monzonite and granodiorite augen gneiss of Buffalo Mountain	*A*	*A*	*A*	c	...	...	...	...	...	...	A	...	*A*	...	*C*	c	C	C	C	C	...	...	...	...	...	...	C	...	...
Quartz monzonite gneiss	*A*	A	A	c	...	...	...	...	...	...	...	...	A	...	C	c	C	C	C	C	...	c	...	...	...	...	C	...	...
Mafic intrusives	a	...	c	...	...	...	A	c	A	...	*A*	...	C	...	C	c	...	...	...	...	...	...	c	c	...	...	c	...	...
Country rocks:																													
Felsic gneiss to amphibolite	*A*	a	A	c	...	...	...	...	...	...	C	a	A	...	C	c	C	C	c	c	c	a	...	...	...	...	C	...	...
Pelitic schist and gneiss	A	a	*A*	A	C	...	...	...	...	c	...	C	*A*	a	c	c	...	...	...	c	c	a	...	...	c	...	c	c	c

TABLE 6. — *Locations and normative*

[Located in same order as in table 5.

Normative minerals	Sample No.												
	528	521	522	527	523	526	347	437	157	525	520	551	544
Q	30.87	31.62	32.68	26.97	27.29	27.38	30.98	22.69	24.85	26.38	27.77	11.53	13.53
or	33.84	30.61	30.16	27.99	28.49	30.38	28.49	25.49	28.83	29.22	27.27	16.50	30.66
ab	32.14	29.10	28.99	30.78	29.94	29.15	30.36	31.14	29.36	28.84	30.46	28.33	30.62
an	1.59	3.95	3.25	7.70	5.67	6.78	5.15	10.87	8.71	7.79	6.73	20.10	14.77
ne	...	...	...	...	...	...	...	...	...	...	...	...	...
di	...	...	...	...	...	...	...	...	...	...	...	2.23	.51
C	.69	1.04	1.57	.90	1.60	1.09	1.07	.38	.50	.94	1.07	...	...
hy	.12	1.84	1.38	2.42	3.31	2.54	1.75	3.66	2.63	2.19	2.86	9.49	6.17
ol	...	...	...	...	...	...	...	...	...	...	...	...	...
mt	.19	.72	.88	1.67	1.53	1.25	1.16	3.08	2.78	2.52	1.81	5.55	1.81
cm	...	...	...	...	...	...	...	...	...	...	...	...	...
hm	.34	...	...	...	...	...	...	...	...	...	...	...	...
il	.09	.26	.24	.64	.76	.56	.41	1.28	1.15	.91	.84	2.57	.90
ap	.03	.13	.03	.20	.23	.20	.16	.53	.43	.30	.33	1.24	.33
cc	...	.02	...	.02	.07	.07	.02	.05	.05	.02	.05	.09	.11
fr	.12	.30	.30	.21	.54	.30	.09	.48	.36	.39	.28	.67	.14
hl	...	.02	.04	.02	.02	.02	...	.04	.04	.04	.02	.05	.04
(H_2O^+)	.08	.36	.46	.48	.56	.29	.35	.29	.31	.43	.50	1.50	.39

Sample locality and description

Sample No.	Map unit (fig. 3)	Section	T. N.	R. W.	Elevation (ft)	Locality description	Sample description
528	Xrp	SE¼ 8	7	84	8,750	4,150 ft S. 78° E. of summit of Rocky Peak, Rocky Peak 7½-minute quadrangle.	Hypidiomorphic-granular texture with planes of sheared grains.
521	Yg	NE¼ 25	8	84	10,060	200 ft south of southernmost point on shore of Lake Margaret, southeast corner of Floyd Peak 7½-minute quadrangle.	Hypidiomorphic-granular texture.
522	Yg	(Unsurveyed)	8	83	10,600	3,950 ft N. 82° W. of west end of Luna Lake, Mount Ethel 7½-minute quadrangle.	Do.
527	Yra	(Unsurveyed)	7	84	9,800	1,900 ft S. 73° E. of summit of hill 10,033 near head of east fork of Gunn Creek, Rocky Peak 7½-minute quadrangle.	Hypidiomorphic-granular, interlocking texture.
523	Yra	(Unsurveyed)	8	83	11,140	6,750 ft N. 74.5° W. of summit of Mount Ethel, Mount Ethel 7½-minute quadrangle.	Hypidiomorphic-granular texture.
526	Yra	NE¼ 36	8	84	9,460	East of the South Fork of Mad Creek, 4,550 ft. S. 78° W. of summit of Horse Thief Peak, northwest corner of the Buffalo Pass 7½-minute quadrangle.	Do.
347	Yra	(Unsurveyed)	8	83	9,920	East of the South Fork of Mad Creek, 1 mile N. 43° W. of summit of Horse Thief Peak near boundary between Mount Ethel and Buffalo Pass 7½-minute quadrangles.	Do.
437	Yrp	NW¼ 22	8	84	9,350	On north side of hill, 5,550 ft N. 57° E. of junction of North and Middle Forks of Mad Creek. Floyd Peak 7½-minute quadrangle.	Hypidiomorphic-granular, subporphyritic to porphyritic texture.
157	Yrp	NW¼ 8	7	84	9,100	2,150 ft N. 29° E. of summit of Rocky Peak, Rocky Peak 7½-minute quadrangle.	Hypidiomorphic-granular, subporphyritic texture.
525	Yrp	SW¼ 14	8	84	9,520	On trail 1,950 ft. S. 55° W. of summit of hill 10,129, about 1½ miles east of Swamp Park, Floyd Peak 7½-minute quadrangle.	Hypidiomorphic-granular, porphyritic texture.
520	Yrp	SE¼ 32	8	84	7,920	1,400 ft. N. 78° E. of summit of hill 8,151, northeast of the junction of Mad Creek and the South Fork of Mad Creek, Rocky Peak 7½-minute quadrangle.	Hypidiomorphic-granular, subporphyritic texture.
551	Yd	SE¼ 21	7	84	7,680	In tributary of Gunn Creek 5,500 ft S. 67.5° W. of peak 9,262, Rocky Peak 7½-minute quadrangle.	Hypidiomorphic-granular, subdiabasic texture.
544	Xb	(Unsurveyed)	7	83	10,088	North side of Buffalo Pass road at benchmark 10088, Buffalo Pass 7½-minute quadrangle.	Mortar texture.

mineral constituents of analyzed rocks

Leaders, . . ., indicate not determined]

Sample No. — Continued													
555	554	550	553	549	524	545	116	631	593	616	226	22	19
18.86	17.25	27.39	33.81	2.41	10.79	17.00	...	...	...	...	...	5.40	7.35
27.49	29.72	32.50	31.39	12.19	17.28	21.98	.30	...	...	...	18.78	13.38	14.87
30.30	30.30	25.11	25.74	27.32	30.15	31.42	2.61	...	...	...	23.59	36.11	35.48
11.76	13.35	5.87	3.75	22.42	17.16	12.80	11.70	...	...	...	13.75	15.73	15.29
...	...	...	...	...	...	...	...	...	...	...	3.04	...	...
...	.32	...	...	6.82	2.72	...	...	...	...	...	16.72	10.64	7.40
.64	...	1.78	1.58	...	...	.56	.18	...	...	...	...	...	...
5.69	5.22	3.31	2.22	19.91	9.38	5.49	29.79	...	...	...	...	8.55	11.26
...	...	...	...	...	...	...	30.77	...	...	...	11.57	...	...
2.13	1.97	1.04	.28	2.56	5.63	4.99	16.96	...	...	...	5.54	4.13	3.60
...	...	...	...	...	...	...	.29	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	2.58	...
.87	.79	.74	.29	3.12	3.40	2.34	.35	...	...	...	3.18	2.10	1.77
.33	.30	.26	.10	1.23	1.79	1.33	.05	...	...	...	1.58	.91	1.08
.75	.20	.23	.39	.09	.02	.52	.16	...	...	...	.16	.09	.94
.14	.12	.12	.04	.36	.67	.72	...	...	...	...	...	...	...
.04	.04	.04	.02	.07	.07	.05	...	...	...	...	...	...	...
.97	.40	.64	.39	1.41	.78	.62	6.84	...	...	...	2.12	.40	.99

***Sample locality and description* — Continued**

Sample No.	Map unit (fig. 3)	Section	T. N.	R. W.	Elevation (ft)	Locality description	Sample description
555	Xb	(Unsurveyed)	6 or 7	83	9,870	3,900 ft N. 17° E. of summit of Buffalo Mountain, Buffalo Pass 7 1/2-minute quadrangle.	Mortar texture.
554	Xb	(Unsurveyed)	6 or 7	83	10,160	Along powerline 3,250 ft S. 15° W. of benchmark 10088, Buffalo Pass 7 1/2-minute quadrangle.	Do.
550	Xm	(Unsurveyed)	7	83	10,540	Along powerline 6,600 ft S. 68° E. of benchmark 10300 near Buffalo Pass, Buffalo Pass 7 1/2-minute quadrangle.	Hypidiomorphic-granular, quartz-mosaic, subporphyritic texture.
553	Xm	(Unsurveyed)	6	83	10,030	Along road 3,750 ft S. 37° E. of Lake Dinosaur, Buffalo Pass 7 1/2-minute quadrangle.	Hypidiomorphic-granular, quartz-mosaic texture.
549	Fine-grained porphyry dike.	(Unsurveyed)	7	83	10,540	1,250 ft S. 61° W. of Soda triangulation station, Buffalo Pass 7 1/2-minute quadrangle.	Megadiabasic texture.
524	. . .do.	SW 1/4 14	8	84	9,640	North of trail 1,650 ft S. 39° W. of the summit of hill 10,129 about 1 1/2 miles east of Swamp Park, Floyd Peak 7 1/2-minute quadrangle.	Diabasic, porphyritic texture.
545	. . .do.	(Unsurveyed)	7	83	10,070	Near Buffalo Pass road 300 ft. N. 68° W. of benchmark 10088, Buffalo Pass 7 1/2-minute quadrangle.	Do.
116	Small ultramafic intrusive.	NW 1/4 28	9	84	9,005	In bald spot of red soil just east of top of hill 9,035 about 3/4 mile east-southeast of Wapiti Ranch, Floyd Peak 7 1/2-minute quadrangle.	Myrmekitic, poikilitic, corona texture.
631	Feldspathic biotite gneiss, Xg.	(Unsurveyed)	9	82	9,300	3,000 ft N. 66° W. of west junction of Grizzly-Helena trail with Lone Pine Creek road, northwest corner of Pitchpine Mountain 7 1/2-minute quadrangle.	Granular, interlocking texture.
593	. . .do.	(Unsurveyed)	8	82	9,370	North of Beaver Creek 2,400 ft S. 36.5° E. of peak 10,225, northwest corner of Teal Lake 7 1/2-minute quadrangle.	Gneissic, granular texture.
616	. . .do.	(Unsurveyed)	7	83	9,925	Near top of small knoll 3,250 ft N. 50° E. of east end of Round Mountain Lake, Buffalo Pass 7 1/2-minute quadrangle.	Do.
226	Tertiary intrusive.	SE 1/4 16	8	85	7,980	On linear knob 950 ft N. 71.5° W. of hill 8,920 on Moon Hill, Clark 7 1/2-minute quadrangle.	Diabasic, porphyritic, xenocrystic texture.
22	. . .do.	SE 1/4 36	9	85	8,930	4,600 ft due east of Greenville mine near summit of hill 8,934, Floyd Peak 7 1/2-minute quadrangle.	Trachytic, porphyritic, vesicular texture.
19	. . .do.	NW 1/4 36	9	85	8,590	4,100 ft N. 54° E. of Greenville mine on south side of knob 8,629. Floyd Peak 7 1/2-minute quadrangle.	Hyalotrachytic, xenocrystic texture.

basalts have been considered to be younger than the porphyries, and specific intersecting field relationships reported over the years, although rare of mention, would tend to confirm this. Tertiary igneous rocks of two distinct types, rhyolitic and basaltic, were mentioned by Gale (1906, p. 29, 30) in the Hahns Peak area, but no statement of relative age of these two types was provided. In the Yampa coal field Fenneman and Gale (1906, p. 32) spoke of two fairly well defined groups of post-Cretaceous eruptives, and "basalt" is shown younger than "acid porphyry" on their plate 1; but no intersections were mapped. George and Crawford (1909, p. 211,212) noted: "While there are several varieties of porphyry in the (Hahns Peak) district, they may, in the main, be considered closely related phases of a series rather than distinct types. They include rhyolite, dacite, latite, andesite, and quartz basalt." However, they later (p. 212, 213) spoke of several ages of rhyolite and also noted (p. 215, plate in pocket) a quartz basalt dike cutting rhyolite porphyry southwest of Columbine. This mafic dike is mapped as two dikes by Barnwell (1955, p. 48, pl. 5), both cutting rhyolite porphyry throughout their length; but Segerstrom and Young (1972, pl. 1) recognized only intermediate porphyry throughout part of this same area. An olivine basalt dike has been reported as cutting a rhyolite porphyry laccolith in the crest of the Tow Creek anticline between Milner and Pilot Knob (Crawford and others, 1920, p. 36–39, pl. 3; Coffin and others, 1924, p. 57–58, pls. 1, 3), and this is the basis in this area for the joint conclusion that there were two periods of Tertiary igneous activity. However, the critical relationships in the Tow Creek crest have been mapped somewhat differently by Bass, Eby, and Wood (1955, pl. 19) and by Buffler (1967, pls. 1, 2). Christensen (1942, p. 29–32, 55–61, 172–174, geologic map) reported two distinct series of volcanics in the Elkhead Mountains, all said to be of "Pliocene (post-Browns Park)" age. First eruptions were of intermediate composition, mainly light-colored latites and trachytes, with some trachyandesites. Following a period of erosion, olivine basalt flows were poured out (perhaps at several times), followed by trachybasalts, lamprophyres, and analcite-bearing rocks. "Definitely younger" (Christensen, 1942, p. 45) lamprophyre dikes are shown cutting trachyte flows on Meaden Peak. In his overview of the Tertiary geology of the Elkhead region, Buffler (1967, p. 95–100) reported that most of the volcanic rocks can be subdivided into two general groups: light-colored intermediate porphyritic trachytes and dark basalts and lamprophyres. Buffler stated: "The age relationship between the intermediate rocks and the basic rocks is still not clear, as the two rock types were never observed directly associated with each other." Because the Browns Park Formation, which on Sand Mountain underlies intermediate rocks, is at the same elevation as basic intrusions just to the south, but contains no locally derived basic volcanic debris, Buffler concluded that the intermediate and basic rocks here "are contemporaneous or more likely that the basic rocks are somewhat younger." Buffler also reviewed other evidence indicating several late periods of mafic extrusion along the Colorado-Wyoming State line at the northern extremity of the Elkhead Mountains. Segerstrom and Young (1972, p. 38, 40, 41) reported a dike of dark alkali trachyte or quartz andesite cutting the altered rhyolite at Hahns Peak. Hahns Peak itself is reported to be the site of a volcano where rhyolite porphyry with a central breccia pipe (Segerstrom and Young, 1972, cross sec. *A–A′*; Bowes and others, 1968, p. 179) was extruded in immediate post-Browns Park time (Segerstrom and Kirby, 1969, p. B19–B22).

Southeast of the area of this report in the northwestern Rabbit Ears Range a full spectrum of extrusive and intrusive rocks from basalt to rhyolite is present (Hail, 1968, p. 50–84, pls. 1, 2, 3). The trend may run generally from rhyolite to basalt with time but data are insufficient to prove this; the youngest rock may be the basanite dike that cuts trachyandesite on Diamond Mountain. Izett (1966, p. B42–B46; 1968, 21–55) has mapped a Pliocene(?) basalt overlying a complex series of mafic to silicic extrusives and intrusives ranging in age from Cretaceous to Miocene (?) in the Hot Sulphur Springs area.

Laboratory data on composition and radiometric ages are as yet insufficient to give the exact composition-versus-time sequence of igneous rocks in this part of Colorado. However, indications are that relations of both composition and timing are more complex than some early, relatively simple models would have had us believe. First let us consider composition: Analyses of 28 eruptive rocks from the Park Range and Elkhead Mountains (including the three average analyses of Tertiary intrusives from table 5) are compared in figure 15 with analyses of 53 eruptives from the Rabbit Ears Range (mostly within a 7-mile radius of Diamond Mountain) and with 20 analyses from Izett's Hot Sulphur Springs area using Rittmann's (1952) parameters, as commonly applied to fine-grained intrusive and extrusive rocks. The three fields of analyses shown are quite similar to one another; in fact, their areas of overlap are pronounced and this may be more important than the areas of individuality. The points upon which the fields of figure 15 are based are scattered randomly but are more or less continuously scattered throughout the areas shown, and the rocks represented are a wide range of basalts, trachybasalts, trachyandesites, trachytes, latites, quartz latites, rhyodacites, and rhyolites. Although saturated or slightly undersaturated basalts may be the youngest rocks, from the compositional data it seems clear that the other rocks form a continuum of all common compositions including basalts.

Do the radiometric ages confirm that the basalts are the youngest rocks? Not at all, although there are some uncertainties and although many critical areas still need to be radiometrically dated. In the Elkhead Mountains 10 K-Ar dates are available on biotite, sanidine, or whole rock from both basalts and felsite porphyries (McDowell, 1966; Buffler, 1967; Segerstrom and Young, 1972). The average of five felsites, two from Hahns Peak, is 9.3±0.3 m.y. But two authors think two of these dates are too young, possibly due to argon leakage (Buffler, 1967, p. 102; Segerstrom and Young, 1972, p. 40), and this might make the actual average age 10 or 11 m.y. This compares with Buffler's range of 9.5–11.1±0.5 m.y. for two basalts and a lamprophyre and Segerstrom and Young's two dates of 10.7 and 11.5± 0.4 m.y. on the intermediate dike cutting the porphyry of Hahns Peak. Although only one of these dated rocks (the Hahns Peak dike) has also been analyzed chemically, the K-Ar dates clearly indicate that Elkhead Mountains magmas of diverse composition were active over a span of time not greater than several million years near the Miocene-Pliocene boundary. This is about the same time, 9.7±0.5 m.y. ago, that basalts were pouring out on Grand Mesa (U.S. Geol. Survey, 1966, p. A81) and, 10 m.y. ago, on the White River uplift (Mutschler and Larson, 1969). The latter event began much earlier, 21 m.y. ago, than anything yet dated in the Elkhead Mountains, about the same time as the two dated groups of basaltic volcanics at Yarmony Mountain south of Steamboat Springs (24.5±1.0 and 21.5±1.0 m.y., Strangway and others, 1969; York and others, 1971) and the rhyolitic airfall ash (24.8±0.8 m.y.) in the lowermost part of the Browns Park Formation 25 miles northwest of Maybell (Izett and others, 1970, p. C150). No radiometric ages are available from the Tow Creek, Columbine, or Meaden Peak dikes or from the rocks they cut. Naeser, Izett, and White (1973, p. 498) reported late Oligocene to early Miocene intrusive activity (23–30 m.y.) from zircon fission track ages on 15 effusive rocks from the Rabbit Ears Range, Trail Mountain quadrangle, Green Mountain Reservoir area, and Red Mountain area. Izett (1966, p. B45; 1968, p. 35–37; see also Taylor and others, 1968, p. 42) reported K-Ar sanidine dates of 29±3 and 33±3 m.y. on quartz rhyolite tuffs from Hideaway Park and northwest of Hot Sulphur Springs, respectively. In the Cameron Pass area east of North Park, Corbett (1968, p. 6, 28) has mapped mafic Eocene volcanics that are overlain and are intruded by silicic volcanics providing K-Ar dates of 27 and 28 m.y.

TERTIARY DIKES VERSUS PRECAMBRIAN DIKES

Some Park Range Tertiary dikes can be mistaken for some Precambrian intrusives, notably the fine-grained porphyry dikes or the small ultramafic intrusives. Some authors have described rocks in the vicinity as Tertiary that may well be Precambrian; others may be tempted to make the reverse mistake. Field diagnosis of the relative age of some intrusives is obvious while diagnosis of others may be difficult; petrographic study of the difficult ones can often lead to an unequivocal decision. Intrusives that cut rocks younger than Precambrian are obviously younger than Precambrian. Other features, such as a glassy groundmass, vesicularity, alteration products related to near-surface oxidation, or a certain "look" of feldspar or olivine phenocrysts, quartz xenocrysts, or a flow-structured groundmass, may prove a Tertiary origin; being cut by younger Precambrian rock (for example, fig. 10*B*) is clear evidence of Precambrian origin. But some intrusives display none of these features, they cut only Precambrian rocks, are not known to be cut by other Precambrian rocks, and are not capable of being or have not been dated radiometrically. These rocks are problems in outcrop or hand specimen, but table 4 illustrates several useful microscopic criteria. Some Tertiary intrusives studied differ from the Precambrian ones in containing high temperature sanidine and cristobalite as well as minor groundmass glass or vesicles not visible in hand specimen and also a distinctively zoned plagioclase. Tertiary mafic minerals are generally fresh or unaltered or, if partly altered, the alteration is distinctive, as olivine to reddish iddingsite rather than colorless serpentine or chlorite. Precambrian porphyry dikes and small ultramafic intrusives on the other hand never contain high temperature minerals, glass, vesicles, or the same kind of zoned plagioclase. Olivine and pyroxene are absent from the fine-grained porphyry dikes, and hornblende is green or blue rather than brown or brownish green. Olivine and pyroxene are present, even abundant, in some of the ultramafic intrusives, but as yet there are no known Tertiary ultramafic intrusives in this area. Chlorite and epidote alteration is very conspicuous in many Precambrian intrusives, much more so than in any Tertiary intrusive.

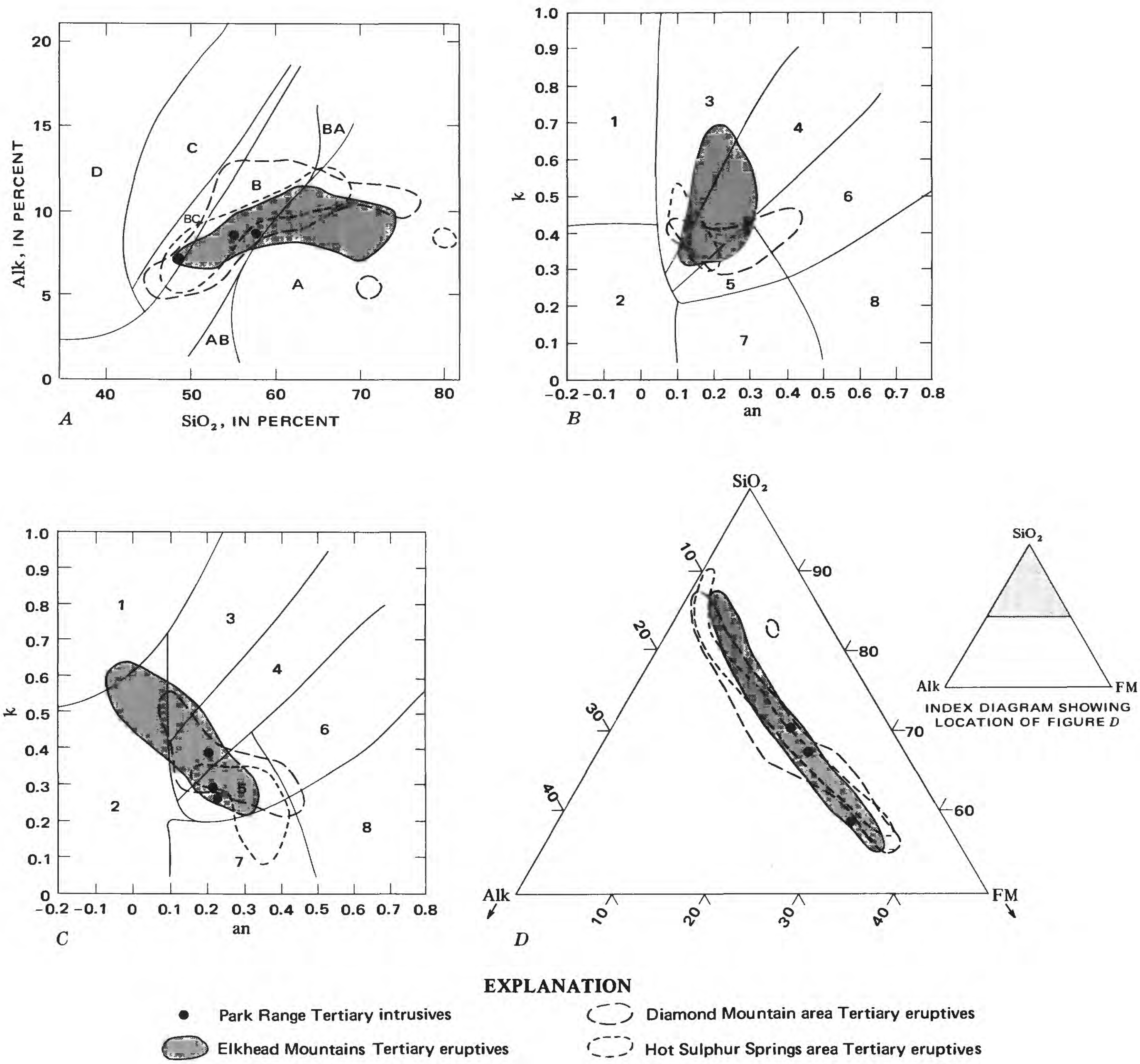
Chemically, little difference exists between Tertiary and Precambrian intrusives although a few minor elements may have statistically significant variations. Lanthanum and fluorine may be higher, and nickel lower, in Precambrian porphyry dikes as a group. And the ultramafic intrusives certainly tend to be higher in chromium, palladium, and platinum and lower in strontium, yttrium, and zirconium than the average rock of any other group.

NORTHWEST VERSUS NORTHEAST PORPHYRY DIKES

Despite repeated attempts, no consistent difference in lithology, petrography, or chemistry between the groups of northwest-trending and northeast-trending Precambrian porphyry dikes has been discovered. (In table 5, field Nos. 549 and 545 represent the northwest-trending dikes, and No. 524 is northeast trending.) In fact, nearby dikes with the same trend locally differ more in the degree of their alteration or recrystallization than the difference between averages for each dike set. The emplacement of either dike set may have taken place over a considerable period of time.

PEGMATITES— ARE THEY RELATED TO A PARTICULAR MAGMA SERIES?

The few available salient facts about whether most pegmatites are related to a particular magma series follow.



1. The mineral composition, which shows minor variations in the grain size and abundance of muscovite, biotite, and garnet, is monotonously similar throughout the area and, in fact, is similar to that of most other pegmatites in other crystalline terranes elsewhere. Chemical composition, not available here, would be expected to be equally unrevealing.
2. Many pegmatites are concentrated in swarms adjacent to the contacts of the Mount Ethel pluton (figs. 5*C*, 9, 11), suggesting that these pegmatites may in some way be related to this magma series.

◀ FIGURE 15 (facing page). — Comparison of northern Colorado Tertiary igneous rocks using Rittmann chemical parameters. Graphs *A*, *B*, and *C* from Rittmann (1952, figs. 4, 5, and 6, respectively) with data field overprints from the Elkhead Mountains (Hague and Emmons, 1977, p. 176–179, 2 analyses; Clarke, 1904, p. 187, 1 analysis; Clarke, 1910, p. 118, 1 analysis; Ross, 1926, p. 225, 4 analyses; Segerstrom and Young, 1972, table 5, 12 analyses; E. J. Young, 1968, written commun., 5 analyses), Diamond Mountain area in the Rabbit Ears Range (Hague and Emmons, 1877, p. 125, 126, 2 analyses; Hail, 1968, table 3, 51 analyses; also see Washington and Larsen, 1913, p. 450 for one analysis that plots off these graphs), and Hot Sulphur Springs area (Izett, 1968, table 8, 20 analyses). All analyses recalculated to 100 percent after subtraction of volatiles. The Rittmann parameters shown in this figure are

$$SiO_2 = SiO_2,\quad Alk = K_2O + 1.5\ Na_2O,\quad FM = Fe_2O_3 + 1.1\ (FeO + MnO) + 2MgO,$$

$$k = \frac{K_2O}{Alk} \text{ and } an = \frac{0.9\ Al_2O_3 - Alk}{0.9\ Al_2O_3 + Alk}$$

In the Rittmann system of nomenclature, appropriate chemical parameters of fine-grained eruptives are first fitted onto graph *A* to obtain a letter (with all but one of these analyses, it is either A or B), and then the chemical parameters are fitted onto either graph *B* for letter A or graph *C* for letter B to obtain a number. With the letter and the number one obtains the Rittmann name of the rock from a table. (See Rittmann, 1952, for details.)

A. Comparison on Alk-to-SiO_2 graph of Park Range Tertiary intrusives with other northern Colorado Tertiary eruptives. Rittmann field: A = oversaturated rocks; B = saturated rocks, C and D = undersaturated rocks. Rocks in fields AB, BA, or BC follow special rules to fit in fields A, B, or C.

B. Comparison on k-to-an graph of oversaturated (Rittmann field A) northern Colorado Tertiary eruptives. Fields 1, 2, and 3 = various kinds of rhyolites; 4 = quartz latites; 5, 6 = rhyodacites; 7 and most of 8 = dacites.

C. Comparison on k-to-an graph of saturated (Rittmann field B) Park Range Tertiary intrusives with other northern Colorado Tertiary eruptives. Fields 1, 2, and 3 = various kinds of trachytes; 4 = latites; 5, 6 = trachyandesites for low FM and trachybasalts for high FM (FM requirements vary); 7, 8 = andesites for low FM and basalts for high FM (FM requirements vary.)

D. Ternary comparison of SiO_2, Alk, and FM of Park Range Tertiary intrusives with other northern Colorado Tertiary eruptives.

3. Lead-alpha ages of monazite and xenotime from "pegmatite, Park Range, Routt County, Colorado" are 1,430 and 1,420 m.y., respectively (Jaffe and others, 1959, p. 128), apparently indicating that some Park Range pegmatites were emplaced contemporaneously with the rocks of Mount Ethel pluton.
4. The K-Ar age of muscovite from pegmatite within felsic gneiss at the Farwell mine 7 miles north of the area of this report is 1,680±50 m.y. (Segerstrom and Young, 1972, table 3). They reported (1972, p. 16) that the felsic gneisses define an Rb-Sr whole-rock isochron of 1,650–1,700 m.y. and many of these felsic gneisses look similar to some rocks of the Buffalo Pass pluton in the area of this report, suggesting that some pegmatites that cut the older gneisses may be essentially coeval with them.
5. As noted previously in this report, at Northgate, pegmatite swarms near intrusive quartz monzonite of "younger Precambrian" (Mount Ethel equivalent) age are belived to be of "older Precambrian" age (Steven, 1957, pl. 48).

Conclusion — Lithologically similar pegmatites are related in time to both major magma series in the area, but the volume related to each series needs further definition. However, the time relationship permits, but does not prove, a common origin. Some or all pegmatites of exactly the same age as nearby plutons may have been derived from the metamorphic country rocks during high-grade metamorphism coincident with plutonic intrusion.

MOUNT ETHEL AND BUFFALO PASS PLUTONS, SIMILARITIES AND DIFFERENCES

The Mount Ethel pluton possesses many chemical and mineralogic trends that parallel the time sequence of its mapped units. These trends tend to differ slightly from those in the Buffalo Pass pluton. Some graphical plots indicate that the fine-grained porphyry dikes are more like the Mount Ethel trend than the Buffalo Pass trend. Fluorite appears to be a key accessory mineral in distinguishing the 1,400-m.y.-old Mount Ethel rocks from the 1,800-m.y.-old Buffalo Pass rocks, and the analyzed fine-grained porphyry dikes have a fluorine content comparable to rocks of the Mount Ethel pluton.

Within the Mount Ethel pluton the rocks, from oldest to youngest, range from diorite and granodiorite through quartz monzonite (most of the pluton) and granite to leucogranite. The oldest rocks are dark colored and medium to coarse grained while the youngest rocks are light to very light colored and medium to fine grained. Parallel to the time-color-texture trend are several chemical and mineralogical trends: The SiO_2

increases from about 57 percent to about 75 percent, the total iron-magnesium oxides decrease from greater than 11 percent to less than 1 percent, the alkali oxides increase from about 6 percent to about 9.5 percent, and CaO decreases from about 6 percent to less than 1 percent (table 5); the trend is also one of decreasing Sr and increasing Rb (table 1); there is a decline in the anorthite content of the plagioclase parallel to the decrease in CaO and increase in alkali oxides; the sequence is also characterized by a general increase in potassium feldspar and muscovite and a decrease in biotite, hornblende, and total mafic minerals; quartz and plagioclase tend to be more constant in amount but with many less predictable fluctuations (tables 4, 5). Fluorite is a common accessory mineral that will be discussed in some detail in the following section. (See "Accessory fluorite.")

The Buffalo Pass plutonic "sequence" is one of inference inasmuch as the relative ages of the two mapped units are not known. The quartz monzonite and granodiorite augen gneiss of Buffalo Mountain of the Buffalo Pass pluton is lithologically most similar to the quartz monzonite porphyry of Rocky Peak of the Mount Ethel pluton; similarly, the equigranular quartz monzonite gneiss of the Buffalo Pass pluton is comparable to the quartz monzonite of Roxy Ann Lake, or younger rocks, of the Mount Ethel pluton. (See p. 12.) It is possible that many of the statements made about the chemical and mineralogical trends within the Mount Ethel pluton also apply in the same way to this Buffalo Pass plutonic "sequence." (See tables 2, 4, and 5.) However, there are also subtle to significant differences between the two plutons: The lack of euhedral phenocrysts in the pre-Buffalo Pass or synkinematic Buffalo Pass rocks has already been mentioned. Blue-green hornblende is much more common in Buffalo Pass rocks than in supposedly comparable Mount Ethel rocks, and K_2O, and hence microcline, is more abundant in Buffalo Pass rocks than in Mount Ethel rocks for comparable values of SiO_2.

The chemical similarities and differences between the rocks of the two plutons are well illustrated in the normative mineral plots of figure 16. Although the series are near the median of analyzed rocks as a whole (fig, 16*D*), they still possess some distinctive properties. On the ternary plots (figs. 16*A*, 16*B*, 16*C*) the Mount Ethel rocks form a linear trend bunched toward the more silicic or alkalic end of the trend. It is interesting that the fine-grained porphyry dikes, which overlap the Mount Ethel plutonic rocks in age, appear to lie on and to extend this trend at the more sodic or calcic end of the spectrum. The Buffalo Pass rocks, especially the Buffalo Mountain rocks, appear to be always more orthoclase rich relative to the other constituents, and hence the plot slightly off the trend of the younger rocks. The field-demonstrated time sequence of the Mount Ethel rocks from mafic to silicic is generally corroborated by experimental results in the Ab-Or-SiO_2-H_2O and Ab-An-Or-H_2O systems. Although the experimental systems do not contain all the constituents of the natural ones, experimental results show that the rocks could be the product of magmatic differentiation under conditions of general crystal-liquid equilibrium. (But see comment on p. 33.) In figure 16*A* the trend of the series is consistent with the expectable trend of an Ab-Or-SiO_2 liquid toward the isobaric temperature minimum and the quartz-feldspar equilibrium boundary at a P_{H_2O} of 1000–5000 bars, the latter perhaps most likely. Bateman and others (1963, p. D35) have translated 5,000 bars into a probable depth of differentiation of at least 11 miles. Those silicic compositions apparently in the quartz field may actually be in the feldspar field because of the influence of anorthite on the boundary as shown by James and Hamilton (1969) and as illustrated in figure 16*B*. Figure 16*C* demonstrates a progressive decrease in the normative anorthite content of the plagioclase (parallel to that actually present in the rocks) as the alkali feldspar equilibrium boundary is approached. As most of these rocks have a plagioclase in the oligoclase range in equilibrium with microcline, it is possible that, at 5,000 bars P_{H_2O}, such rocks would have crystallized in the temperature range from 705°C to 740°C (Yoder and others, 1957, p. 212, 213).

FIGURE 16. (facing page). — Plots of normative minerals of analyzed Park Range Precambrian plutonic rocks compared with experimental and statistical data. ▶

A. Quartz-albite-orthoclase diagram showing progressive variation of quartz-feldspar equilibrium boundaries with H_2O pressure; pluses indicate isobaric temperature minima for 500, 1,000, 2,000, and 3,000 bars; triangles, isobaric eutectics for 5,000 and 10,000 bars (experimental data from Tuttle and Bowen, 1958, p. 54–56; Luth and others, 1964, p. 765, 766).

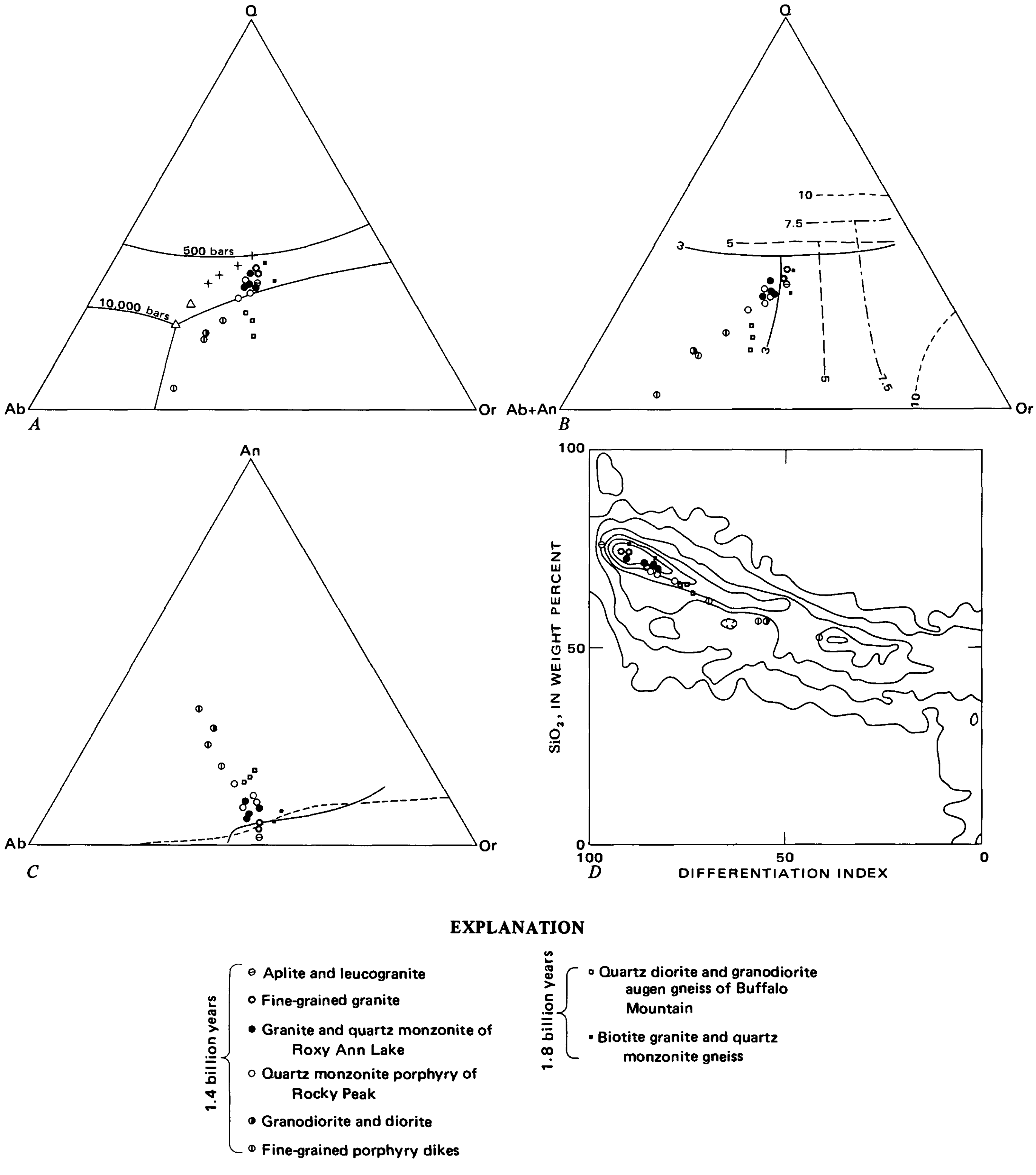
B. Quartz-plagioclase-orthoclase diagram showing progressive shift in quartz-feldspar equilibrium boundaries (at 1,000 bars P_{H_2O}) with 3, 5, 7.5, and 10 percent anorthite (experimental data from James and Hamilton, 1969, p. 118, 120).

C. Feldspar diagram showing plagioclase-alkali feldspar equilibrium boundary (dashed line, 5,000 bars P_{H_2O}, Yoder and others, 1957, p. 211; solid line, projected quartz-saturated liquidus at 1,000 bars P_{H_2O}, James and Hamilton, 1969, p. 123).

D. Silica versus differentiation index (for these rocks this is the sum of Q + Ab + Or) compared to a contoured diagram for the 5,000 analyses in Washington's tables. (See Thornton and Tuttle, 1960, p. 674.)

ACCESSORY FLUORITE

Many Mount Ethel plutonic rocks (more than 50 percent of the samples studied) differ from the Buffalo Pass plutonic rocks in containing a minor amount of accessory fluorite, and, because this is a useful local dis-



criminatory petrographic criterion and also has some economic significance, these results are considered in some detail here. The distribution of fluorite by map unit or similar broad category of rock is given in table 7, and the geographic localities for fluorite observed in thin section are shown in figure 17. Most of the observed fluorite clearly falls within or close to the outer boundaries of the Mount Ethel pluton, although a few of the fluorite-bearing samples plotted in figure 17 may be from unmapped inclusions or inliers rather than

TABLE 7.—*Fluorite in Park Range rocks northeast of Steamboat Springs*

Park Range rocks	Number of thin sections with observed fluorite	Number of thin sections without observed fluorite	Percent per unit of thin sections with observed fluorite
Tertiary intrusives	2	10	17
Tertiary sediments	1	25	4
Mesozoic sedimentary rocks[1]	0	35	0
Fine-grained porphyry dikes[1]	1	32	3
Mylonite and pegmatite[1]	3	11	21
Mount Ethel pluton:			
Leucogranite	1	4	20
Granite and quartz monzonite	16	19	46
Quartz monzonite of Roxy Ann Lake	105	44	70
Quartz monzonite porphyry of Rocky Peak	21	33	39
Granodiorite	0	9	0
Buffalo Pass pluton:			
Quartz monzonite and granodiorite augen gneiss of Buffalo Mountain	0	13	0
Quartz monzonite gneiss	0	6	0
Mafic intrusives	0	15	0
Country rocks:			
Felsic gneiss to amphibolite	4	79	5
Pelitic schist and gneiss	2	56	3
Total	[2]156	[2]391	29

[1] Because of mineralogy or texture, small amounts of fluorite might have been missed in some thin sections of these rocks.
[2] Total number of thin sections here is greater than that given in table 4 because several thin sections have more than one lithology.

plutonic rock. These rocks typically contain less than 0.5 percent fluorite, but, locally, there are individual outcrops or large areas that contain from 0.5 to 2 percent disseminated fluorite (fig. 17). Table 7 shows that fluorite appears to have been concentrated in rocks near the middle of the Mount Ethel plutonic sequence. Percents of samples containing fluorite in the Mount Ethel and related units, generally from oldest to youngest are the following: granodiorite, none; fine-grained porphyry dikes, 3 percent; quartz monzonite porphyry of Rocky Peak, 39 percent; quartz monzonite of Roxy Ann Lake, 70 percent; granite and quartz monzonite, 46 percent; and leucogranite, 20 percent. These figures compare with an average of 7 percent in all other units; fluorite was not observed in any samples of the Buffalo Pass pluton. On this evidence alone, one of the following two conclusions seems justified:

1. Most of the fluorite is of magmatic origin and was formed by some process of magmatic differentiation that culminated near the middle of the Mount Ethel magmatic cycle 1.4 billion years (b.y.) ago; this conclusion is favored in this report;
2. If the fluorite is younger than 1.4 b.y., and perhaps formed as a hydrothermal replacement, then rocks of the Mount Ethel pluton must be a more favorable host than surrounding rocks, and rocks near the middle of the Mount Ethel plutonic sequence must be progressively more favorable hosts than rocks near either end of the series. Because the rocks of the Mount Ethel pluton are similar compositionally to other rocks outside of the pluton and because the middle rocks are not obviously more favorable hosts, this conclusion is not favored in this report.

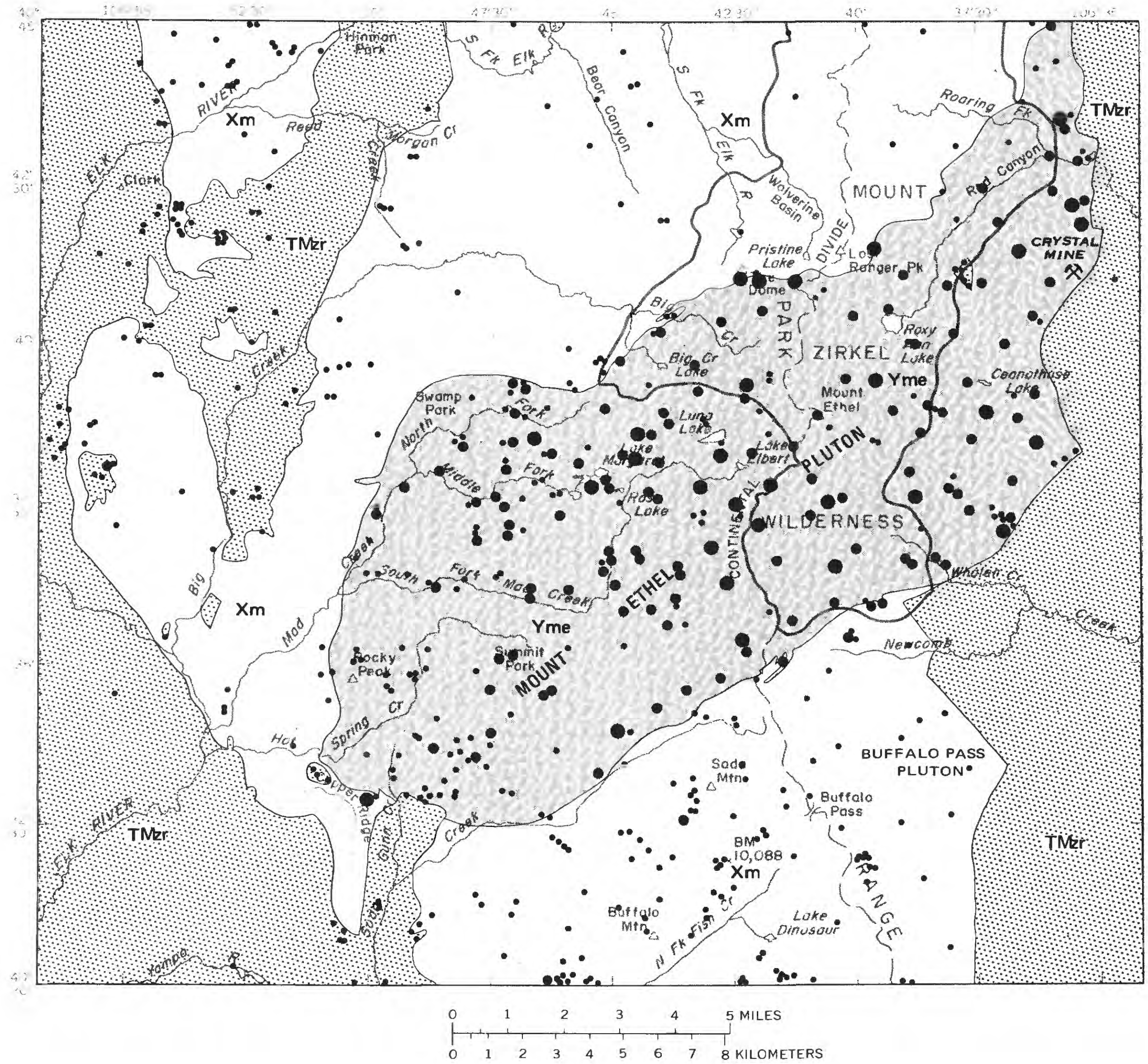
The chemical evidence suggests a progression in chemical fluorine content through the Mount Ethel plutonic sequence that permits a magmatic origin for the mineral, fluorite. Chemical fluorine is most abundant in the most mafic rocks of the Mount Ethel pluton, the granodiorite unit and the fine-grained porphyry dikes, and is least abundant in the leucogranite; intermediate amounts are present in the intermediate rocks (table 5). Thus, although there appears to be a progression in chemical fluorine content through the intrusive sequence, this progression is different from that for the content of the mineral, fluorite. This is apparently so because the chemical fluorine seeks mafic minerals in the most mafic rocks and only crystallizes as the mineral, fluorite, when there are not enough mafic minerals to absorb it. From studies of available chemical analyses of mafic minerals it seems likely that most of the Mount Ethel nonfluorite fluorine is contained in biotite with decreasing amounts in hornblende, apatite, and sphene.

The petrographic evidence concerning much of the interstitial fluorite also tends to confirm conclusion (1). Nine photographs depicting the texture and habit of interstitial fluorite in quartz monzonites and granites of the Mount Ethel pluton are presented in figure 18. Three kinds of fluorite, perhaps representing three ages of fluorite, may be distinguished in these rocks on the basis of texture, habit, and mineral association:

(1) Magmatic fluorite. Anhedral fluorite, crystals the same general size as and associated with, interstitial to, or including mafic minerals (figs. 18*A*, 18*E*), mafic and felsic minerals (figs. 18*B*, 18*G*), or felsic minerals (fig. 18*D*). This type is volumetrically most important.

(2) Magmatic to deuteric fluorite. Fluorite in long thin veins cutting other magmatic minerals but also associated in the veins with other magmatic minerals like microcline, sphene, and epidote (figs. 18*H*, 18*I*). This type is relatively rare.

(3) Fluorite coincident with deuteric or later (some perhaps much later) alteration. Generally anhedral, locally euhedral, small grains of fluorite usually within plagioclase partly to completely altered to sericite and muscovite (figs. 18*C*, 18*F*). This fluorite is common and may be intimately associated with small grains and veinlets of late calcite (not illustrated).

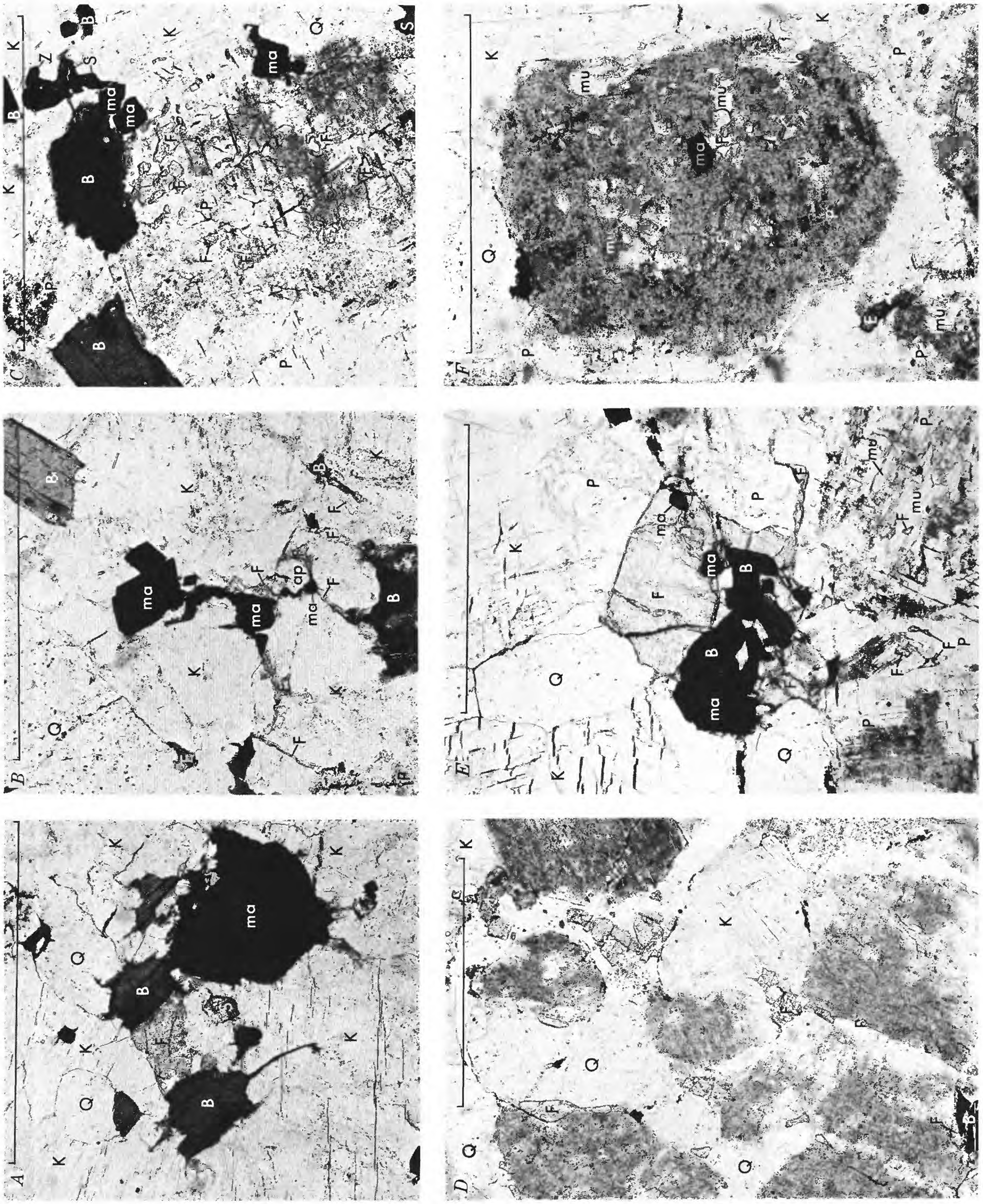


EXPLANATION

TMzr	Post-Precambrian rocks – Mainly Tertiary and Mesozoic sedimentary rocks
Yme	Precambrian Y rocks of Mount Ethel pluton
Xm	Precambrian X metamorphic wallrocks
•	Locality for thin section containing no observed fluorite
●	Locality for thin section containing <0.5 percent observed fluorite
⬤	Locality for thin section containg >0.5 percent observed fluorite

FIGURE 17. — Location of accessory fluorite in rocks of part of the northern Park Range.

One or more of the above varieties of fluorite may be found in the same thin section (for example, figs. 18*B*, 18*I*). Note that some fluorite formed before sericitization (fig. 18*D*), some formed just after sericitization (fig. 18*I*), whereas some formed long after sericitization (fig. 18*F*).


A
B
C
D
E
F

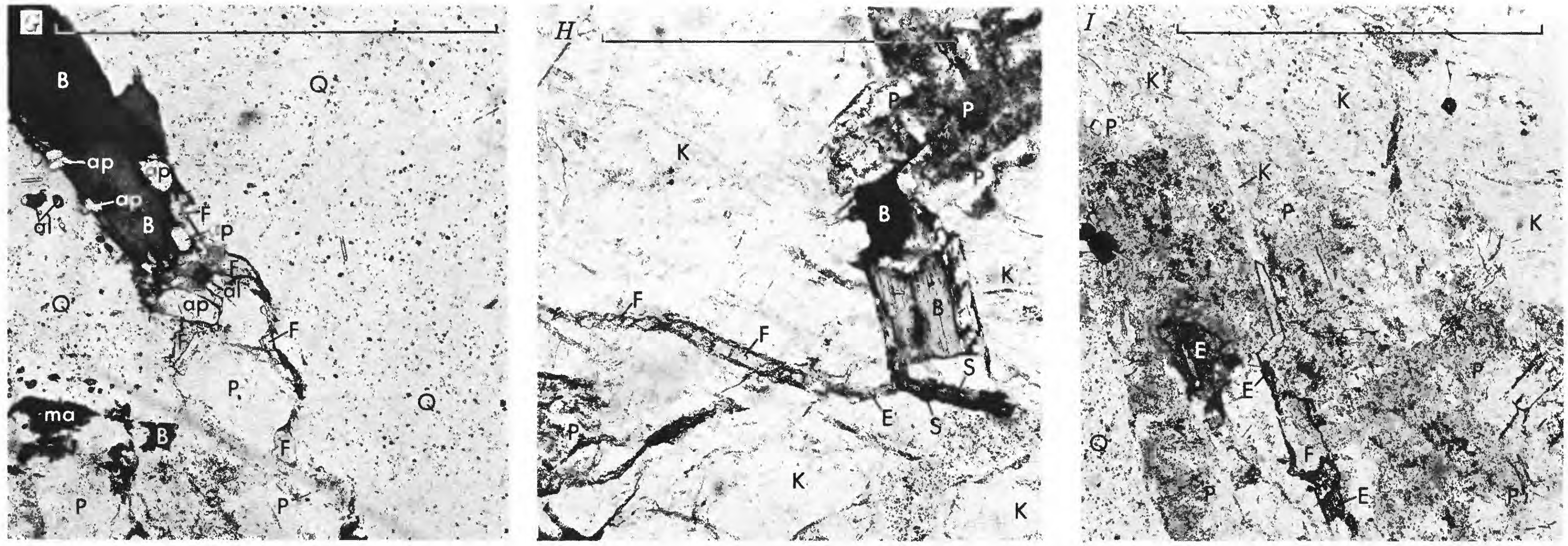


FIGURE 18. — Photomicrographs of fluorite in quartz monzonites and granites of Mount Ethel pluton. Scale bar equals 1 mm in each photograph; all photographs taken by Louise S. Hedricks in plane polarized light. Crystals: al, allanite; ap, apatite; B, biotite; E, epidote; F, fluorite; K, microcline; ma, magnetite; mu, muscovite; P, plagioclase, generally partly sericitized; Q, quartz; S, sphene; Z, zircon.

A. Interstitial fluorite associated with mafic minerals in fine-grained granite from Whalen Creek. This rock is from a dike cutting the rock represented by photographs *B* and *I*.

B. Interstitial fluorite associated with mafic and felsic minerals in quartz monzonite of Roxy Ann Lake from Whalen Creek.

C. Fluorite in a partly sericitized plagioclase grain in quartz monzonite of Roxy Ann Lake from the South Fork of Mad Creek.

D. Fluorite interstitial to plagioclase and quartz in quartz monzonite of Roxy Ann Lake near Ceanothuse Lake.

E. Fluorite including magnetite and biotite in quartz monzonite of Roxy Ann Lake from head of Newcomb Creek.

F. Fluorite concentrated in a single sericitized plagioclase grain from quartz monzonite of Roxy Ann Lake between Big Creek Lake and Luna Lake.

G. Interstitial fluorite associated with mafic and felsic minerals in quartz monzonite of Roxy Ann Lake from head of Newcomb Creek. Fluorite, generally clear and colorless, is purple immediately surrounding allanite grain.

H. Fluorite-containing vein cutting microcline from granite mapped with quartz monzonite of Roxy Ann Lake northeast of Lake Elbert.

I. Fluorite-containing vein cutting sericitized plagioclase from quartz monzonite of Roxy Ann Lake in Whalen Creek. Photograph *I* 2 cm from photograph *B* of same thin section.

Although the fluorite has not been dated radiometrically, some petrographic evidence confirms the ancient age of the fluorite. The usually colorless fluorite commonly becomes colored pink to purple to deep purple next to zircon or allanite (for example, fig. 18*G*), probably owing to radiation damage to the lattice of the fluorite crystal over a long period of time. In this sense these color haloes are similar to pleochroic haloes in biotite, hornblende, or cordierite, except that the present color haloes are not pleochroic (do not change color) in the isotropic fluorite. Some work has been done on dating pleochroic haloes (for example, Hayase, 1954; Deutsch and others, 1956), and analogous efforts might be successful in directly dating the color haloes in these fluorites. Phair and Shimamoto (1952, p. 664) have noted that in Jamestown, Colo., thorium and uranium haloes in fluorite crystals are especially numerous where the fluorite is dark. Other indirect evidence of ancient, probably Precambrian, fluorite comes from a single thin section of brecciated, mylonitized pegmatite (the 0.5 percent fluorite point near the extreme southwestern tip of the Mount Ethel pluton, fig. 17). This thin section contains centimeter-size angular pegmatite fragments in an anastomosing network of dark mylonite veins whose individual mineral constituents are so fine grained as to be partly unresolvable with a petrographic microscope. Fluorite veins as much as 0.1 mm wide cut some breccia fragments and are themselves truncated at the margins of the breccia fragments; a younger generation of fluorite in this same rock forms euhedral cubes as much as 0.03 mm wide replacing the mylonite matrix. If the mylonite is comparable in age (1.2 b.y.) to the nearest directly dated mylonite (Abbott, 1972), then the fluorite veins truncated by the mylonite must be >1.2 b.y. old.

Fluorite has been observed in some other quartz monzonites of probabaly equivalent age in the vicinity. The quartz monzonites on Sheep Mountain (fig. 2) and Delaney Butte in North Park (Hail, 1965, pls. 2, 3) are an upfaulted continuation of the Mount Ethel pluton; interstitial fluorite has been observed in both places. It is also present in the intrusive quartz monzonite at Northgate (Steven, 1957, pl. 48) that Behrendt, Popenoe, and Mattick (1969, p. 1523) believed may be continuous with the Mount Ethel pluton. Interstitial fluorite has been observed in thin sections of the following Sherman Granite bodies mapped by Houston and others (1968, pl. 1) in the Medicine Bow Mountains of Wyoming: (1) the large quartz monzonite body southeast of Mountain Home, (2) fine-grained quartz monzonite south of Ring Mountain, and (3) the quartz monzonite body at Sheep Mountain southeast of Centennial, Wyo. The present study has also confirmed fluorite in quartz monzonite of both the Inner and Outer Cap Rock (Eggler, 1968, p. 1551) and the Log Cabin Granite of Kirst (1968) at Virginia Dale northwest of Fort Collins, Colo. Fluorite is a trace constituent in several facies of the St. Kevin Granite, Holy Cross quadrangle, Colorado (Tweto and Pearson, 1964, p. D30). However, the usefulness of fluorite as a criterion for differentiating 1.4-b.y.-old from 1.8-b.y.-old granites may be purely local. Segerstrom and Young reported colorless fluorite from two samples of felsic gneiss and one sample of augen gneiss (1972, table 1, p. 11) on the shoulders of Farwell Mountain, either one or both of which may be equivalent to Buffalo Pass rocks. Fluorite has also been observed in the "older granite" on Jelm Mountain, Wyo. (Houston and others, 1968, pl. 1).

ECONOMIC IMPLICATIONS

Much fluorite was deposited contemporaneously with igneous mineral grains of the Mount Ethel pluton, and it has been demonstrably mobile in subsequent Precambrian time. It seems possible, if not likely, that this Precambrian fluorite was mobile at other Phanerozoic times, for example, in the Laramide orogeny (Steven, 1960, p. 395, 396) or Tertiary time, and, if so, it could have contributed to the economic Tertiary fluorite vein deposits in the North Park area. Similar mobilization of Precambrian lead and gold to form Tertiary deposits at Hahns Peak has been postulated by Antweiler, Doe, and Delevaux (1972, p. 312, 313) on the basis of isotopic evidence.

Fluorite veins have been exploited or prospected recently at five localities in the North Park area: two vein zones north of Northgate (Steven, 1960), the Crystal mine (fig. 17), a vein zone from 10,700- to 10,914-foot elevation on the ridge northwest of the Crystal mine, and a vein zone crossing the top of Delaney Butte. All these vein zones occur in rocks mapped as or equivalent to the quartz monzonite of Roxy Ann Lake, or in thin altered Tertiary sediments directly overlying the same quartz monzonite — the quartz monzonite that contains most of the interstitial fluorite (table 7). Steven (1960, p. 401) reported that the Northgate veins are richer where they cross the competent quartz monzonite or Tertiary sediments overlying the quartz monzonite, but they are relatively barren where they cross inclusions of hornblende gneiss country rock. All the vein zones strike northwest to northeast and contain white, purple, or green, comb-structured, mammillary fluorite, except the vein zone on Delaney Butte where it strikes east-west and contains colorless to white euhedral fluorite. The Delaney Butte zone appears to widen westward. Fault breccia reefs are abundant in the vicinity of the Crystal mine (fig. 17) and some of these containing significant fluorite may not yet have been thoroughly prospected: for example, 22.2 percent fluorite was measured in a brecciated, mylonitized quartz monzonite a mile north of the Crystal mine at the 9,250-foot elevation on the south side of an east-northeast-trending spur 450 feet southeast of Spring Creek. The rhyolitic (?) intrusion reported at the Crystal mine (Popenoe and others, 1970, p. 343) has not been confirmed by this investigation, but aplite dikes or quartz monzonite breccia reefs in the vicinity could easily be mistaken for rhyolite. Possibly, new economically recoverable fluorite deposits (for example, see The Denver Post, Sunday, June 11, 1972, p. 76) will be found along fluorite-cemented fault breccias in the northeastern part of the Mount Ethel pluton or elsewhere in the pluton where the more abundant intergranular fluorite (fig. 17) could have served as a source for redistribution by Tertiary solutions.

CORRELATION OF PARK RANGE ROCKS WITH OTHER IGNEOUS ROCKS OF COLORADO AND NEARBY WYOMING

General correlations of intrusive rock suites between separate areas in Colorado and Wyoming have been made possible by many existing radiometric dates. Some refinement of these general correlations can be accomplished with visual (field) observations of lithologies and structures, some with petrographic comparisons, and fewer with chemical comparisons. Much more comparative work of all kinds could and should be done, especially detailed mapping of field relationships, comparisons of different field areas, and radiometric dating of presently undated or difficultly datable rocks.

The state of knowledge in 1974 of the temporal relations of Precambrian geologic events in Colorado and adjacent Wyoming is diagrammed in figure 19. Assigned age relations of various igneous and structural events have been compiled separately for six subareas with an overall summary based first on radiometric dates and second on relative ages of radiometrically undated events with respect to the known dates.

Figure 19 shows the three main Precambrian plutonic events now well known in Colorado that produced the rocks of Boulder Creek age (1.7±0.1 b.y.), the rocks of Silver Plume age (1.4±0.1 b.y.), and the rocks of Pikes Peak age (1.05±0.05 b.y.) (Peterman and others, 1968; Hedge, 1970, Stern and others, 1971). The granodiorites and associated quartz monzonites of Boulder Creek age of the Front Range are represented in the Park Range by the quartz monzonites at Buffalo Pass, in the Needle Mountains by the Tenmile, Whitehead, and Bakers Bridge Granites and perhaps the Twilight Gneiss (Barker, 1969), in the Black Canyon of the Gunnison by the Pitts Meadow Granodiorite (Hansen and Peterman, 1968), and elsewhere in Colorado and nearby Wyoming by numerous unnamed granitoid rocks. The rocks of the Silver Plume, Longs Peak–St. Vrain, and Log Cabin batholiths of the Front Range (Peterman and others, 1968) fall in the same general time span as the rocks of the Mount Ethel pluton of the Park Range, the Eolus and Trimble Granites of the Needle Mountains (Barker, 1969), the Vernal Mesa and Curecanti Quartz Monzonites of the Black Canyon of the Gunnison (Hansen and Peterman, 1968) and the Uncompahgre Plateau (Hedge and others, 1968), the St. Kevin Granite of the Sawatch Range (Pearson and others, 1966), the Sherman Granite of Wyoming and northern Colorado (Peterman and others, 1968; Hills and others, 1968), and other smaller bodies elsewhere in the vicinity. The Pikes Peak batholith with its satellitic plutons of the southern Front Range is the only large billion-year-old batholith of the region (Hutchinson, 1960b; Hedge, 1970). The only rocks of a remotely similar age in the Park Range are small dikes; fine-grained microgranophyre dikes near the west end of Gore Canyon 20 miles south of this area have been dated at 1.13±0.15 b.y. (Rb-Sr whole rock) (Barclay and Hedge, written commun., 1967; Barclay, 1968, p. 71–75); "granite porphyry" from Slavonia immediately north of this area has furnished zircon that gave a lead-alpha date of 739 m.y. (Jaffe and others, 1959, p. 128). Granites of a 2.4 b.y. age are found northwest of the Mullen Creek–Nash Fork shear zone in Wyoming, but rocks of this age are not known southeast of this shear zone in Wyoming or Colorado (Houston and others, 1968; Hills and others, 1968).

Figure 20 depicts the statistical distribution of 107 Colorado plutonic rocks of Boulder Creek and Silver Plume age concentrated near the experimental granite minima (fig. 16). The reader will note that, within the framework of the available chemical analyses, the concentrations of most analyzed rocks for each affinity are the same but that the range of composition of the rocks of Silver Plume affinity is more restricted. The more potassium feldspar-poor compositions, especially trondhjemitic varieties, are not represented during the 1.4±0.1 b.y. plutonic episode. At least one of these, the Twilight Gneiss is now thought to have originated as volcanic or hypabyssal igneous rock that was metamorphosed to high grade within 50 or 75 m.y. after its emplacement (Barker, Peterman, and Hildreth, 1969a). Figure 20*D* indicates that the field of the most highly differentiated rocks coincides approximately with the field of most abundant compositions (Fig. 20*A*). and that there is a smooth, though somewhat irregular, transition to this field from the least differentiated rocks. In short, the more differentiated rocks tend

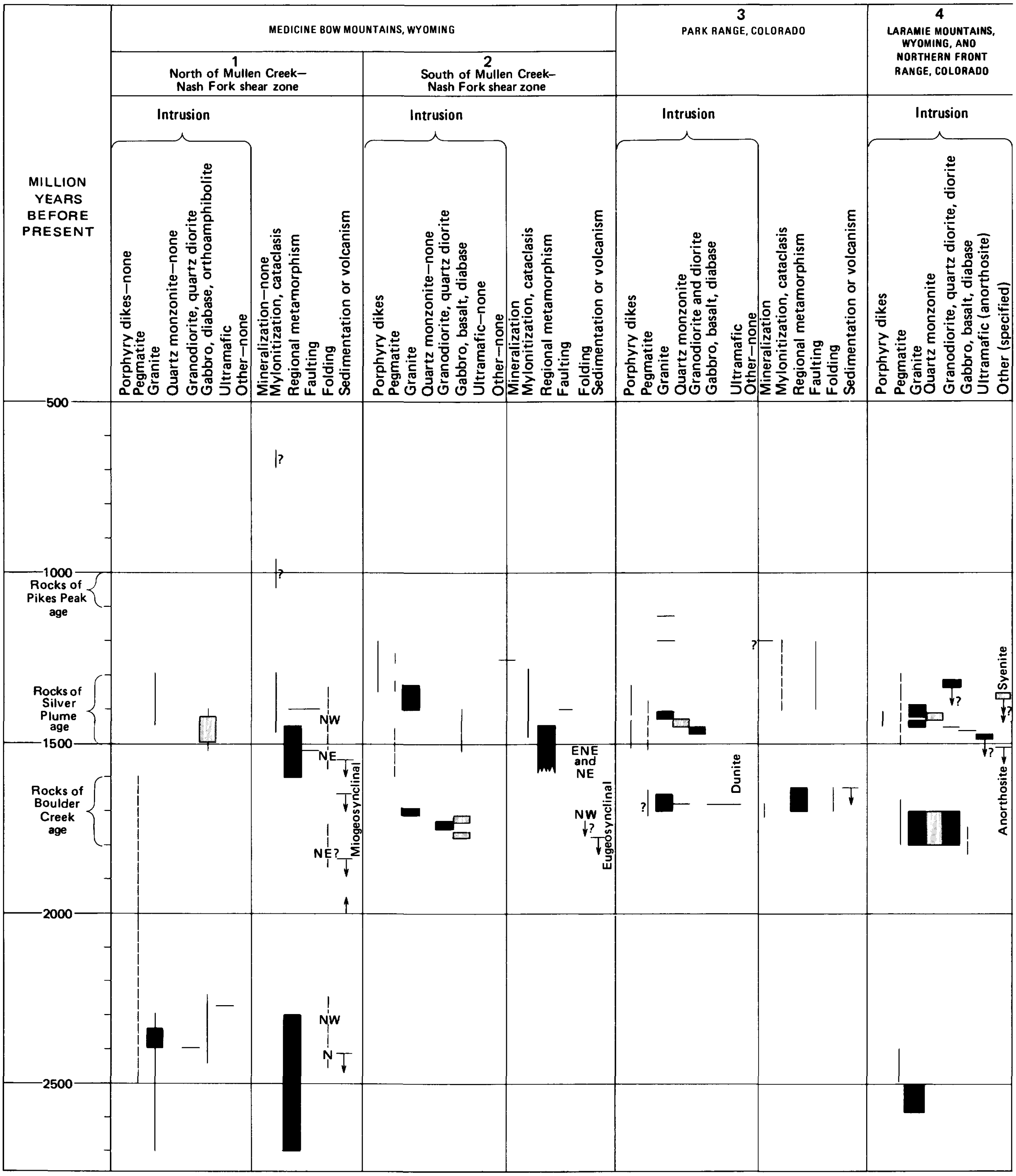
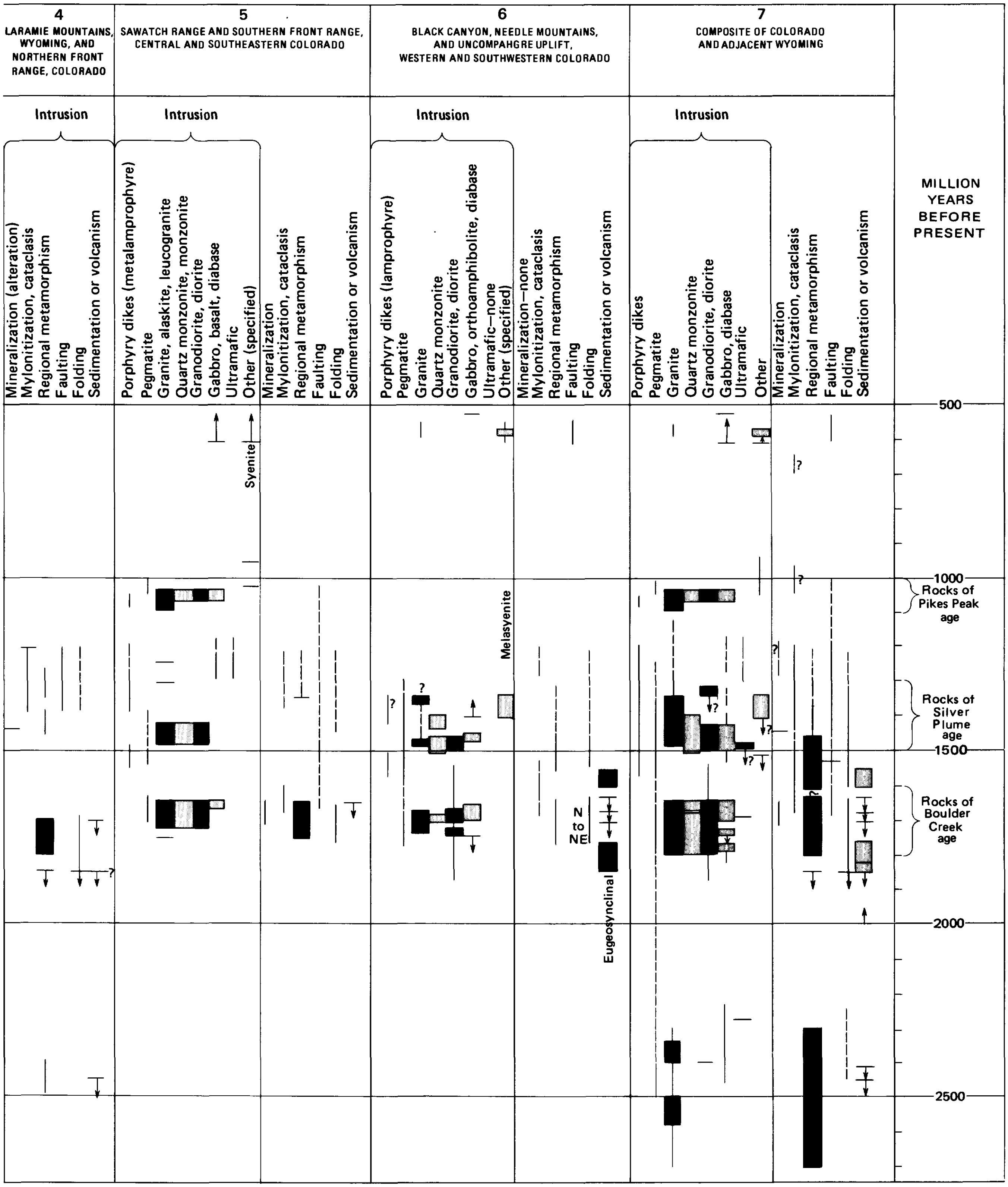


FIGURE 19. — Assigned temporal relations of Precambrian geologic events in Colorado and adjacent Wyoming. Arrows point in the direction of are queried where uncertain. Boxes show major events; lines show less important events, and they are



the true age of events that so far can only be dated as "older than" or "younger than" with respect to radiometrically known dates; these dashed in less certain parts of their ranges. Sources of data listed in the table on the following page.

Sources of data for figure 19

1,2. Hills, Gast, and Houston (1965, 1967); Hills, Gast, Houston, and Swainbank (1968); Houston and others (1968); Houston, Hills, and Gast (1966).

3. This paper; J. C. Antweiler (written commun., 1965); Antweiler (1966); J. C. Antweiler, M. H. Delevaux, and B. R. Doe (written commun., 1968); C. S. V. Barclay and C. E. Hedge (written commun., 1967); Jaffe, Gottfried, Waring, and Worthing (1959, p. 128); Kenneth Segerstrom and C. E. Hedge (written commun., 1970); Segerstrom and Young (1972); U.S. Geological Survey (1968, p. A28).

4. Abbott (1972); Aldrich and others (1957, 1958); Condie (1969a, b); Eggler (1968); Eggler, Larson, and Bradley (1969); Fenton and Faure (1969); Ferris and Krueger (1964); Giletti and Gast (1961); Harrison and Wells (1959); Hedge, Peterman, and Braddock (1967); Hepp (1966); Hills and Armstrong (1971); Klugman (1960); Moench, Harrison, and Sims (1962); Peterman and Hedge (1967); Peterman, Hedge, and Braddock (1968); Smithson and Hodge (1969).

5. Brock and Singewald (1968); Bryant, Miller, and Scott (1971); Doe and Pearson (1969); Gross and Heinrich (1966); Hawley, Huffman, Hamilton, and Rader (1966); Hedge (1970); Hedge, Peterman, Case, and Obradovich (1968); Hutchinson (1960a, b); Hutchinson and Hedge (1968); Lovering and Goddard Gross and Heinrich (1966); Hawley, Huffman, Hamilton, and Rader (1966); Hedge (1970); Hedge, Peterman, Case, and Obradovich (1968); Hutchinson (1960a, b); Hutchinson and Hedge (1968); Lovering and Goddard (1950, p. 64--65); Pearson, Hedge, Thomas, and Stern (1966); Peterman and Hedge (1967); Stern, Phair, and Newell (1971); Taylor and Sims (1962); Tweto and Sims (1963); Wells (1967); Wetherill and Bickford (1965); Wobus (1969).

6. Barker, Peterman, and Hildreth (1969a, b); Barker, Peterman, and Marvin (1969); Bickford, Wetherill, Barker, and Lee-Hu (1969); Cudzilo (1971); Hansen and Peterman (1968); Hedge, Peterman, Case and Obradovich (1968); Mose and Bickford (1969); Silver and Barker (1968); U.S. Geol. Survey (1969, p. A41, A116).

7. Composite of columns 1–6.

to be more abundant than the least differentiated rocks, a situation incompatible either with partial crustal melting and rheomorphism or with differentiation by fractional crystallization at this or any other single level of the crust. Differentiation from more mafic rocks by either mechanism must have taken place at a deeper crustal level. Subsequently, silicic rocks rose through the crust leaving behind mafic rocks disproportionately increased in amount compared to their initial volume.

SHERMAN–SILVER PLUME DICHOTOMY

Current radiometric dating techniques are generally unable to discern any differences in the ages of intraplutonic activity, and so precise temporal correlation of specific magmatic events in separate areas cannot be made. Nevertheless, there are certain petrographic similarities or petrogenetic parallels between the rock suites of separate plutons, especially those of Silver Plume age. These are worth noting even though it is not known whether similar rocks are due to parallel evolution of separate batches of magma intruded at slightly different times or to simultaneous magmatic intrusion with synchronous evolution of all plutons. The general time progression from diorite and granodiorite through quartz monzonite to granite and leucogranite evident in the Mount Ethel pluton is also repeated in some other plutons. The most evident similarities are with one of the best studied nearby areas, the Virginia Dale ring dike complex between Fort Collins, Colo. and Laramie, Wyo. (Eggler, 1968; Eggler and others, 1969; Peterman and others, 1968). Here, the sequence of igneous events, generally from outermost to innermost parts of the pluton, is (1) (oldest) hornblende gabbro; (2) diorite, andesite, and hybrid rocks; (3) coarse-grained Trail Creek Granite of Eggler (1967) including both the main unringed batholith and the outermost ring of the ring complex, in that order, the latter being somewhat more aluminous than the former; (4) coarse-grained and porphyritic quartz monzonite at Cap Rock including an outer incomplete ring and an inner complete ring, in that order; and (5) medium-grained Log Cabin Granite of Kirst (1968), in the center of the pluton. The coarser grained rocks including both nonporphyritic Trail Creek Granite and both porphyritic quartz monzonites at Cap Rock are together called Sherman Granite, and the medium-grained Log Cabin Granite is equated with type Silver Plume Granite. That the Log Cabin and Silver Plume are younger than the Sherman is shown not only by the more central position of the Log Cabin in the ring complex but also by the fact that a northwest-trending porphyritic andesite dike swarm that cuts Sherman in the Virginia Dale area (Eggler, 1968, pl. 1) is cut by Silver Plume Granite in the Big Thompson Canyon east of Estes Park (Hepp, 1966, p. 65). Reported radiometric ages of the Log Cabin, and its equivalent, the Silver Plume, and the Sherman Granite overlap (Log Cabin and Silver Plume range=1.21–1.45 b.y.: Aldrich and others, 1958, p. 1130; Peterman and others, 1968, p. 2290; Stern and others, 1971, p. 1624–1626; Sherman Granite range=1.31–1.44 b.y.: Aldrich and others, 1957, p. 656; Aldrich and others, 1958, p. 1130; Giletti and Gast, 1961, p. 455; Hills and others, 1968, p. 1770; Peterman and others, 1968, p. 2287–2289), and the Log Cabin–Sherman age difference in northern Colorado "appears to be less, and possibly significantly less, than 40 m.y." (Peterman and others, 1968, p. 2289). In the Mount Ethel pluton the coarse-grained quartz monzonite porphyry of Rocky Peak appears to be the lithologic correlative of the coarse-grained Sherman Granite of the Virginia Dale area, especially of the porphyritic quartz monzonites at Cap Rock, while the medium-grained muscovite-containing quartz monzonite of Roxy Ann Lake and

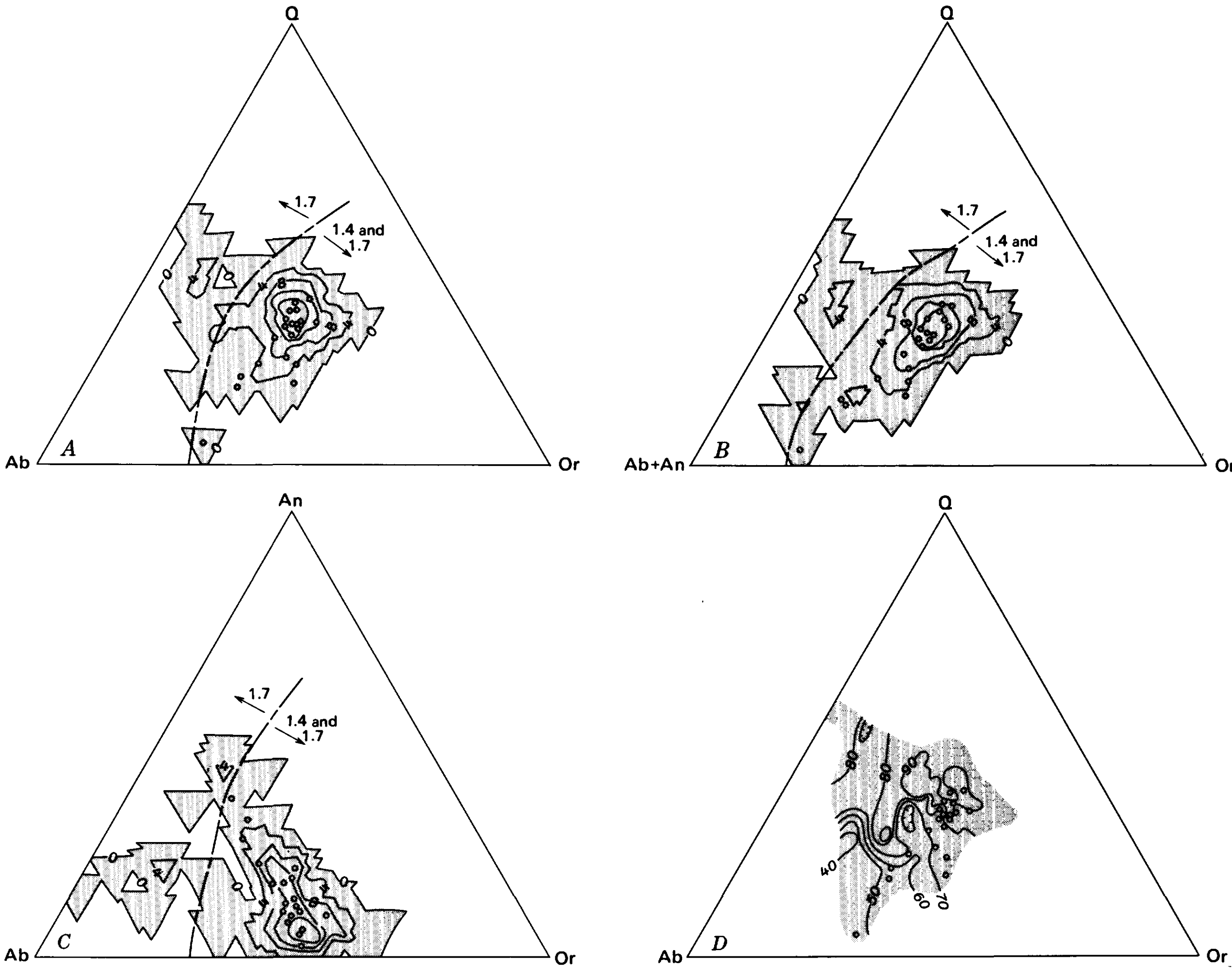


FIGURE 20. — Three frequency distributions (*A*, *B*, *C*) and one contoured differentiation index diagram (*D*) comparing ternary plots of normative minerals of 107 analyzed and dated Colorado Precambrian plutonic rocks with those of the Park Range. Frequency contours = 0-, 4-, 8-, 12-, and > 16- percent per one-percent area. The differentiation index diagram was constructed by contouring the differentiation index value for each rock (Q + Ab + Or in every case) plotted at its appropriate location in the ternary diagram. Rocks of 1.4 ± 0.1 b.y. age are restricted to the right side of the dashed line in the appropriate diagrams; whereas rocks of 7 ± 0.1 b.y. age are distributed throughout the area represented. Points are Park Range plutonic rocks detailed in previous figures. Besides these 20 analyses, data include 19 analyses from southwest Colorado (Barker, 1969), 33 from central and western Colorado (J. E. Case, written commun., 1965; Hansen, 1964; W. R. Hansen, written commun., 1966, 1967; Hansen and Peterman, 1968; Hedge and others, 1968; Pearson and others, 1966; Tweto and Pearson, 1964), and 35 from northern Colorado (Eggler, 1968; Lovering and Tweto, 1953; Peterman and others, 1968; Sims and Gable, 1967; Wells, 1967). Seven other analyses available too late for inclusion in these diagrams are given by Stern, Phair, and Newell (1971, p. 1620).

younger granites are a close lithologic match for the medium-grained muscovite-containing Log Cabin and Silver Plume Granites. If this lithologic correlation is correct, the Silver Plume correlatives make up by far the volumetrically greatest part of the Mount Ethel pluton, and the Sherman correlatives make up a smaller part — the reverse of the relative Silver Plume and Sherman volumes in the Virginia Dale pluton.

A similar plutonic sequence appears to be present in the 1.3–1.5-b.y.-old Eolus batholith and related rocks of the Needle Mountains (Barker, 1969; Bickford and others, 1969; Silver and Barker, 1968). Although crosscutting relations are not present between all rock types, the following sequence is determined by the known relations plus many radiometric ages: (1) (possibly oldest) Electra Lake Gabbro (olivine gabbro to granodiorite); (2) quartz diorite of Pine River; (3) rocks mapped as Eolus Granite (ranges from granodiorite — oldest — through biotite-hornblende quartz monzonite — most of batholith — to biotite quartz monzonite, biotite granite, biotite-muscovite granite, and alaskite); (4) porphyritic muscovite-containing Trimble Granite (near the center of the batholith); and (5) rhyolite porphyry and aplite dikes. Here, the predominant quartz monzonites might be the equivalent of the quartz monzonite porphyry of Rocky Peak or the Sherman Granite, while the various muscovite-containing granites might be the equivalents of the quartz monzonite of Roxy Ann Lake or the Silver Plume Granite.

Elsewhere in Colorado, the split between a slightly older porphyritic Sherman equivalent and a slightly younger, finer grained, muscovite-containing Silver Plume equivalent may also be present. In the Black Canyon of the Gunnison, the older but volumetrically predominant mesokatazonal Vernal Mesa Quartz Monzonite, a very coarse grained porphyritic biotite quartz monzonite and granodiorite, may be a Sherman equivalent while the younger, volumetrically less important, epimesozonal Curecanti Quartz Monzonite, a medium grained biotite-muscovite quartz monzonite or granite in separate plutons, may be a Silver Plume equivalent (Hansen, 1964; 1968; 1971; Hansen and Peterman, 1968). A batholith of Vernal Mesa and younger separate bodies of biotite-muscovite granite are also reported from the Uncompahgre Plateau (Aldrich and others, 1958; Hedge and others, 1968). The fine-grained to coarsely porphyritic biotite-muscovite granite to granodiorite of the St. Kevin batholith may be the Silver Plume equivalent in the Sawatch Range (Tweto and Pearson, 1964; Pearson and others, 1966). Older porphyritic quartz monzonite of Eleven Mile Canyon (Sherman lithologic equivalent?) has been intruded by fine- to medium-grained quartz monzonite tentatively correlated with Silver Plume in the Florissant quadrangle of the southern Front Range (Wobus, 1969).

MAFIC DIKES

Tabular dikes of late Precambrian age, variously described as "porphyry," "lamprophyre," or just "mafic" are present in many areas of Colorado, and intrusions appear to have occurred over a very long span of time. Some dikes have been dated directly; most can be bracketed indirectly but usually not within precise limits. In a few areas, dikes of two ages can be observed or deduced even though hand specimens of the two types may be indistinguishable from each other. (For example, the porphyry dikes of pre- and post-quartz monzonite of Roxy Ann Lake age described in this report; see also Pearson and others, 1966, p. 1113; Gable, 1968, p. E35; and Hansen and Peterman, 1968, p. C86–C87, for similar phenomena in the Sawatch, Morrison, and Black Canyon areas.) Evidence for at least five periods of mafic dike-producing magma intrusion is available in the Medicine Bow Mountains of Wyoming (Houston and others, 1968). When all available data are assembled for the Precambrian of Colorado and adjacent Wyoming (fig. 19), the following statements seem pertinent:

1. Basalt or diabase dike-producing events were prominent north of the Mullen Creek–Nash Fork shear zone (Houston and others, 1968) from about 2.45 to 2.24 b.y. ago. As far as is known, these are not recorded anywhere in Colorado.
2. Porphyry or lamprophyre dike-producing events were prominent somewhere in Colorado from about 1.52 b.y. to probably 1.16 b.y. ago, possibly to 1.05 b.y. ago. No single area had dike activity throughout this time. Some areas as noted experienced two pulses but these double events seem not to have been completely simultaneous in all separate areas.
3. Late mafic dike events occurred locally after 600 m.y. ago.
4. Evidence is lacking for mafic dike events during the Precambrian in Colorado and Adjacent Wyoming except at the times summarized above.

North and northwest of this area in Wyoming and in adjacent Montana as many as seven ages of basalt intrusion have been recognized in the range 0.7 to >2.6 b.y. (Mueller, 1970; Rowan and Mueller, 1971), and the Beartooth Mountains "nonfolded dike set" in the range 1.2 to 1.5 b.y. may be equivalent to the Colorado porphyry-lamprophyre dike set, the one represented in the Park Range. Prinz (1964) recognized three ages of Precambrian dikes and one age of Tertiary(?) dikes; one of these Tertiary(?) dikes was later dated by K-Ar whole rock at 1.5. b.y. old. (Condie and others, 1969). The latter authors dated many different dikes by K-Ar whole-rock from the Beartooth Mountains of Montana and Wyoming, the Bighorn Mountains, the Owl Creek Mountains, and the Wind River Range of Wyoming and recognized four ages of dikes in the range 0.7 to 2.5 b.y. Other dating techniques and m.y. too young (Heimlich and Banks, 1968 — Bighorn Mountains; Spall, 1971 — Wind River Range; Rowan and Mueller, 1971 — Beartooth Mountains). Rosholt and Peterman (1969) have indicated 1.6 b.y. as a time of extensive diabase dike emplacement in the Granite Mountains of Wyoming. John C. Reed, Jr. (oral and written communs., 1972; Reed and Zartman, 1972, p. 404; 1973, p. 576) reported that a 150-foot diabase dike in the Teton Range of Wyoming was intruded between 1.3 and 2.5 b.y. ago, possibly closer to the younger age (U.S. Geological Survey, 1971). It may well be, as Condie and others

(1969) and Mueller (1970) contended, that dike intrusion in this part of the earth's crust was confined to certain definite periods of time between which no dikes were intruded, although future data may extend the known times of dike intrusion.

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