Igneous Rocks in the Bingham Mining District, Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 629-B

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By WILLIAM J. MOORE

GEOLOGIC STUDIES OF THE BINGHAM MINING DISTRICT, UTAH

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A petrologic study of intrusive and extrusive igneous rocks in a classic mining area

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By WILLIAM J. MOORE

ABSTRACT

Igneous rocks in the Bingham area include two small monzonitic stocks, a series of younger latitic dikes, and, east of the mining district, a sequence of latitic breccias and flows. The igneous rocks were emplaced or erupted over a period of about 8 million years in latest Eocene and early Oligocene time (39–31 million years ago). Progressive increases in silica content and in proportions of alkali feldspar to plagioclase suggest that the rocks were derived from a single magma source. Stratigraphic reconstruction gives a maximum depth of cover of 7,500 feet at the time of monzonitic plutonism. The magma system was probably fluid-undersaturated ($P_{fluid} < P_{load}$) early in the igneous history, but separation of a fluid phase occurred at least twice in the later stages of magmatism. This enrichment in hydrous fluids is considered to be a further consequence of the same differentiation process that led to increasingly silicic or potassic bulk compositions or both. Vertical displacement and concomitant erosion of fault-bounded blocks of roof rock may have facilitated emplacement of the intrusive complex at the present level of exposure.

INTRODUCTION

This report describes the intrusive igneous rocks in the Bingham mining district and the extrusive igneous rocks in an area adjoining the district to the east and south. Because the unmineralized rocks are emphasized in this report, it should be regarded as background for subsequent reports in this series detailing the geology of the ore deposits at Bingham.

The Bingham mining district is in the east-central Oquirrh Mountains, about 20 air miles southwest of Salt Lake City, Utah. Igneous rocks of the district, broadly defined, are exposed in parts of the Bingham Canyon, Lark, and Tickville Springs 7½-minute quadrangles. Two small epizonal stocks plus numerous dikes and sills intrude upper Paleozoic rocks in the district proper. Volcanic flows and laharic breccias cover the lower east slopes of the Oquirrh Mountains and make up about 60 percent of the bedrock exposures in the east-trending Traverse Range (figs. 1, 2). Although not as closely related to the ore deposits as units of the intrusive complex, the volcanic rocks in the Bingham district display close chemical affinities to the intrusions and are considered here as part of a single extended magmatic episode.

In general terms, the rocks may be described as monzonitic or latitic; textural and mineralogical variations are apparently greater than differences in bulk chemical composition. Several small rhyolitic plugs and related vitrophyric flows represent the greatest departure from intermediate compositions in the entire igneous suite.

Limiting ages, based on radiometric dates, range from latest Eocene for the oldest intrusive body to middle Oligocene for the topographically highest unit in the volcanic sequence. Similarities in composition and age between igneous rocks at Bingham and those in the nearby Tintic and Park City mining districts define a regional epoch of middle Tertiary magmatism and metallization in north-central Utah.

Several reports concerned directly with the igneous petrology of the Bingham district had already been published by the time this study began (1965). The earliest report (Boutwell 1905), a brief and generalized treatment completed before the inception of open-pit mining, noted textural differences between the monzonitic and latitic rocks and presented four chemical analyses of fresh and mineralized monzonite from underground workings. Butler, Loughlin, Heikes, and others (1920) provided new chemical analyses to illustrate the general sim-

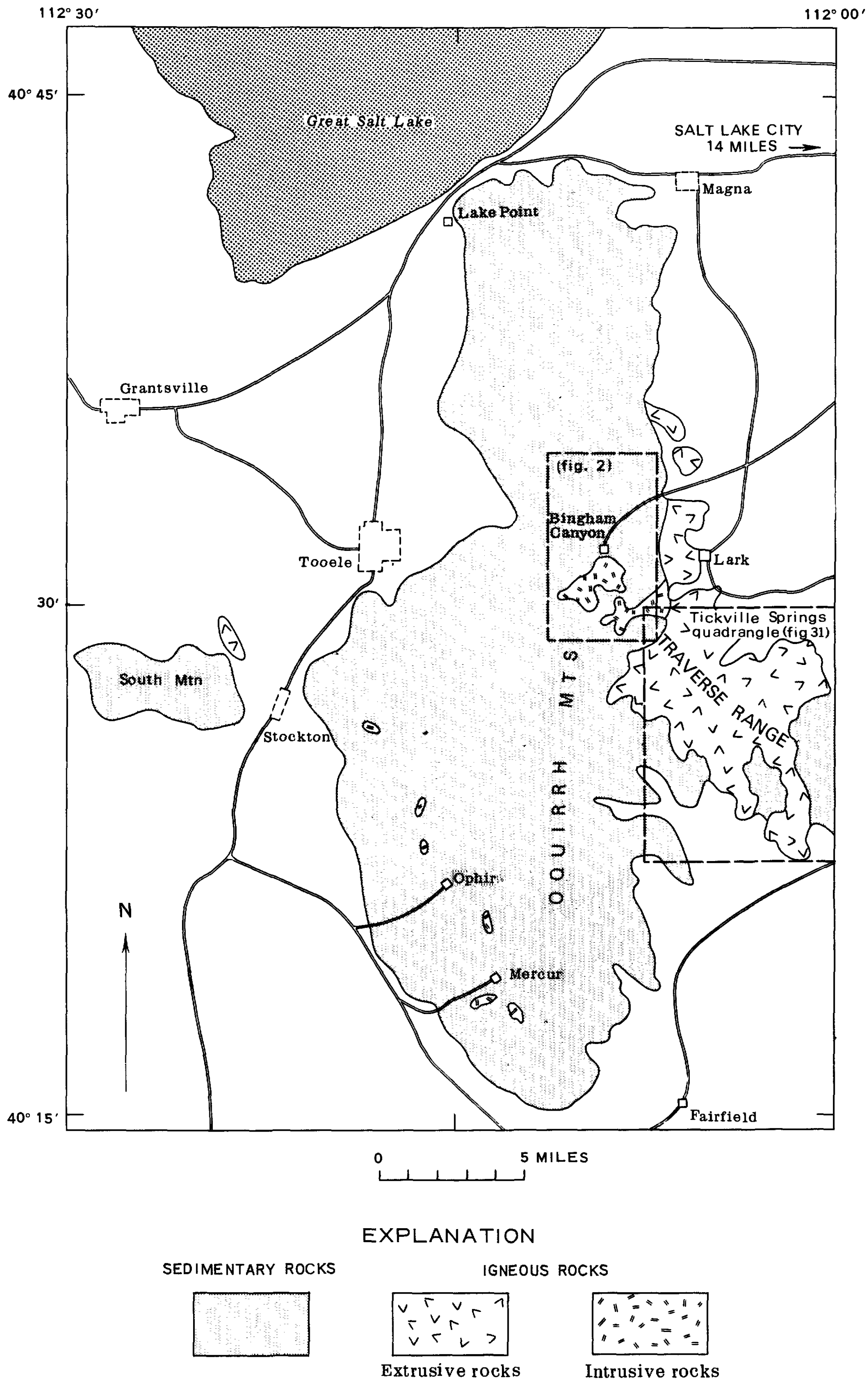


FIGURE 1.—Generalized distribution of igneous rocks in the Oquirrh Mountains and areas of figures 2 and 31. Adapted from Tooker and Roberts (1970, fig. 4).

ilarity of the main intrusions in the Tintic, Park City, and Bingham districts but were dependent largely on Boutwell's petrographic descriptions. Gilluly (1932) presented additional evidence favoring a probable comagmatic origin and mid-Tertiary age for intrusive and extrusive rocks in the Bingham area.

In contrast to the concepts of magma differentiation advanced by Gilluly and other writers, Stringham (1953) suggested that several of the major "igneous appearing" rock units may have been formed by processes of granitization. Although results of subsequent studies support the magmatic model proposed earlier (Peters and others, 1966; Moore, 1969), vestiges of Stringham's rock classification are still in use. For example, the terms "granite" and "granite porphyry" are applied to monzonitic rocks of the Bingham stock that have undergone pervasive hydrogen metasomatism. (See Stringham, 1966; Bray, 1969; Smith, 1969.)

The conflicting terminologies reflect differences of opinion regarding the petrologic evolution of host rocks in the Bingham copper ore body. Chemical and mineralogical changes resulting from hydrothermal alteration cannot be defined or followed without a well-established initial point of reference, thus the emphasis on unmineralized rocks in this report. Given this unified framework, an evaluation of alteration and mineralization process at Bingham is possible.

ACKNOWLEDGMENTS

Permission to work in underground mines of the Bingham district was kindly granted by officials of the U.S. Smelting Refining and Mining Company and The Anaconda Company; the helpful advice offered by their operating personnel is appreciated. Among the geologists who have generously shared their knowledge of the district, I particularly wish to thank Dick Rubright and Owen Hart of U.S.S.R. & M.; John Hunt and Julian Hemley of Anaconda; and Allan James, Wilbur Smith, Eldon Bray, Ed John, Blaine Willis, and Jeren Swensen of the Kennecott Copper Corporation. Careful technical reviews by N. G. Banks and Roger Ashley have improved the presentation of the results.

METHODS OF STUDY

Fieldwork for this study was begun in the fall of 1965 and was largely completed in the fall of 1968. Reconnaissance areal mapping in the Tickville Springs 7½-minute quadrangle was begun in 1968. Because of restricted surface access in the district, detailed mapping was confined largely to underground workings of the U.S. Smelting Refining and Mining Company and The Anaconda Company.

The east half of the Last Chance stock was studied over a vertical interval of about 2,400 feet in the U.S. mine. Projected limits of the mine area are shown in figure 3. This work, including detailed mapping and sampling of selected areas at scales ranging from 1 inch = 10 feet to 1 inch = 30 feet, was undertaken in conjunction with a broader study of the replacement and fissure ores in the mine.

The south and east margins of the Bingham stock were examined and sampled in parts of the Bingham haulage tunnel (~5,600-ft elev); the Niagara tunnel (~6,600-ft elev), accessible from the U.S. mine; and the Mascotte tunnel (~ 5,600-ft elev), accessible from the Lark shaft (fig. 3). Major lithologic variations and sample locations were noted on existing company maps.

A series of latitic dikes, some of which cut the stocks, were studied in the Utah Metals tunnel (~7,000-ft elev). Latitic dikes and sills similar to those of the Utah Metals tunnel were also sampled in the Butterfield and St. Joe tunnels (~6,000-ft elev) in the southeastern part of the district (fig. 3). In addition, representative samples of the major mineralized igneous rock types in the Kennecott Copper Corporation's open-pit mine have been collected by colleagues of the author in 1963 and by the author in 1967 and 1968.

Field investigations were interspersed with petrographic and mineralogic studies. Mineral percentages (modes) for nearly 150 igneous rocks were determined from thin sections containing alkali feldspar stained by sodium cobaltinitrite according to the method of Bailey and Stevens (1960) and Laniz, Stevens, and Norman (1964). The failure of previous investigators to use this simple but diagnostic method may explain the apparent confusion regarding felsic mineral proportions in the fine-grained igneous rocks at Bingham. Point-count estimates of volume percentages are based on at least 500 points for the granitoid and porphyritic granitoid rocks and 300 points for porphyritic latites and rhyolites with submicroscopic groundmass textures; each mode represents an area of about 500 mm^2.

Preliminary modes were correlated with bulk specific gravity values determined in the laboratory. Subsequent determinations were made daily in the field to provide a crude measure of compositional

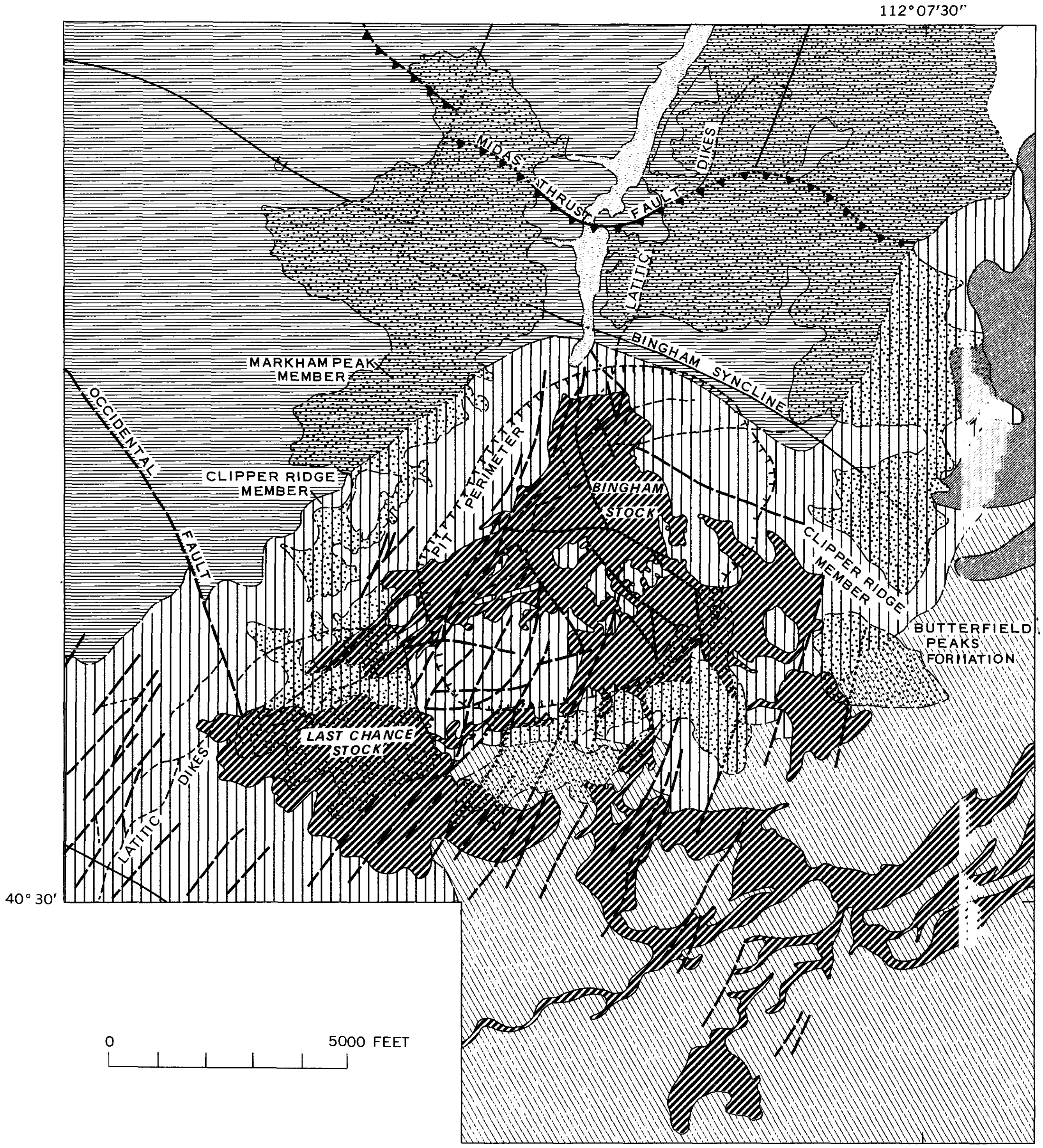
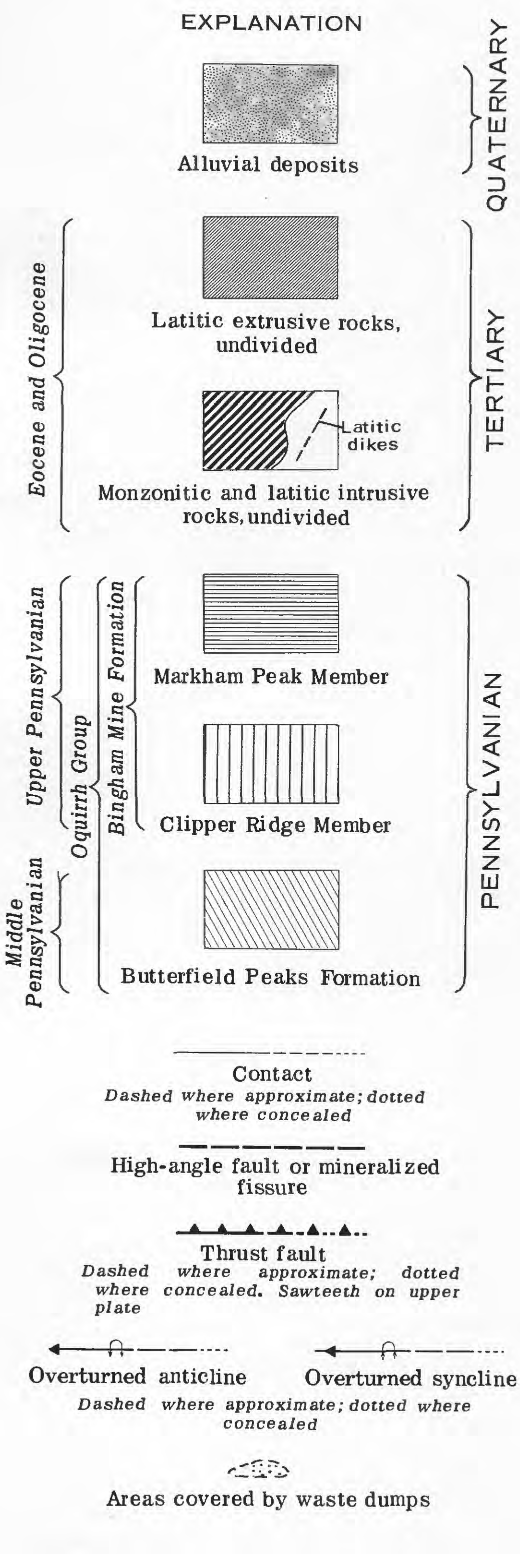


FIGURE 2.—Generalized geologic map of the Bingham area. Adapted from Tooker (1971), Bray (1969), and unpublished mapping by staff of the Kennecott Copper Corp.



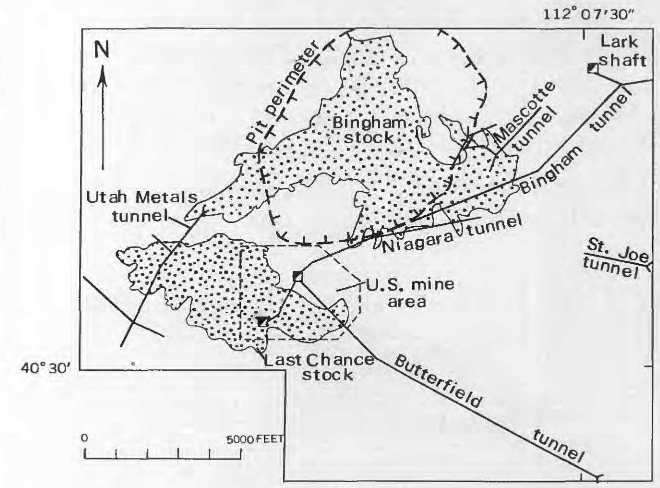


FIGURE 3.—Underground workings examined in this study.

variability and to aid in delineating gradational transitions between igneous facies.

Chemical analyses using rapid methods (Shapiro and Brannock, 1956) and semiquantitative spectrographic analyses for 35 unmineralized igneous rocks are reported. Compositions of alkali feldspars from selected samples were determined by an X-ray powder method relating weight percentage of the orthoclase component to angular position of the ($\bar{2}01$) reflections (Wright and Stewart, 1968). Plagioclase compositions were obtained by standard oil immersion methods. Molecular proportions of iron and magnesium in biotite and clinopyroxene samples from the Last Chance stock were determined by partial chemical analysis. Also included in the discussion are results of 15 potassium-argon age determinations, most of which were reported previously (Moore and others, 1968).

INTRUSIVE IGNEOUS ROCKS

LAST CHANCE STOCK

GENERAL FEATURES

The Last Chance stock intrudes the southwest limb of the Bingham syncline and crops out in an oval area measuring about 6,000 by 3,000 feet; the major axis trends west-northwest. Limited underground observations suggest that the large donut-shaped body in the south-central part of the district (fig. 2) is an extension of the stock, and the two presumably connect at a shallow depth. Narrow apophyses extending from the main mass are found on all levels of the U.S. mine (6,600–4,200-ft elev). Intrusive contacts in general are sharply irregular and discordant and dip steeply outward from the center of the stock. Dips are locally reversed or determined by the attitude of prominent limestone horizons, which strike northwest and dip northeast. (See Rubright and Hart, 1968, fig. 5.)

The stock contains rotated inclusions of mixed metasedimentary lithology (fig. 4); the largest blocks are as much as several hundred feet in maximum dimension and commonly occur near margins of the stock on upper levels of the mine. Evidence from a few localities suggests that some blocks were dislodged by an advancing magma (fig. 5) but, overall, the country rocks are not noticeably deformed or forced apart.

FIGURE 4.—Angular siliceous limestone fragments in border phase of Last Chance stock. Note narrow clinopyroxene reaction rims. Sample collected at surface south of Utah Copper pit by R. D. Rubright, resident geologist, U.S. Smelting Refining and Mining Co.

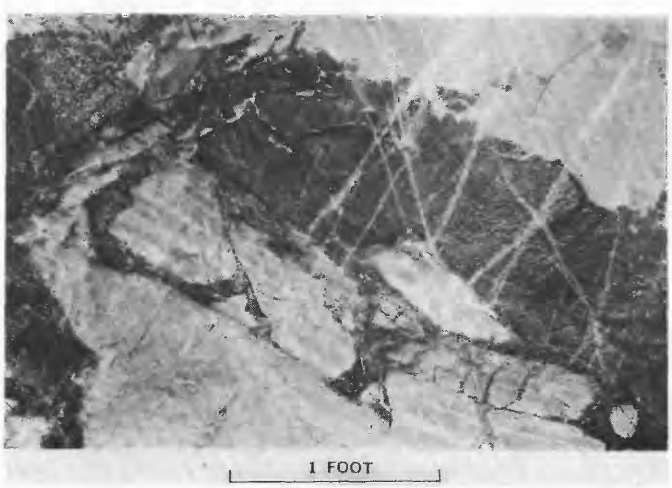


FIGURE 5.—Block stoping of light-colored banded metalimestone by dark-colored dikelike apophysis of Last Chance stock. From 1800 level, U.S. mine.

Small volumes of rock in border zones of the Last Chance stock have been locally affected by assimilation of calcareous sediments. These hybrid variants will be discussed apart from rocks making up the main mass of the stock.

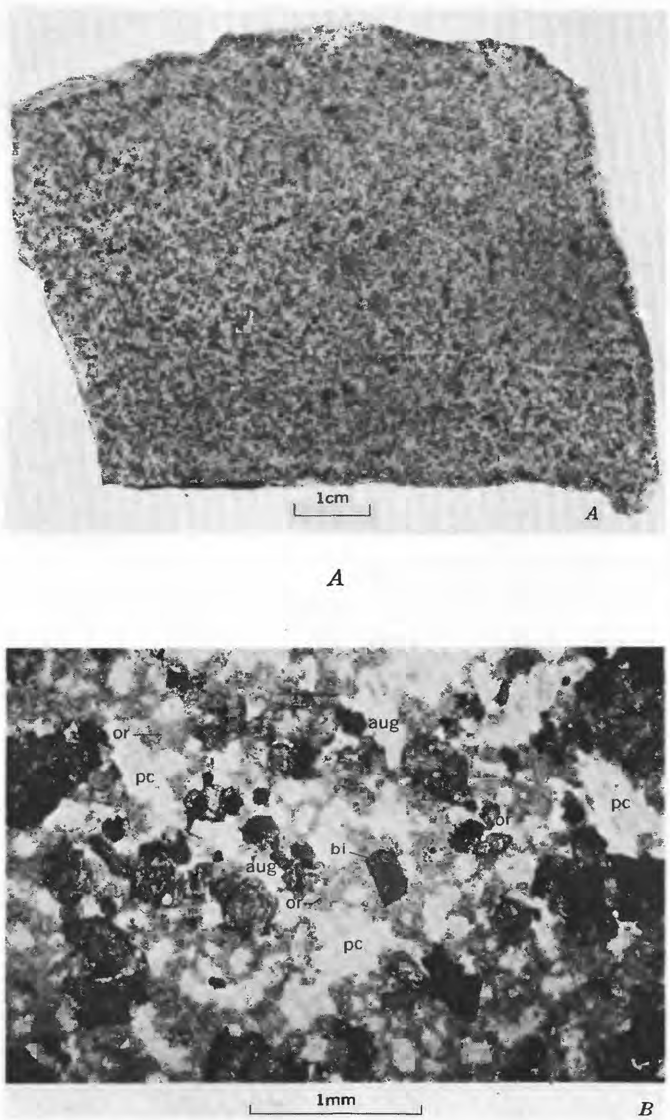
Contact metamorphic or metasomatic rocks form an irregular and relatively narrow zone around the Last Chance stock. Calc-silicate minerals are rarely found more than 1,000 feet from intrusive contacts. Dense white to pale-green wollastonite-quartz-diopside hornfels with interbedded lenses of marble and metaquartzite make up the entire stratigraphic section in the U.S. mine; locally the calc-silicate rocks are coarse and contain small pods or aggregates of pale-brown grossularite and idocrase. Volume proportions of the calc-silicate minerals vary considerably and apparently reflect original compositional differences in the sedimentary rocks. Metasomatic changes in limestones adjacent to the stock are confined to irregular banded zones, at most a few feet wide, which generally parallel intrusive contacts.

Available reports give token recognition to petrographic features of the Last Chance stock. Boutwell (1905) described the major mineral components and recognized gradational transitions between monzonite and quartz monzonite facies; he considered the Last Chance and Bingham stocks to be interconnected. Stringham (1953) stated that "the Last Chance rock is distinctly different from Bingham rock," apparently with respect to chemical and mineral composition, but he did not specify relative age relations. Bray (1969) suggested that the stocks merge gradationally.

Indifference toward the petrology of the Last Chance stock is perhaps justifiable in an immediate economic sense; the stock shows relatively small variations in composition and does not contain disseminated-type ore. But in a broader geologic context the stock assumes greater importance, for the very absence of disseminated copper mineralization in rocks closely related in time and space to the Bingham stock must be accounted for in a comprehensive model of hydrothermal alteration and metallization.

PETROGRAPHY

The Last Chance stock is composed of intergrading medium- to dark-gray augite-hornblende-biotite monzonite and quartz monzonite. The rocks are subequigranular and have an average grain size of about 0.5 mm. No regular decrease in grain size near margins of the stock was observed, suggesting relatively rapid crystallization throughout the pluton and intrusion into heated sedimentary rocks. Larger crystals of biotite or augite or both give the rocks a porphyritic appearance in hand specimens (fig. 6*A*), but this textural term will be reserved for certain intrusive units of the Bingham stock in which the megascopic contrast in grain size is better developed. Despite the abundance of biotite in the stock, no foliation or platy alinement was observed megascopically. Likewise, other indicators of internal structure (for example, oriented inclusions or schlieren) are totally lacking.



A

B

FIGURE 6.—Typical sample from Last Chance stock. *A*, Biotite-augite monzonite, Niagara tunnel level. *B*, photomicrograph of sample in *A* (or, orthoclase; pc, plagioclase; aug, augite; bi, biotite).

Hand specimens of rocks from the Last Chance stock are distinguished by a fine-grained texture and generally dark-gray color. Subhedral to anhedral crystals of plagioclase are medium gray. Interlocking anhedra of alkali feldspar are light gray to white. Interstitial quartz grains are light gray to colorless and are not readily recognized. Black rectangular cleavage flakes of biotite and subhedral crystals of clinopyroxene and amphibole in various shades of green are evenly distributed in the rock.

In thin sections the rocks have a hypidiomorphic-granular texture (fig. 6*B*). Plagioclase (An_{33-45}, based on $n\alpha$ determinations for five samples) occurs in euhedral to subhedral crystals that commonly display albite twinning and slight normal zoning; the crystals have an average length of about 0.4–0.6 mm. Untwinned cryptoperthitic orthoclase (Or_{72-75}, bulk composition for seven samples based on the X-ray determinative curves of Wright and Stewart, 1968) is present in anhedral crystals with average diameter of 0.2–0.5 mm; the orthoclase is commonly clouded by dark submicroscopic inclusions. Quartz occurs interstitial to all major minerals in clear grains with sharp extinction and average diameters of 0.05–0.15 mm.

Pale-green to colorless diopsidic augite is the major mafic mineral in over half of the samples from the Last Chance stock and occurs in euhedral to subhedral crystals with average diameters of about 0.7 mm. Partial chemical analyses for three samples give an average molecular composition of $Ca_{0.43}Mg_{0.45}Fe_{0.12}$. An amphibole of undetermined composition forms incomplete rims on many of the augite crystals and also occurs in discrete subhedral to anhedral grains. The amphibole displays yellowish-brown to pale-green pleochroic colors and has average dimensions of about 0.6 mm. Plates of medium- to dark-chocolate-brown biotite ($Mg_{0.73}Fe_{0.27}$, average for two partial chemical analyses) reach 1.5 mm but average about 0.5 mm in length; the plates commonly are scalloped but are not altered.

Of the common accessory minerals, the most abundant are magnetite, which occurs interstitially to the other minerals and as scattered inclusions in pyroxene or amphibole, and apatite, which occurs as tiny euhedral inclusions in plagioclase crystals. Traces of rutile and zircon are also noted in some sections.

MODAL DATA

In selecting samples for modal analyses, every effort was made to include only those that are neither contaminated nor hydrothermally altered and, at the same time, to establish maximum lateral and vertical coverage in the U.S. mine. In general the results (table 1) agree well with the average composition of surface samples reported by Stringham (1953). Felsic minerals make up 65–80 volume percent of the Last Chance stock. Plagioclase ranges from 26 to 45 percent, orthoclase from 13 to 39 percent and quartz from 3 to 11 percent. Mafic minerals make up 16–31 percent of the rock and include 3–18 percent of augite, 2–16 percent of amphibole, and 5–13 percent of biotite. Total opaque plus accessory mineral content ranges from 2 to 8 percent. The limited compositional variability, especially for the felsic constituents, is further substantiated by specific gravity determinations for 66 samples, which range from 2.70 to 2.80 and average 2.76. More than 90 percent of the values, however, fall between 2.72 and 2.78 (fig. 7*C*).

Felsic mineral abundances recalculated to 100 percent (fig. 7*A*) clearly indicate the monzonitic character of the stock; one sample each falls in the syenodiorite and granodiorite fields. Variations with respect to location and depth are random. Of the mafic minerals (fig. 7*B*), biotite proportions vary less than those of either augite or amphibole; thus the rocks can be characterized as either pyroxene-rich or amphibole-rich monzonites, with the former type predominating.

Systematic variations among the modal minerals given in table 1 are not well developed. Plots prepared for various mineral pairs indicate a weak positive correlation between the abundances of K-feldspar and quartz and somewhat stronger negative correlations between the abundances of K-feldspar and plagioclase, K-feldspar and pyroxene, and pyroxene and amphibole. These variations are thought to stem from compositional inhomogeneities at the time of emplacement.

CHEMICAL DATA

Chemical and normative data for samples of the Last Chance stock are presented in table 2. Individual chemical analyses deviate only slightly from average values calculated for the nine samples; the average values correspond closely to those reported by Nockolds (1954) for five hornblende-biotite monzonites. Minor element concentrations also hold no surprises; all are of the same order of magnitude as those reported by Turekian and Wedepohl (1961) for "high-calcium granitic rocks."

The proportions of normative quartz, K-feldspar, and albite for the samples of table 2 are plotted in figure 7*D*. Normative quartz proportions are gener-

TABLE 1.—*Modes, in volume percent, of the Last Chance stock*

[n.d. = not determined]

Sample	Quartz	K-feldspar	Plagioclase	Pyroxene	Biotite	Amphibole	Opaque and accessory minerals	Specific gravity
1	4.7	17.6	41.9	16.5	11.7	2.0	5.5	2.71
2	8.6	33.7	25.8	11.2	10.0	7.0	3.7	2.76
3	5.4	29.4	32.3	18.4	8.8	2.3	3.5	2.80
4	8.4	31.6	41.6	9.3	5.3	1.8	1.9	2.73
5	5.5	24.9	27.0	17.6	12.8	5.9	6.2	n.d.
7	11.1	12.8	44.7	13.7	4.9	4.4	8.4	2.79
8	9.4	35.0	27.4	8.6	9.4	6.2	4.0	2.73
11	4.3	29.0	35.4	13.2	8.4	6.1	3.5	2.75
14	6.2	33.7	27.8	13.5	10.0	4.0	4.7	2.79
15	9.2	35.4	31.5	6.2	9.7	4.3	3.6	2.72
16	4.1	31.9	32.4	11.6	11.1	5.0	3.9	2.77
23	10.4	38.9	28.2	8.7	7.2	3.4	3.2	2.73
24	6.2	29.4	31.0	8.6	8.8	13.9	2.1	2.78
25	8.3	28.5	28.3	8.8	6.2	15.6	4.3	2.75
26	4.8	29.6	27.3	16.6	9.9	6.7	5.1	2.76
38	10.6	32.3	32.2	3.1	6.6	12.8	2.4	2.78
40	5.3	28.8	41.0	15.2	5.9	1.2	2.6	n.d.
53	7.0	30.4	30.0	12.6	10.0	4.4	5.6	2.77
54	10.5	23.0	38.6	4.0	9.3	10.4	4.2	2.75
55	6.6	26.4	35.0	7.5	6.3	12.0	6.2	2.78
56	7.0	33.5	31.9	8.0	6.9	7.6	5.2	2.75
57	6.6	32.0	31.0	11.6	4.9	11.3	3.6	2.77
58	10.6	26.0	29.0	8.1	6.6	15.1	4.6	2.77
67	6.8	30.0	35.0	7.2	5.3	9.8	5.9	2.76
71	6.0	32.8	29.5	13.2	9.3	4.9	4.3	2.77
73	6.5	36.9	29.9	5.4	9.2	9.2	2.9	2.74
75	3.4	32.2	33.6	10.2	10.4	7.2	3.0	2.73
76	4.8	31.2	35.9	11.1	7.9	7.1	2.0	2.71
Average	7.1	29.9	32.7	10.7	8.3	7.2	4.1	2.76

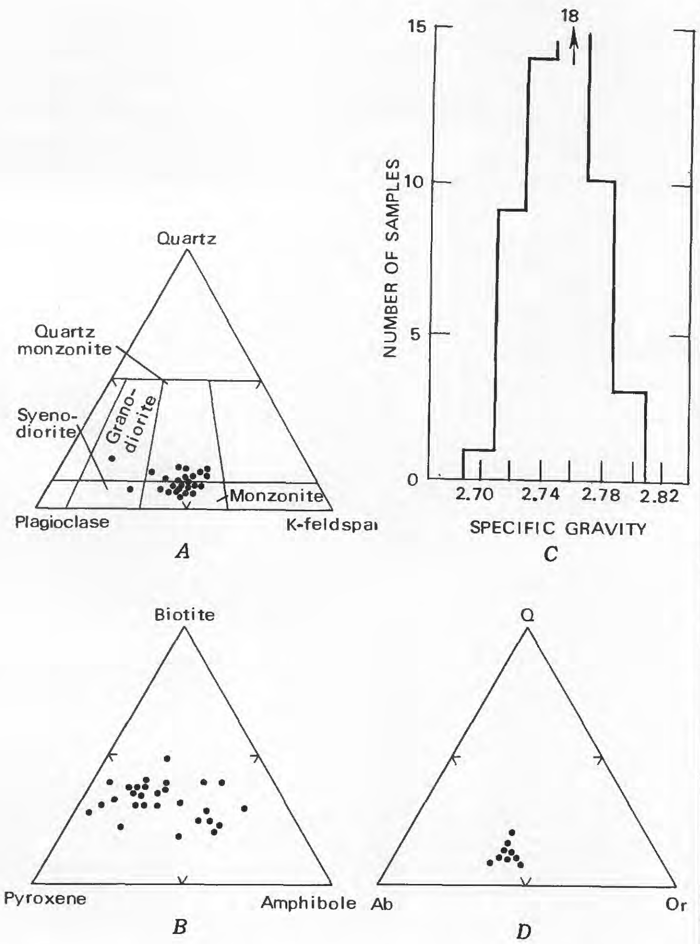


FIGURE 7.—Samples from Last Chance stock. *A*, *B*, Model mineral proportions. *C*, Variations in specific gravity. *D*, Proportions of normative salic minerals.

ally comparable to modal values (see fig. 7*A*), but the cluster of points is shifted laterally toward the normative albite corner. The expanation for this shift probably lies in the arbitrary nature of norm calculations: the Or equivalent of potassium in modal biotite is less than the Ab equivalent of sodium in crytoperthitic alkali feldspar.

HYBRID VARIANTS

In contrast to the generally uniform lithology of the main mass of the Last Chance stock are two distinctive and interrelated hybrid variants that occur locally in the border zones. One is a mixture of pale-pink alkali feldspar and quartz with aplitic texture; the other is a greenish-black medium-textured rock composed of euhedral diopsidic augite and minor feldspar. Both variants have crystallized from a monzonitic magma contaminated by bordering calcareous rocks.

FEATURES OF OCCURRENCE

Small irregular bodies of dark pyroxene-rich rock are generally found within 100 feet of large limestone xenoliths or calcareous wallrocks (fig. 8). The

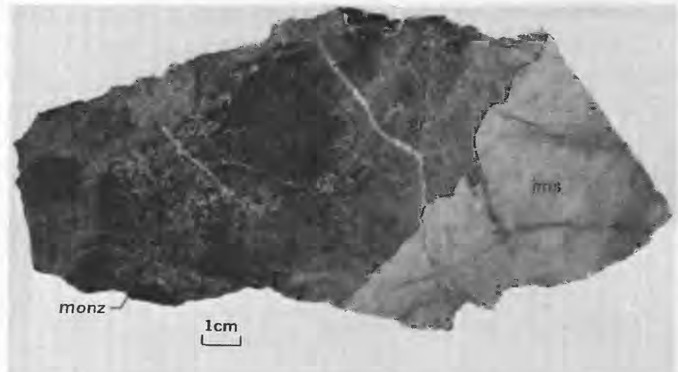


FIGURE 8.—Contact between monzonite of the Last Chance stock (left) and siliceous limestone (right). Grossularite-rich band (gr) with sharp irregular contact against recrystallized wollastonite-bearing limestone (lms) merges gradationally with pyroxene-rich hybrid monzonite (monz). Sample from 1800 level, U.S. mine.

aplitic hybrid forms segregations or diffuse intergrowths in border phases of the stock (fig. 9) but, more commonly, occurs in thin dikes that cut both silicated limestone and monzonite. The aplite dikelets are found as much as several hundred feet from contacts between intrusive and sedimentary rocks. The borders of dikelets that cut silicated limestone are marked by a narrow selvage of pale-green diopsidic pyroxene that may extend outward in bedding-oriented stringers (fig. 10). Alkali feldspar-quartz intergrowths also form the matrix of silicated limestone breccias in the contact zone. Pyroxene rims commonly become more diffuse toward the center of individual limestone fragments, indicating that silication followed brecciation (fig. 11; also see fig. 4).

Isolated underground exposures of the Last Chance contact zone are found from the uppermost to lowermost accessible levels in the U.S. mine. In all areas permitting detailed observations, contaminated rocks form an extremely restricted and discontinuous shell adjacent to, but not necessarily concordant with, the metasedimentary rock contact. Beyond the limits of obvious megascopic evidence of contamination (for example, pyroxene clots or aplite stringers), monzonite with modal pyroxene quantities slightly higher than average grades imperceptibly over several tens of feet into uncontaminated rock. Specific gravity trends were used to estimate the local configuration and extent of contaminated monzonite in certain areas; two typical areas are shown in figure 12.

PETROGRAPHY

The light-colored hybrid rocks have a sugary to fine hypidiomorphic-granular texture. The pale-pink to creamy color of dikelike occurrences stands in stark contrast to the darker monzonite but blends closely with metasedimentary wallrocks. The dark hybrid rocks characteristically have a slightly coarser and more nearly idiomorphic texture with dark-green pyroxene euhedra set in a white feldspar base.

Major mineral phases, consisting of K-feldspar, pyroxene and quartz, are easily identified with a hand lens. Biotite is notably absent in both light and dark variants. Tiny pyrite grains are scattered in both types but normally are more abundant in the aplites.

In thin sections, alkali feldspar of bulk composition Or_{68}–Or_{89} occurs in subhedral crytoperthitic to microperthitic crystals; average grain sizes range from 0.2 to 0.4 mm, with exceptional crystals in the

TABLE 2.—*Chemical data for the Last Chance stock*

[Chemical analyses by rapid methods by U.S. Geological Survey Analytical Laboratories under the direction of Leonard Shapiro. Semiquantitative spectrographic analyses by Chris Heropoulos, U.S. Geological Survey. Results are expressed in parts per mil'ion to the nearest number in the series 10,000, 7,000, 5.000, 3,000, 2,000, 1,500, 1,000, etc.; these numbers represent approximate midpoints of group data on a geometric scale. The precision of a reported value is approximately plus or minus one interval about 68 percent of the time or two intervals 95 percent of the time. Last column of spectrographic analyses reports median values. Elements looked for but not found: Ag, As, Au, Bi, Cd, Eu, Hf, Hg, In, P, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn. Samples from table 1]

	1	2	4	5	8	11	14	15	16	Average
				Chemical analyses (weight percent)						
SiO_2	63.4	59.0	60.8	57.6	60.1	58.6	58.9	60.2	59.1	59.7
Al_2O_3	15.6	14.9	15.3	14.7	14.8	15.2	14.8	15.6	15.0	15.1
Fe_2O_3	1.9	2.5	2.4	2.3	2.5	2.6	2.1	2.3	2.0	2.3
FeO	2.4	3.3	3.0	3.5	2.9	3.4	3.8	3.4	3.7	3.3
MgO	2.6	4.5	3.4	6.2	4.0	4.3	4.8	3.5	4.2	4.2
CaO	3.3	5.4	5.4	6.2	4.8	5.8	6.2	5.1	5.7	5.3
Na_2O	3.8	3.5	3.6	3.7	3.9	3.8	3.5	3.8	3.5	3.7
K_2O	4.3	4.3	3.8	3.1	4.2	3.7	3.8	4.0	4.6	4.0
H_2O	1.30	1.10	.84	.94	.78	.99	.47	.40	.74	.84
TiO_2	.69	.84	.84	.87	.81	.86	.86	.86	.86	.83
CO_2	.10	.16	.05	.12	.11	.05	<.05	<.05	<.05	.06
P_2O_5	.32	.39	.39	.52	.46	.42	.49	.43	.49	.43
MnO	.04	.03	.03	.15	.15	.03	.11	.13	.15	.09
S	<.05	<.05	<.05	<.05	<.05	<.05	<.05	.08	<.05	<.05
Total	100	100	100	100	100	100	100	100	100	100
				Spectrographic analyses (parts per million)						
B	0	0	0	10	0	0	0	0	10	0
Ba	2,000	3,000	2,000	3,000	3,000	2,000	3,000	2,000	3,000	3,000
Be	3	2	2	2	3	2	2	1	2	2
Ce	300	200	150	500	300	200	200	200	200	200
Co	15	30	20	30	30	30	20	20	20	20
Cr	70	150	70	150	200	100	200	70	150	150
Cu	70	30	70	150	70	50	15	70	70	70
Ga	20	15	15	30	30	20	15	15	15	15
La	200	150	150	200	150	150	150	150	150	150
Mo	7	5	5	3	5	5	5	5	5	5
Nb	20	15	10	10	20	15	10	10	10	10
Nd	100	100	70	50	100	70	0	0	0	70
Ni	50	70	50	70	150	50	100	50	100	70
Pb	70	50	50	70	50	30	50	50	70	50
Sc	15	20	15	20	20	20	20	20	20	20
Sr	1,500	2,000	1,500	1,500	1,500	2,000	2,000	2,000	2,000	2,000
V	100	100	100	300	300	150	200	200	200	200
Y	20	30	20	30	30	20	20	20	20	20
Yb	2	2	2	3	2	2	3	3	3	2
Zr	300	200	200	200	200	150	300	300	300	200
				Norms (weight percent)						
Q	14.5	6.7	11.1	4.6	7.9	6.2	6.2	8.4	5.2	7.4
or	25.5	25.7	22.7	18.3	25.1	22.2	22.6	23.8	27.4	23.7
ab	32.2	30.0	30.8	31.3	33.4	32.6	29.8	32.4	29.8	31.4
an	12.8	12.4	14.5	14.4	10.6	13.7	13.5	13.8	11.7	13.0
wo	.4	4.6	5.2	5.1	4.0	5.3	5.9	3.7	5.6	4.4
en	6.5	11.2	8.6	15.5	10.0	10.7	12.0	8.7	10.5	10.4
fs	1.8	2.7	3.0	3.4	2.2	2.7	4.0	3.0	4.0	3.0
mt	2.8	3.7	3.5	3.3	3.7	3.8	3.1	3.4	2.9	3.4
il	1.3	1.6	1.6	1.7	1.6	1.7	1.6	1.6	1.6	1.6
ap	.8	.9	.9	1.2	1.1	1.0	1.2	1.0	1.2	1.0

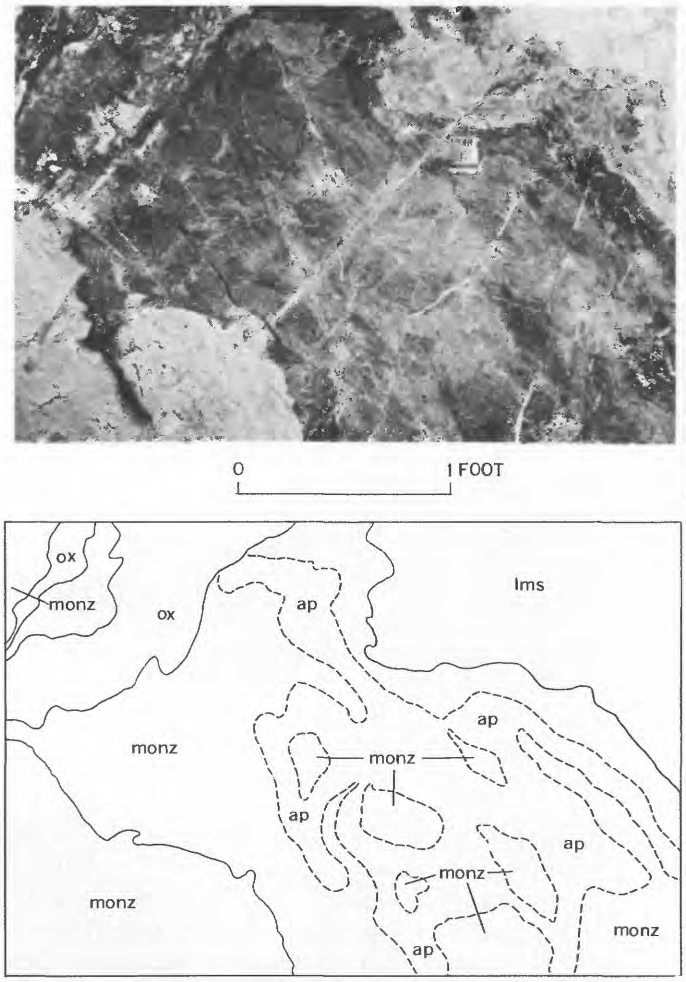


FIGURE 9.—Ribbons of aplitic hybrid phase (ap) in monzonite (monz) of the Last Chance stock at contact with limestone (lms). Matchbook for scale. From 1400 level, U.S. mine. Monzonite in lower left corner is covered; oxide films (ox) in upper left.

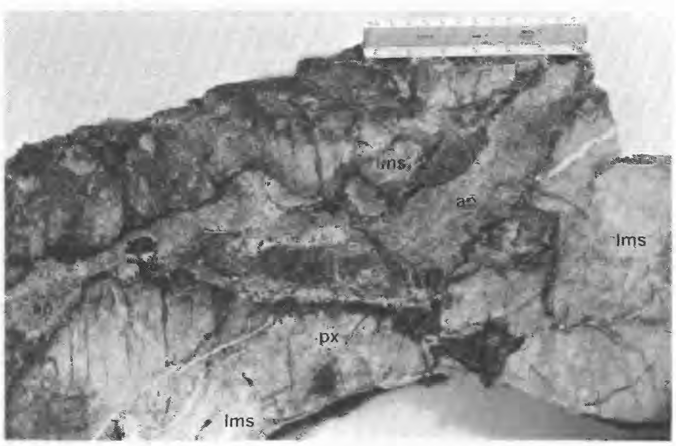


FIGURE 10.—Dikelike segregation of aplitic hybrid phase (ap) with diopsidic pyroxene selvage (px) cutting silicated limestone (lms). Sample from Niagara tunnel level, U.S. mine. Scale is 6 inches long.

FIGURE 11.—Silicated limestone breccia with matrix composed of aplitic K-feldspar and quartz. Sample from 2400 level, U.S. mine.

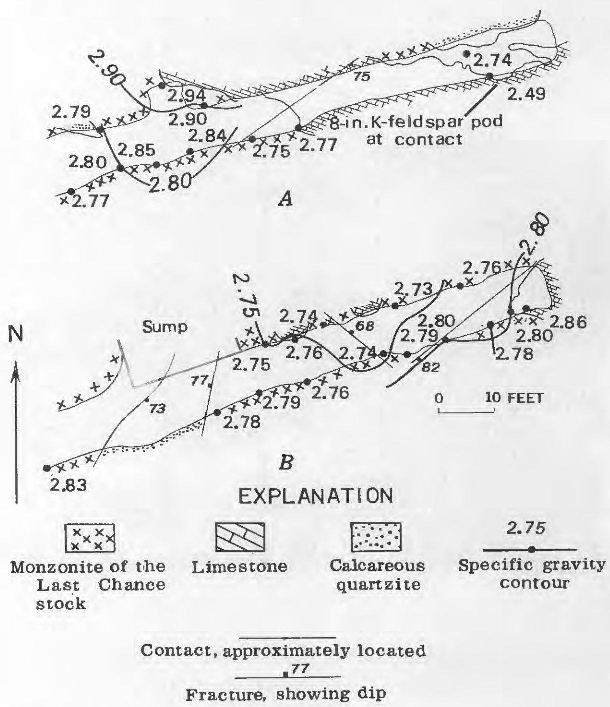


FIGURE 12.—Specific gravity trends in monzonite of the Last Chance stock adjacent to limestone contacts. Areas shown are near southeast margin of stock in U.S. mine. *A*, 200 level. *B*, 400 level.

pyroxene-rich rocks up to 1–2 mm long. Micrographic intergrowths of alkali feldspar and quartz are a characteristic feature of the aplites (fig. 13). Subhedral crystals of clear plagioclase, few of which are longer than 0.5 mm, are a minor constituent of

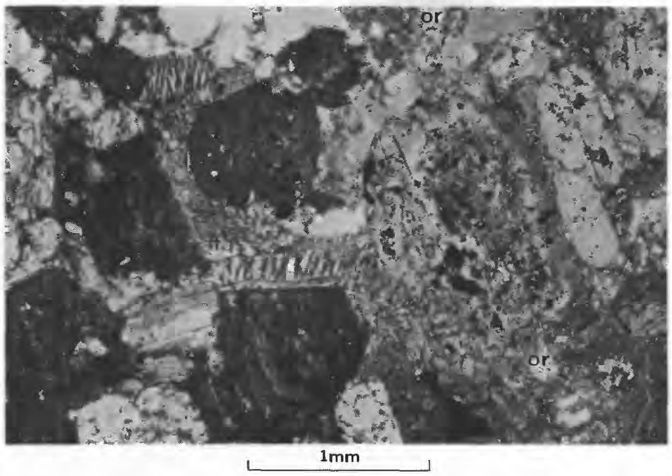


FIGURE 13.—Micrographic intergrowth of K-feldspar and quartz (fq) in aplitic hybrid phase. Stained orthoclase (or) appears light gray.

both variants. Quartz occurs in discrete anhedral grains or in fine intergrowths with calcite generally interstitial to alkali feldspar (fig. 14).

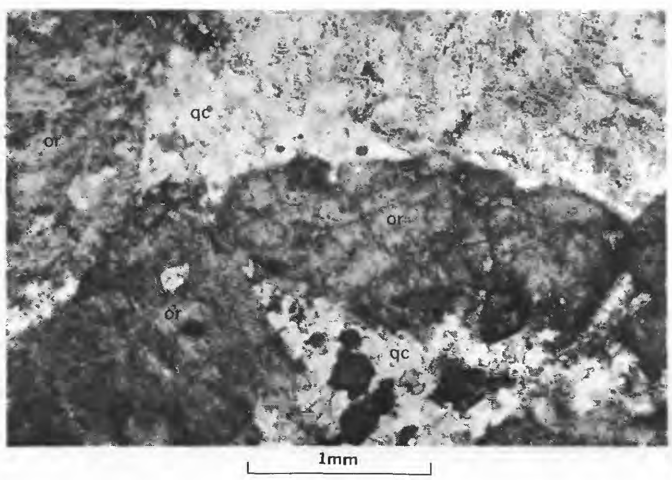


FIGURE 14.—Quartz-calcite intergrowths (qc) interstitial to K-feldspar (or) in aplitic hybrid phase.

Diopsidic augite euhedra in the dark hybrid rocks average about 1 mm in length and commonly are enclosed in a mosaic of larger orthoclase crystals (fig. 15). A small fraction of the pyroxene is replaced by a fibrous uralitic amphibole, but the bulk of the pyroxene is remarkably clear and unaltered. Trace amounts of ragged pale-brown biotite flakes are noted in a few sections.

Opaque and accessory minerals, in order of decreasing abundance, are calcite, apatite, pyrite, and

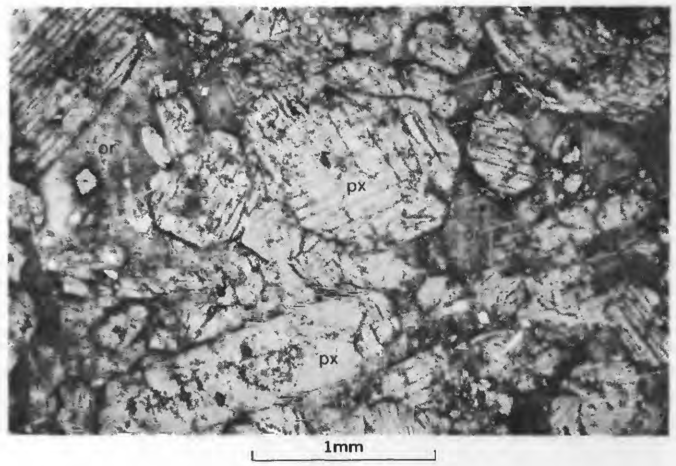


FIGURE 15.—Pyroxene euhedra (px) enclosed in K-feldspar (or). Feldspar in field displays unit extinction.

sphene. Although interstitial occurrences are most common, apatite prisms and pyrite anhedra also occur as inclusions in the major mineral phases.

MODAL DATA

Samples selected for modal and chemical analysis represent compositional "end members." Although not as common as intermediate types, they give a clearer indication of the direction and magnitude of mineralogic and chemical changes resulting from assimilation. In comparison with the average modal composition for the Last Chance stock (table 1), the extremely contaminated variants contain appreciably less plagioclase, amphibole, and essentially no biotite; calcite, pyrite, and sphene contents are uniformly greater (table 3). Quartz, calcite, and pyrite are concentrated in the dark variants. Felsic mineral proportions of the hybrid rocks are shifted markedly toward orthoclase-rich compositions as compared with uncontaminated monzonite (fig. 16*A*). Specific gravity values reflect the inverse relation in modal abundance of K-feldspar and total mafic minerals (fig. 16*B*).

CHEMICAL DATA

Compared with the average composition of uncontaminated monzonite (table 4), the pyroxene-rich rocks of the Last Chance stock contain about one-half to one-fourth the amount of Al_2O_3, K_2O, and Na_2O and about two to four times as much MgO + CaO. The aplites are significantly enriched in K_2O, CO_2, and S and impoverished in FeO and MgO.

TABLE 3.—*Modes, in volume percent, of hybrid rocks from margins of Last Chance stock*

Sample	Quartz	K-feldspar	Plagioclase	Pyroxene	Biotite	Amphibole	Pyrite	Calcite	Apatite	Sphene	Other	Specific gravity
				Light-colored (orthoclase-rich) rocks								
13	8.4	73.0	---	---	---	---	0.9	11.3	---	3.2	3.2	2.51
17	14.3	73.6	1.1	3.2	---	3.2	1.1	2.6	---	.7	.2	2.55
18	5.9	73.2	8.7	---	0.8	---	1.1	8.5	---	---	1.8	2.49
19	12.6	71.6	7.1	---	.9	5.8	.9	1.1	---	---	---	2.54
51	6.1	85.8	.7	---	---	---	.2	.1	.2	.4	.5	.52
Average	9.5	75.4	3.5	0.6	0.3	1.8	0.8	5.5	---	0.9	1.5	2.52
				Dark-colored (augite-rich) rocks								
6	0.4	23.8	5.3	67.2	---	---	---	---	2.5	0.4	0.4	3.07
7	---	28.1	13.6	47.7	---	6.4	0.5	---	1.4	.7	1.6	2.91
37	.8	9.9	3.4	81.8	---	---	.1	.3	1.7	.6	1.4	3.04
41	5.2	24.5	3.0	60.2	---	---	.9	.2	1.0	1.0	4.0	2.99
Average	1.6	21.6	6.3	64.2	---	1.6	0.4	0.1	1.7	0.7	1.8	3.00

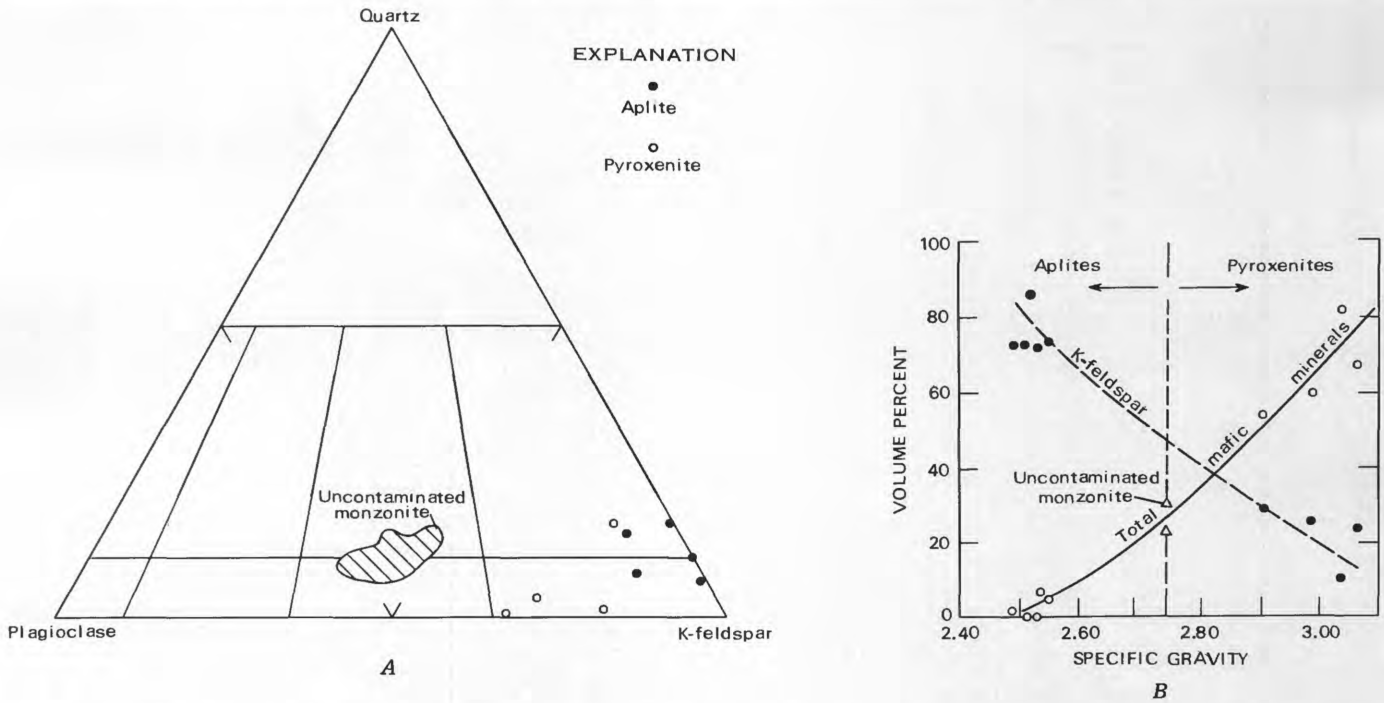


FIGURE 16.—Hybrid rocks from the Last Chance stock. *A*, Felsic mineral proportions. *B*, Relations between specific gravity and modal mineral abundance.

The chemical analyses reflect changes in composition that, for the most part, could be guessed from modal data. Large differences in specific gravity, however, make a comparison of weight percentages somewhat misleading. Figure 17 shows gains and losses of major oxides in the contaminated rocks on an equal volume basis: average weight fractions, grams per 100 grams, are multiplied by specific gravity, grams per cubic centimeter, and the results expressed as grams per 100 cubic centimeters. The baseline represents values calculated from the data of table 2 for average uncontaminated monzonite of the Last Chance stock. It is noted that SiO_2, Al_2O_3, and Na_2O are depleted in both the light and dark hybrid rocks. Furthermore, the aplites contain K_2O in excess of the quantity subtracted from an equal volume of pyroxene-rich rock. The antithetic changes in FeO, MgO, and CaO are in qualitative agreement with estimates of modal mineral proportions.

BINGHAM STOCK

GENERAL FEATURES

The main mass of the composite Bingham stock is several thousand feet north and east of the Last

TABLE 4.—*Chemical data for hybrid rocks from margins of Last Chance stock*

[Chemical analyses by rapid methods by U.S. Geological Survey Analytical Laboratories under the direction of Leonard Shapiro. Semiquantitative spectrographic analyses by Chris Heropoulos, U.S. Geological Survey. Results are expressed in parts per million to the nearest number in the series 10,000, 7,000, 5,000, 3,000, 2,000, 1,500, 1,000, etc.; these numbers represent approximate midpoints of group data on a geometric scale. The precision of a reported value is approximately plus or minus one interval about 68 percent of the time or two intervals 95 percent of the time. Last column of spectrographic analyses reports median values. Elements looked for but not found: Ag, As, Au, Bi, Cd, Eu, Hf, Hg, In, P, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn. Samples from table 3]

	Light-colored (orthoclase-rich) rocks		Dark-colored (augite-rich) rocks		Uncontaminated Last Chance monzonite (average values [1])
	13	18	6	37	Average
Chemical analyses (weight percent)					
SiO_2	60.1	60.0	52.9	50.8	59.7
Al_2O_3	15.5	15.1	7.5	4.4	15.1
Fe_2O_3	1.5	1.8	1.5	.4	2.3
FeO	.08	.28	4.7	4.9	3.3
MgO	.40	.61	8.5	11.9	4.2
CaO	4.8	6.0	17.9	22.2	5.3
Na_2O	1.0	3.7	1.2	.7	3.7
K_2O	11.2	7.0	2.9	.3	4.0
H_2O	.87	.35	.58	1.25	.84
TiO_2	.74	.45	.66	.57	.83
CO_2	3.0	3.8	.32	$<.05$	.06
P_2O_5	.06	.08	.8	1.1	.43
MnO	.04	.02	—	.13	.09
S	1.0	1.2	.10	.16	$<.05$
Total	100	100	100	99	100
Spectrographic analyses (parts per million)					
B	—	10	—	—	0
Ba	3,000	2,000	2,000	200	3,000
Be	—	5	—	—	2
Ce	150	150	200	150	200
Co	7	7	50	50	20
Cr	15	7	150	300	150
Cu	150	70	300	1,500	70
Ga	15	30	10	15	15
La	50	100	200	100	150
Mo	7	—	5	—	5
Nb	15	15	10	—	10
Nd	150	100	150	70	70
Ni	10	2	70	150	70
Pb	20	70	30	50	50
Sc	50	—	50	70	20
Sr	2,000	1,500	1,500	1,500	2,000
V	50	50	150	200	200
Y	20	15	50	50	20
Yb	1	2	3	3	2
Zr	150	700	200	100	200
Norms (weight percent)					
Q	8.9	8.8	0.4	0.3	7.4
or	66.1	41.3	17.2	1.8	23.7
ab	8.4	31.2	10.2	6.2	31.4
an	4.5	3.9	6.5	8.0	13.0
wo	—	—	31.5	40.2	4.4
en	1.0	1.5	21.3	30.0	10.4
fs	—	—	6.1	7.7	3.0
mt	—	—	2.2	.6	3.4
hm	.3	.6	—	—	—
il	.1	.1	1.3	1.1	1.6
tn	—	.9	—	—	—
ru	—	.7	—	—	—
ap	.1	.2	1.9	2.6	1.0
pr	1.9	2.1	.2	.3	—
cc	6.8	8.6	.7	—	—
C	.1	—	—	—	—

[1] From table 2.

Chance stock and consists of two interconnected northeast-trending lobes with a combined outcrop area of about 1¼ square miles (fig. 2). The porphyry copper ore body at Bingham coincides roughly with the northern lobe, which is composed of porphyritic and equigranular to seriate monzonitic

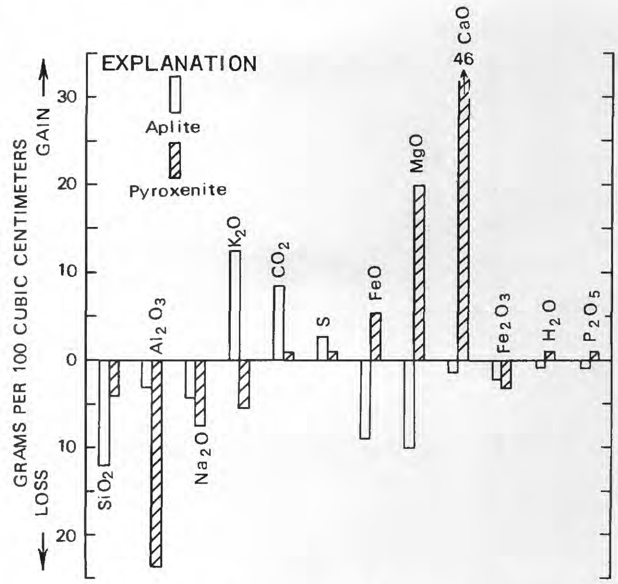


FIGURE 17.—Chemical gains and losses of major oxides in hybrid rocks relative to uncontaminated monzonite of the Last Chance stock, based on equal volume calculations.

rocks cut by northeast-trending latite and quartz latite dikes. These rocks have been intricately fractured and were altered extensively at the time of hydrothermal mineralization. The southern lobe consists largely of equigranular monzonitic rocks that are unmineralized and, at most, weakly altered. A zone of large feldspathized quartzite and garnetized limestone blocks occurs between the two lobes.

Contacts between intrusive and sedimentary rocks observed underground and in Kennecott's Utah Copper mine are very irregular and show no evidence of large-scale deformation during emplacement. Previous reports (Billingsley and Locke, 1941; Peters and others, 1966) suggested that emplacement of the Bingham stock in the axial zone of the Bingham syncline was controlled by the general convergence of structural elements including high-angle faults, thrusts, and tears. The relative importance of individual preemplacement structures, however, is not readily established.

Large included blocks of sedimentary rocks are more common in the Bingham stock than in the Last Chance. They occur primarily in the equigranular phase and are apparently absent in the porphyry phase. Descriptions by Stringham (1953, p. 959–960) suggested that a hybrid phase ("actinolite syenite") containing appreciable amounts of actinolite and epidote surrounds or transects the more calcareous inclusions.

Thermally metamorphosed rocks adjacent to the Bingham stock are similar in kind and extent to those of the Last Chance contact zone; wollastonite-quartz-diopside hornfels and metaquartzites are most abundant. In contrast, however, metasomatic effects are notable only near margins of the Bingham stock. In the Highland Bay mine (Hunt, 1924), some limestones immediately adjacent to the stock are replaced by massive garnet with specularite and tremolite. Large irregular masses of grossularite replace limestone blocks engulfed by equigranular monzonite in the southeastern part of the Utah Copper pit. Stringham's (1953) "feldspar network" and "granitized quartzite" may also be considered a part of the Bingham metasomatic aureole.

Detailed examination of rocks from the Bingham stock was confined to underground exposures along parts of the Bingham, Niagara, and Mascotte haulage tunnels of the U.S. and Lark mines (fig. 3). These areas lie below the periphery of the Utah Copper pit but do not extend into the disseminated copper ore zone. Small-scale mapping and systematic sampling were limited to parts of the Mascotte tunnel and Utah Copper 500 level (fig. 18).

PETROGRAPHY

Prior to Stringham's (1953) study of the Bingham stock, the major igneous phases were generally termed monzonite and monzonite porphyry or "dark" and "light" porphyry (Boutwell, 1905; Butler and others, 1920). Stringham classified the same rocks as "granite" and "granite porphyry," noting, however (1953, p. 952, 961) that these were group names used in a broad sense to include variants ranging in modal composition from orthoclase granite to quartz monzonite or diorite. Igneous rocks observed underground on the southeast margin of the Bingham stock include equigranular to seriate augite-amphibole monzonite or quartz monzonite and porphyritic amphibole quartz monzonite. None contain the proportions of quartz and alkali feldspar reported for rocks from central parts of the stock (Stringham, 1953; Bray, 1969). Contacts between the phases range from sharp to gradational and indicate the following sequence of crystallization or emplacement: (1) augite monzonite, (2) amphibole-augite quartz monzonite, and (3) porphyritic amphibole quartz monzonite. The rock types will be discussed in this order.

The northeast-trending lobe of augite monzonite exposed underground at the easternmost edge of the Bingham stock (fig. 18) is a particularly dark almost flinty rock that probably represents a chilled border phase; comparable rocks were not observed elsewhere in the district. In hand specimen (fig. 19) the rock has a dull-black color. Scattered pyroxene crystals and biotite cleavage flakes are recognizable

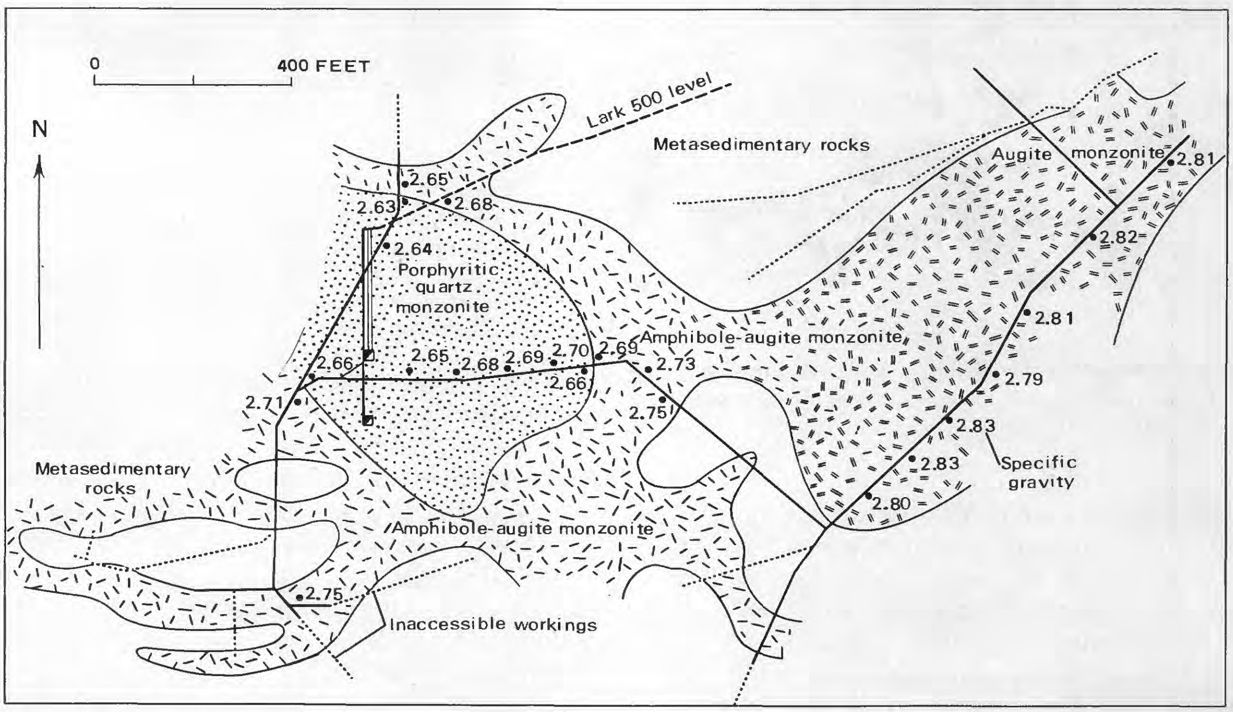


FIGURE 18.—Southeast margin of Bingham stock on Mascotte tunnel level of Lark mine. Differences in rock composition are reflected in specific gravity values.

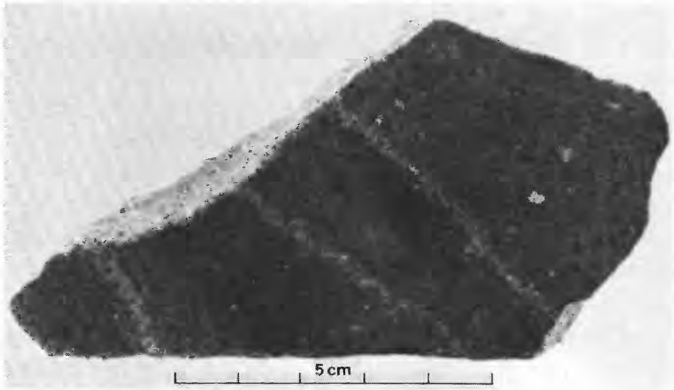


FIGURE 19.—Chilled augite monzonite border phase of Bingham stock. Grades into amphibole-augite monzonite shown in figure 21.

under a hand lens. Then sections of this rock type display a distinctive microporphyritic texture. Subhedral augite crystals and scalloped chocolate-brown biotite flakes occur in a fine granular mixture of plagioclase and K-feldspar (fig. 20). The matrix

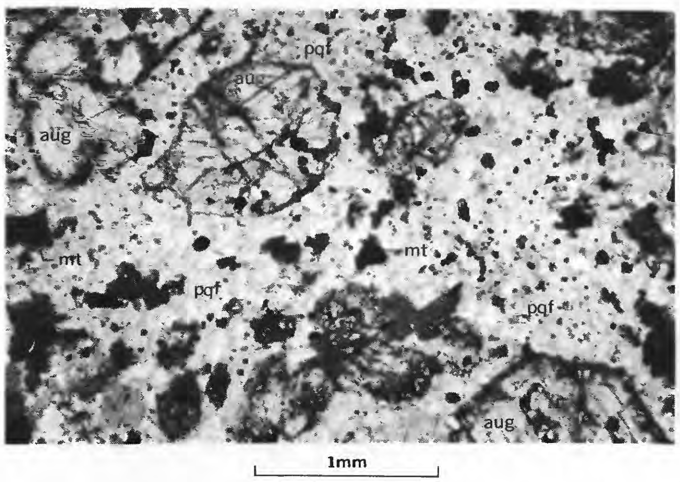


FIGURE 20.—Chilled border phase of Bingham stock showing augite microphenocrysts (aug) in dense matrix composed of plagioclase, K-feldspar, and minor quartz (pqf); mt, magnetite.

contains small amounts of interstitial quartz and several times more magnetite (as much as 6 percent) than any of the other rock types studied.

Westward along the Mascotte tunnel, the border phase grades into a somewhat coarser facies composed of amphibole-augite monzonite and quartz monzonite (fig. 21). Similar rocks are exposed at the south margin of the stock along the Niagara and Bingham haulage tunnels. Except for a slightly

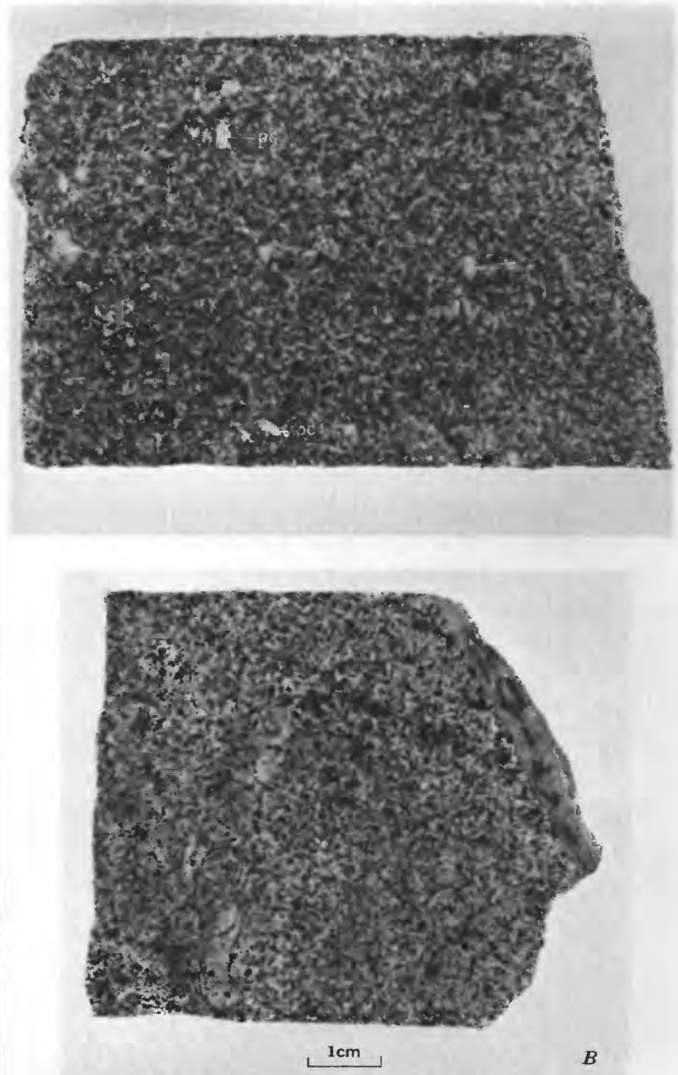


FIGURE 21.—Subequigranular Bingham amphibole-augite monzonite. *A*, Sample containing few plagioclase phenocrysts (pc) from Mascotte tunnel level. *B*, Sample containing ragged patches of orthoclase (outlined) from Niagara tunnel level.

coarser texture and pale-greenish-gray cast that rectangular amphibole crystals give the rock, hand specimens of the Bingham monzonite would be easily confused with those of the Last Chance stock.

Most petrographic features of Bingham monzonite are closely similar to monzonite of the Last Chance stock. Crystals of colorless subhedral diopsidic augite, stubby rectangular amphibole with greenish-yellow pleochroic colors, and scalloped flakes of russet-colored biotite average 0.6–0.8 mm in length. The feldspars occur in subhedral to anhedral crystals with average diameters of 0.2–0.3 mm; alkali feldspar forms rims on some of the larger plagioclase crystals. Quartz anhedra occur interstitial to the other mineral phases. Common accessory minerals, in order of decreasing abundance, are magnetite, apatite, and zircon.

The largest mass of porphyritic rock exposed underground is a blunt apophysis intrusive into amphibole-augite monzonite on the east edge of the Bingham stock (fig. 18). Precise relations between this rock and the "granite porphyry" of the disseminated copper ore zone (Stringham, 1953) are not known. On the Mascotte tunnel and Ohio Copper 500 levels, the rock is a porphyritic amphibole quartz monzonite. Contacts between the porphyry and equigranular monzonite are steeply dipping and either sharp or gradational over an interval of less than 2 feet; the transition interval contains a few plagioclase phenocrysts about 4 mm long. The dikelike form of the porphyry suggests that it is a distinct intrusive phase that was emplaced after crystallization of the enclosing rocks.

Hand specimens of the porphyritic rock (fig. 22) are medium gray to greenish gray. Small white

FIGURE 22.—Porphyritic amphibole quartz monzonite of the Bingham stock from Mascotte tunnel level. Subhedral orthoclase phenocrysts are outlined.

plagioclase crystals are evenly distributed in a granitoid matrix that is similar in texture and composition to the enclosing amphibole-augite monzonite. Perhaps the most distinctive megascopic feature is pale-pink orthoclase in randomly scattered subhedral to ovoid phenocrysts as much as several centimeters long.

In thin sections, plagioclase (An_{30-38}) phenocrysts are subhedral, display faint normal zoning, and average 3–4 mm in length; partial overgrowths of alkali feldspar are common (fig. 23). These pheno-

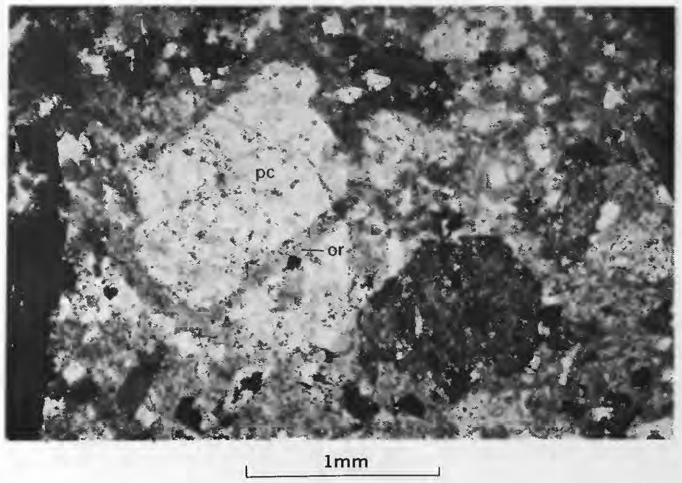


FIGURE 23.—Porphyritic amphibole quartz monzonite shown in figure 22. Note orthoclase rim (or) on partly resorbed plagioclase phenocryst (pc). Stained orthoclase appears light gray.

crysts make up about 10 percent of the rock. Subequant plagioclase grains in the groundmass characteristically occur in mosaic fashion, surrounded by anhedral alkali feldspar and quartz (fig. 23). Cryptoperthitic alkali feldspar phenocrysts (Or_{74-80}) make up about 5 percent of the rock, are several times larger than those of plagioclase, and are invariably rounded.

Two forms of amphibole are noted in thin sections of the porphyritic monzonite, neither of which has been specifically identified. One occurs in subhedral to anhedral grains with clear pale-green to yellow-green pleochroic colors and forms partial reaction rims on augite crystals. The other is faintly pleochroic, cloudy, and occurs in frayed rectangular laths 0.4–0.7 mm long; this variety is thought to be a uralitic reaction product after pyroxene.

Biotite flakes have dark-chocolate-brown to yellow-brown pleochroic colors and average about 0.3 mm in length. Many flakes are scalloped or sievelike in form and are studded with tiny magnetite anhedra. Common accessory minerals in addition to magnetite are apatite and zircon, with traces of epidote and chlorite.

MODAL DATA

Igneous rocks from margins of the Bingham stock, in areas accessible to the writer, are fractured more extensively than those of the Last Chance stock. Many fracture surfaces, particularly in the porphyritic phase, are coated with films of pyrite. Thus, to minimize any possible alteration effects, thin-section blanks were sawed from the center of blocky hand samples measuring 6–8 inches on a side. Modes for the various phases of the Bingham stock are summarized in table 5.

Compared with average ratios of alkali feldspar to plagioclase for the Last Chance stock (table 1), the ratio of all phases of the Bingham stock are higher. This subtle shift in salic mineral proportions is seen more readily in the triangular plot of figure 24*A*. Note also that proportions of modal quartz are highest in the porphyritic phase. Average ratios of pyroxene to amphibole (fig. 24*B*) and total mafic mineral contents decrease in this order: chilled monzonite > equigranular monzonite > porphyritic monzonite, corresponding to the inferred sequence of crystallization. These differences are reflected in specific gravity values shown in figure 18 and summarized for a total of 59 samples in the histogram of figure 24*C*. The amphibole-dominant porphyritic rocks cluster about a value of 2.67, slightly lower than the main equigranular phase; values for the chilled augite monzonite fall between the narrow limits of 2.80–2.84.

CHEMICAL DATA

Chemical analyses and norms for six samples from the Bingham stock (table 6) are generally similar to samples from the Last Chance stock. The relatively higher ratios of modal alkali feldspar to plagioclase in rocks of the Bingham stock are duplicated in a comparison of normative salic mineral porportions (fig. 24*D*). As would be expected from modal contrasts, the greatest differences are noted between the porphyritic phase and the Last Chance monzonite.

These differences, however, are probably of no greater significance than are similarities in chemical and modal composition that suggest a comagmatic origin for the two plutons.

DIKE ROCKS

GENERAL FEATURES

Narrow latitic dikes intrude the Last Chance and Bingham stocks and extend several miles to the southwest and northeast in a belt about half a mile

TABLE 5.—*Modes, in volume percent, of rocks from southeastern part of Bingham stock*

Sample	Quartz	K-feldspar	Plagioclase	Pyroxene	Biotite	Amphibole	Opaque and accessory minerals	Specific gravity
Chilled augite monzonite								
35	3.7	28.6	20.2	26.1	11.4	5.0	4.6	2.84
36	6.5	34.9	24.9	14.9	8.4	5.1	5.2	2.80
66	5.4	24.7	23.0	27.2	10.1	2.8	6.8	2.80
68	5.7	30.8	20.8	25.7	8.2	3.3	5.5	2.82
74	4.5	30.5	25.1	18.9	10.9	4.5	5.6	2.82
Average	5.2	29.9	22.8	22.6	9.8	4.1	5.5	2.82
Amphibole-augite monzonite and quartz monzonite								
21	5.9	33.6	28.1	15.0	8.2	6.3	2.9	2.72
26	4.8	29.6	27.3	16.6	9.9	6.7	5.1	2.76
32	9.1	37.8	27.1	.2	6.7	11.1	8.0	2.63
33	7.2	38.1	22.1	5.2	6.1	18.1	3.2	2.75
62	6.0	43.1	21.9	12.8	7.9	4.9	3.4	2.69
63	7.4	43.1	19.8	3.0	8.9	13.0	4.8	2.66
64	7.6	39.3	21.4	15.4	7.4	5.2	3.7	2.75
65	7.4	43.5	19.5	3.0	5.9	16.6	4.1	2.72
77	7.9	36.9	26.9	10.5	8.7	5.9	3.2	2.71
79	7.8	37.6	24.6	4.8	9.2	11.4	4.6	2.67
107	5.1	40.1	23.8	13.5	9.4	4.1	4.0	2.75
Average	6.9	38.4	23.9	9.1	8.0	9.4	4.3	2.71
Porphyritic amphibole quartz monzonite								
10	8.6	36.5	25.3	3.8	6.3	14.5	5.0	2.69
22	11.0	38.2	17.9	8.3	10.4	9.2	4.6	2.70
34	10.9	44.5	24.6	.4	7.3	9.5	2.8	2.60
39	8.4	45.4	28.0	1.6	5.3	9.3	2.0	2.65
52	6.4	37.8	26.8	1.6	8.6	15.8	3.0	2.73
59	12.8	35.2	23.8	---	6.9	13.3	8.0	2.67
69	9.8	42.4	25.0	2.6	6.0	9.4	6.8	2.69
70	9.5	44.4	23.5	2.5	8.3	9.5	2.3	2.64
Average	9.7	40.6	24.4	2.6	7.4	11.3	4.3	2.67

wide. This trend is roughly parallel to and, perhaps, controlled by the major high-angle fault system in the Bingham district (fig. 2). Other dikes and small plugs occur in the area of predominantly sill-like intrusions southeast of the stocks and in the area of volcanic rocks east of the district. Previous references to the dike rocks at Bingham include brief petrographic descriptions by Zirkel (1876), Stringham (1953), and Smith (1961) and a more detailed treatment by Bray (1969).

The dike rocks were examined underground in the Utah Metals, Butterfield, and St. Joe tunnels (fig. 3) and at the surface in the extreme northwest corner of the Tickville Springs quadrangle. The most extensive exposures of relatively unweathered and unaltered dikes were found in the Utah Metals tunnel; about 5,000 feet of these workings was mapped at a scale of 1 inch=200 feet on a surveyed base provided by The Anaconda Company (fig. 25). Numerous samples were collected

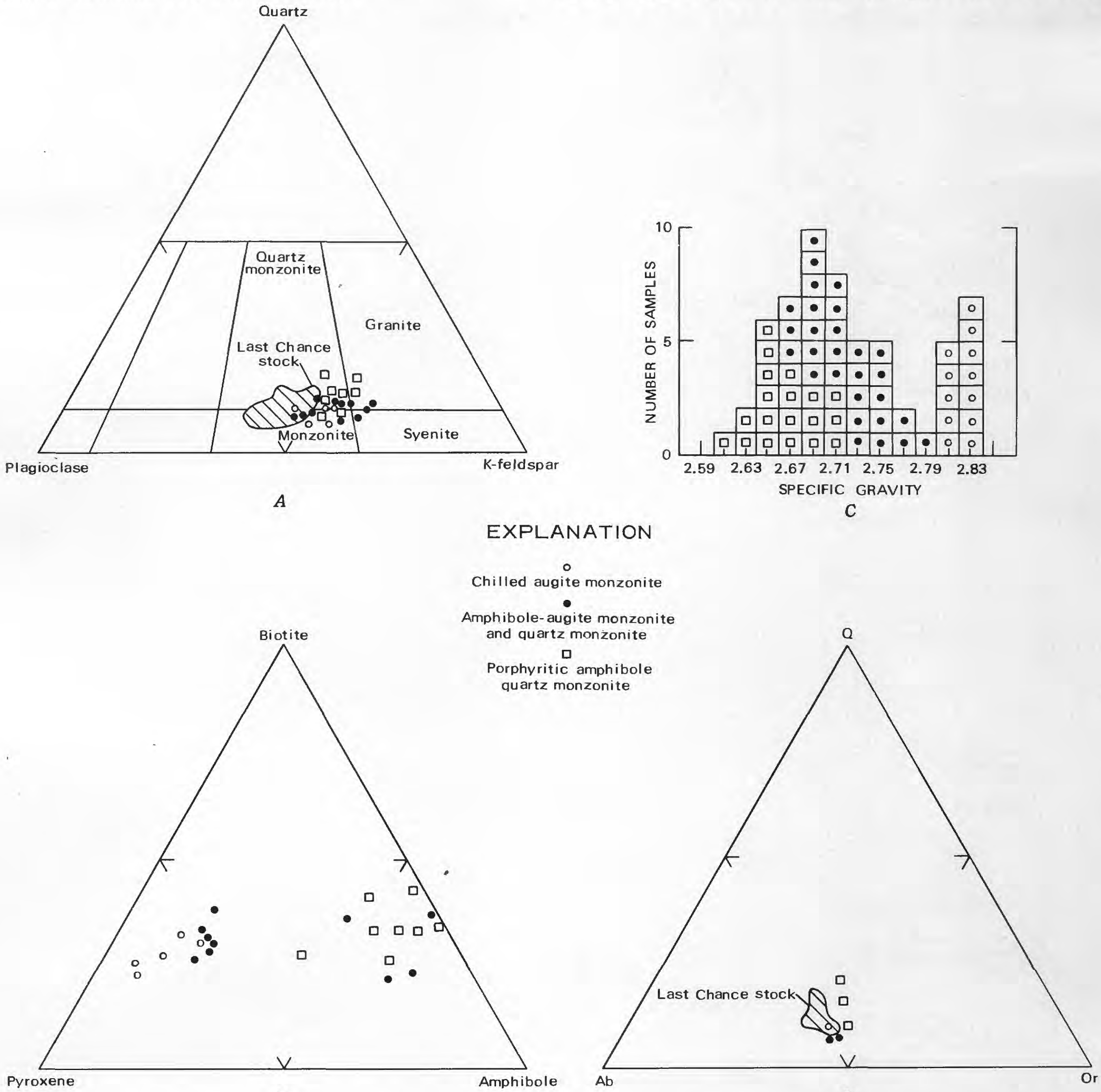


FIGURE 24.—Samples from southeast margin of Bingham stock. *A*, *B*, Modal mineral proportions. *C*, Variations in specific gravity. *D*, Proportions of normative salic minerals.

for petrographic and chemical studies here and in other areas mentioned.

The dike contacts are sharply discordant and planar. Chilled borders are noted in some of the better underground exposures. Border-zone rocks commonly show a subparallel megascopic alinement of biotite plates and tabular plagioclase phenocrysts. Fragmentation during emplacement is indicated by angular inclusions of wallrock ranging in length from several millimeters to as much as several feet. Pebble dikes (fig. 26) and, in one instance, an intrusive contact breccia associated with the latitic dikes may be the result of explosive release of pressures at some stage of crystallization. Field relations are more suggestive of forcible emplacement than for the larger intrusions, even though it cannot be clearly demonstrated that the bordering rocks were shouldered aside.

PETROGRAPHY

The fresh dike rocks are dark gray to medium greenish gray; they weather to shades of tan. Hand

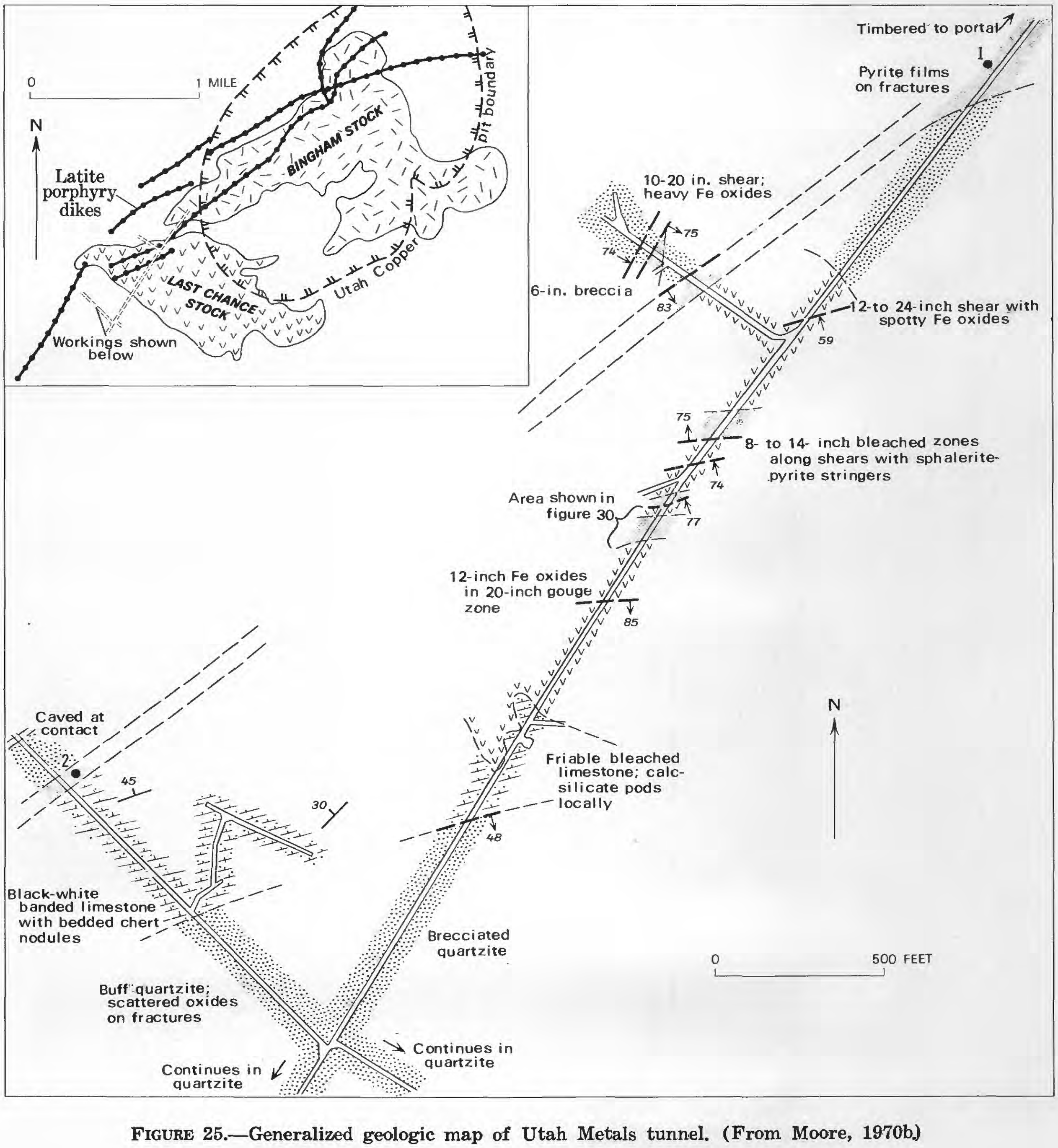
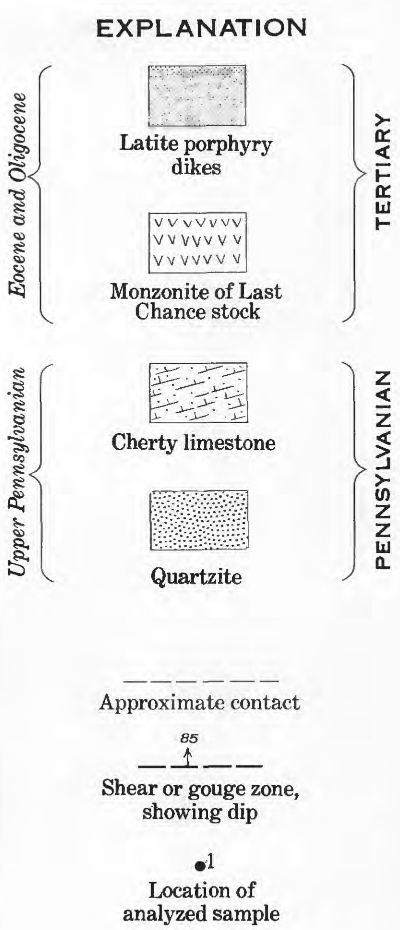


FIGURE 25.—Generalized geologic map of Utah Metals tunnel. (From Moore, 1970b.)

specimens are characterized by white tabular plagioclase phenocrysts, greenish-black hornblende prisms, and black biotite plates as much as 5 mm long that are evenly distributed in an aphanitic groundmass (fig. 27). The border rocks are generally darker and denser, and they contain fewer feldspar phenocrysts than rocks from the center of a dike. Pinkish orthoclase phenocrysts are sparsely scattered in dikes cutting the stocks but are absent from those associated with the volcanic rocks southeast of the district. Small rounded quartz phenocrysts are noted in many samples. Nearly spherical quartz phenocrysts as much as 1 cm in diameter distinguish the youngest intrusive phase at Bingham, a biotite quartz latite porphyry dike (fig. 27), exposed in the Utah Copper pit (Stringham, 1953; Bray, 1969). Another minor but distinctive variant contains abundant acicular actinolite and composite biotite-phlogopite crystals. The significance of this peculiar mineral assemblage has been considered elsewhere (Moore, 1970b).

Thin sections of dike rocks from the Utah Metals tunnel reveal stubby euhedral to subhedral feldspar phenocrysts ranging in average length from 2 to 4 mm. In all samples examined, cryptoperthitic orthoclase is present but is greatly subordinate to plagioclase (fig. 28*A*). Biotite occurs in millimeter-size rectangular and pseudohexagonal plates with dark-brown to yellow-brown pleochroic colors. Pale-yellowish-green hornblende prisms are slightly larger but generally less abundant than biotite. Traces of subhedral colorless augite are noted in a few sections. The phenocrysts are set in a holocrystalline groundmass composed of anhedral feldspar and quartz grains with average diameters of about 0.04 mm. Estimates of relative abundance indicate that orthoclase > quartz >> plagioclase.

Alteration of phenocryst minerals is the most distinctive feature of dike rocks studied in the Utah Metals tunnel. Hornblende and, to a lesser extent,



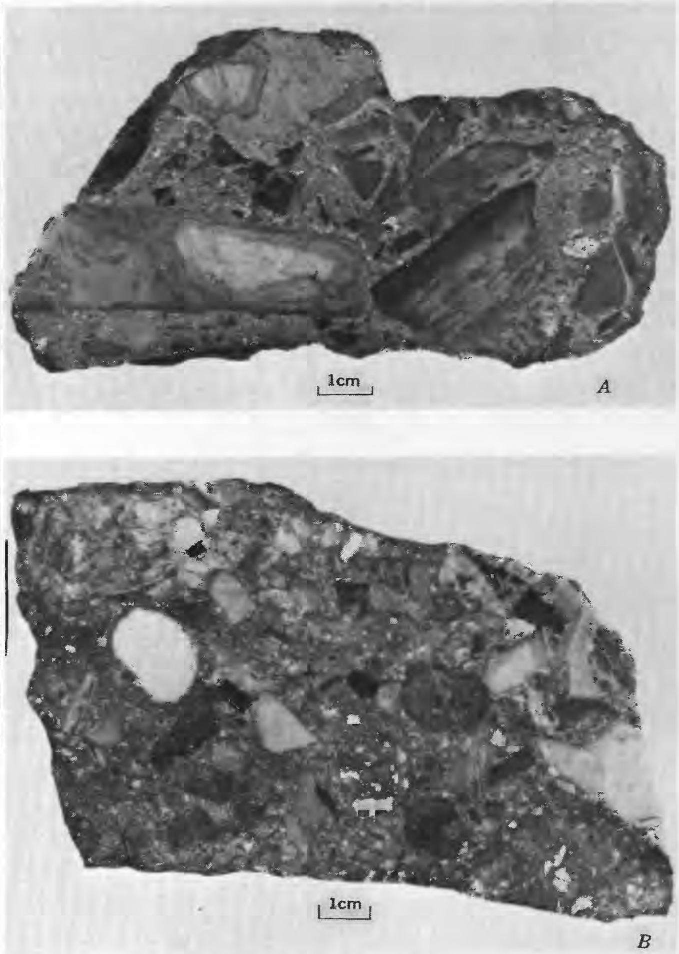


FIGURE 26.—Pebble dikes from Utah Metals tunnel northwest of location 2 in figure 25. *A*, Subangular fragments in matrix composed of iron-stained rock flour. *B*, Subangular to rounded fragments of latite and mixed sedimentary lithologies in matrix composed of silicified latite.

biotite are replaced by compact aggregates of calcite or by chlorite, magnetite, and traces of hematite plus rutile (fig. 28*B*). In addition, plagioclase is variably replaced by feathery to felted aggregates of white mica. K-feldspar phenocrysts are relatively unaffected.

Dikes in the area southeast of the stocks are distinguished from those in the Utah Metals tunnel by the absence of orthoclase phenocrysts and by the abundance of hornblende relative to biotite. In this respect the peripheral dikes resemble the volcanic rocks with which they are closely associated. Stubby white plagioclase and yellowish-green hornblende prisms and dark-brown biotite laths have an average length of about 1 mm; a weak fluidal alinement of elongate biotite laths is noted in some sections.

TABLE 6.—*Chemical data for southeastern part of Bingham stock*

[Chemical analyses by rapid methods by U.S. Geological Survey Analytical Laboratories under the direction of Leonard Shapiro. Semiquantitative spectrographic analyses by Chris Heropoulos, U.S. Geological Survey. Results are expressed in parts per million to the nearest number in the series 10,000, 7,000, 5,000, 3,000, 2,000, 1,500, 1,000, etc.; these numbers represent approximately plus or minus one interval about 68 percent of the time or two intervals 95 percent of the time. Elements looked for but not found: Ag, As, Au, Bi, Cd, Eu, Hf, Hg, In, P, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn. Samples from table 5]

	Chilled augite monzonite	Amphibole-augite monzonite and quartz monzonite			Porphyritic amphibole quartz monzonite			
	36	63	107	Average	22	69	70	Average
				Chemical analyses (weight percent)				
SiO_2	57.6	58.0	57.1	57.6	58.6	61.6	62.5	60.9
Al_2O_3	15.0	15.7	15.6	15.6	15.2	15.1	15.4	15.2
Fe_2O_3	2.3	3.3	3.0	3.2	2.6	2.3	2.5	2.5
FeO	4.4	3.3	3.4	3.4	3.0	2.5	2.4	2.6
MgO	4.9	3.6	4.2	3.9	4.2	3.1	2.8	3.4
CaO	6.4	4.0	5.4	4.7	6.0	4.0	3.5	4.5
Na_2O	3.2	3.8	3.6	3.7	3.3	3.7	3.6	3.5
K_2O	3.8	5.1	4.5	4.8	4.7	4.8	4.7	4.7
H_2O	.84	1.51	1.18	1.34	.66	1.30	1.40	1.12
TiO_2	.94	.95	.93	.94	.83	.70	.72	.75
CO_2	.06	.05	.30	.18	.18	.50	.30	.33
P_2O_5	.46	.57	.52	.55	.45	.37	.39	.40
MnO	.12	.10	.12	.11	.10	.07	.07	.80
S	<.0	<.0	.09	<.05	.40	<.05	.05	.15
Total	100	100	100	100	100	100	100	100
				Spectrographic analyses (parts per million)				
B	0	10	10	---	0	0	15	---
Ba	2,000	3,000	3,000	---	3,000	2,000	2,000	---
Be	3	5	2	---	2	5	5	---
Ce	200	300	200	---	200	200	150	---
Co	30	20	20	---	30	20	15	---
Cr	150	100	70	---	100	70	50	---
Cu	70	150	50	---	70	100	150	---
Ga	15	20	20	---	15	20	20	---
La	150	200	150	---	200	150	150	---
Mo	5	7	3	---	5	7	7	---
Nb	15	20	15	---	10	30	30	---
Nd	100	100	100	---	100	70	100	---
Ni	50	70	70	---	50	50	50	---
Pb	100	100	70	---	70	70	70	---
Sc	20	20	20	---	20	15	15	---
Sr	1,500	2,000	2,000	---	2,000	1,500	1,500	---
V	150	200	200	---	100	150	150	---
Y	20	30	30	---	20	30	20	---
Yb	2	2	2	---	2	3	2	---
Zr	200	300	300	---	200	300	200	---
				Norms (weight percent)				
Q	5.5	4.3	4.2	4.2	6.3	11.2	14.8	10.8
or	22.5	30.2	26.6	28.4	27.9	28.9	27.2	28.0
ab	27.1	32.2	30.5	31.4	28.0	30.4	28.8	29.1
an	15.3	10.7	13.1	11.9	12.8	10.6	12.9	12.1
wo	5.4	2.3	3.5	2.9	5.4	1.5	.0	2.3
en	12.2	9.0	10.5	9.8	10.5	7.7	7.0	8.4
fs	4.8	2.0	2.3	2.2	1.4	1.5	1.2	1.4
mt	3.3	4.8	4.4	4.6	3.8	3.3	3.6	3.6
il	1.8	1.8	1.8	1.8	1.6	1.3	1.4	1.4
ap	1.1	1.4	1.2	1.3	1.1	.9	.9	1.0
pr	0	0	.2	.1	.8	0	.1	.3
C	.0	.0	.0	.0	.0	.0	.1	.03

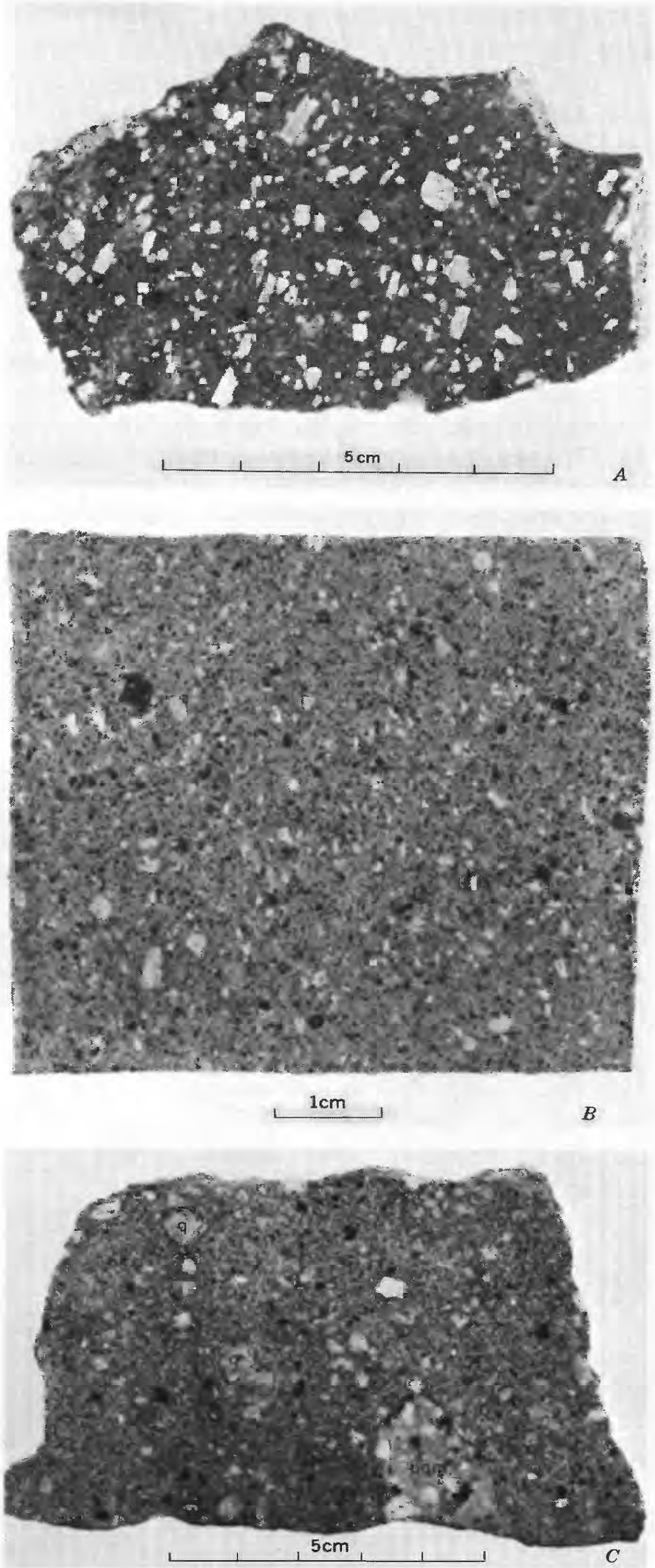


FIGURE 27.—Latitic dike rocks. *A*, Dark border phase of dike shown in figure 30. *B*, Fine-grained hornblende-biotite latite from Butterfield Canyon area in northwest corner of Tickville Springs quadrangle. *C*, Biotite quartz latite containing resorbed quartz phenocrysts (q) and large xenolith of porphyritic quartz monzonite (pqm) from Utah Copper pit.

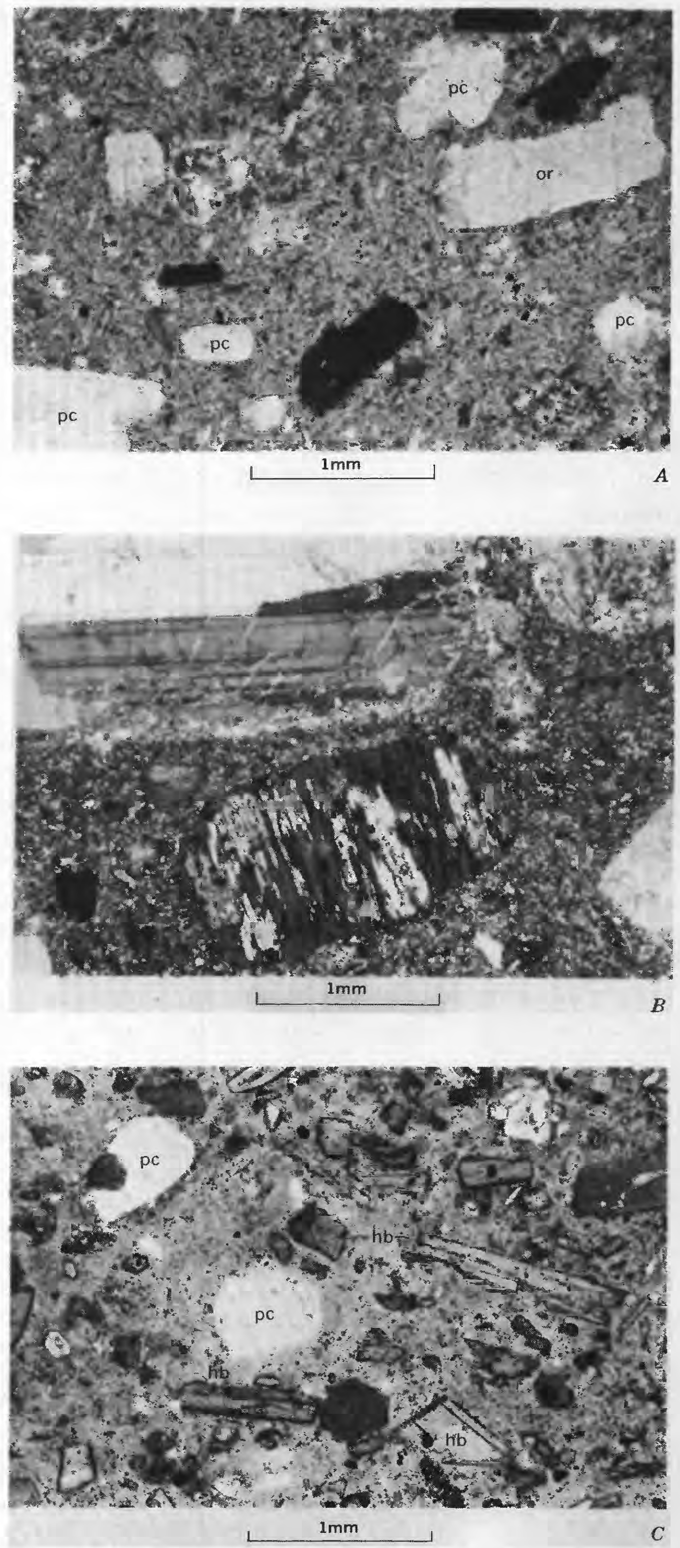


FIGURE 28.—Latitic dike rocks. *A*, Subhedral plagioclase (pc), orthoclase (or), and biotite (black) phenocrysts in aphanitic groundmass; sample from Utah Metals tunnel. Plane-polarized light. *B*, Biotite phenocryst (lower center) replaced along (010) cleavage directions by chlorite and calcite; sample from Utah Metals tunnel. Partly crossed nicols. *C*, Euhedral to subhedral hornblende (hb) and plagioclase (pc) phenocrysts in dense holocrystalline groundmass; sample from Butterfield Canyon.

The phenocryst minerals are set in a fine-grained holocrystalline groundmass (fig. 28*C*) that is tinted various shades of tan by ferric oxide weathering products. Euhedral apatite crystals and scattered magnetite anhedra are minor accessory constituents.

MODAL DATA

Modal analyses for 16 dike rocks are summarized in table 7. Major groundmass minerals, mainly K-feldspar and quartz, could not be consistently resolved under the microscope. Although complete modes are not available for comparative purposes, the variations in proportions of felsic and mafic phenocryst minerals (fig. 29 *A*, *B*) distinguish the subvolcanic dikes from those of the Utah Metals tunnel.

Specific gravities of the dike rocks cluster about a central value of 2.65 (fig. 29*C*). Contrasts in specific gravity and modal mineralogy between the borders and center of a zoned dike are illustrated in figure 30. Plagioclase, K-feldspar, and biotite phenocrysts in the chilled border zone rocks are set in a very fine grained dark-olive-green matrix. Rocks at the center of the dike have a pale-gray-green matrix that is coarser grained and apparently more siliceous and contains no biotite phenocrysts. Biotite and amphibole phenocrysts and tiny magnetite anhedra are relatively more abundant in the border zones. Essentially all mafic phenocrysts in the center are replaced by pseudomorphous chlorite-calcite aggregates. White mica replaces the margins of plagioclase phenocrysts in the border zones. Toward the center, ghostlike phenocryst outlines are preserved by felted sericite intergrowths.

Bray (1969) described similar alteration mineral assemblages in dike rocks from the western part of the district that, according to his interpretation, represent peripheral effects of hydrothermal alteration related to disseminated copper mineralization. The extent of alteration, however, is not clearly related to postcrystallization fractures, and mafic minerals in the monzonite bordering the dike have not been similarly affected. These features suggest that the dike was altered by a hydrous CO_2-bearing fluid that separated from the melt during crystallization and permeated the residual liquid-crystal mixture. An explosive release of fluid pressure may account for the unusual intrusive(?) breccia at the dike's northeast margin.

Alteration assemblages characteristic of the propylitic zone that is peripheral to the disseminated copper ore body at Bingham are found only in rocks near the portal of the Utah Metals tunnel (fig. 3). Here the dikes contain scattered grains and veinlets of pyrite, and the calcic cores of some zoned plagioclase phenocrysts are replaced by epidote-quartz aggregates.

CHEMICAL DATA

Chemical characteristics of the latitic dikes at Bingham (table 8) are generally comparable with the rocks of the Last Chance and Bingham stocks: SiO_2 ranges from 57 to 64 percent, and K_2O is slightly in excess of Na_2O. Thus, although textures and modal mineralogy of the dikes indicate a crys-

TABLE 7.—*Modes, in volume percent, of latitic dike rocks*

Sample	Phenocrysts						Chlorite	Calcite	Pyrite	Opaque oxide and accessory minerals	Groundmass	Specific gravity
	Quartz	K-feldspar	Plagioclase	Pyroxene	Biotite	Amphibole						
Samples from Utah Metals tunnel												
80	---	0.9	22.9	---	4.8	---	4.0	8.6	1.4	2.3	55.1	2.62
81	---	3.7	5.7	---	9.0	2.3	2.3	9.7	---	.7	66.6	2.71
82	---	1.6	4.2	---	6.8	4.8	1.0	.3	.8	.2	80.3	2.65
83	---	1.9	20.3	---	2.5	4.7	.6	---	1.2	.7	68.1	2.60
87	0.9	4.7	19.5	---	3.8	.3	4.7	5.0	---	2.1	59.0	2.67
88	.3	1.4	18.8	---	4.3	3.1	2.9	.6	---	.9	67.7	2.66
89	---	1.4	16.3	2.3	9.2	.8	.6	.3	---	1.1	68.0	2.71
108	2.5	3.1	26.1	---	5.5	.6	4.2	5.0	---	1.2	51.8	2.65
109	1.6	1.9	18.1	---	8.2	3.1	---	4.4	---	2.6	60.1	2.69
110	.3	10.8	16.7	---	3.3	5.2	.3	1.6	---	2.3	59.5	2.65
Average	0.6	3.8	16.9	0.2	5.7	2.5	2.1	3.6	0.3	1.8	63.6	2.66
Samples from surface south and east of Bingham stock												
94	0.30	---	19.4	5.0	3.1	4.4	---	---	---		65.9	2.56
95	3.4	---	20.9	---	4.9	6.8	---	---	---		62.8	2.63
97	.6	---	8.4	---	1.7	15.7	---	---	---		73.3	2.59
177	---	---	8	---	3	28	---	---	---		61	2.67
178	---	---	4	---	2	27	---	---	---		67	2.69
179	2	---	13	---	4	4	---	---	---		77	2.54
Average	1.1	---	12.3	0.8	3.1	14.3	---	---	---		67.8	2.61

tallization history differing from that of the larger intrusive bodies, their intermediate chemical affinities suggest a common parentage.

Groundmass mineralogy of the dike rocks is best inferred from the chemical data. The groundmass in each sample makes up about 60 percent of the rock by volume (table 7) and consists of a very fine grained intergrowth of anhedral feldspars and quartz. From the triangular plot of normative salic minerals in figure 29*D*, feldspar proportions are apparently similar to rocks from the two stocks, and normative quartz percentages are slightly higher. Because the dikes are younger than the stocks, the modest silica enrichment may be a consequence of progressive differentiation in the parent magma chamber. Note that two points in figure

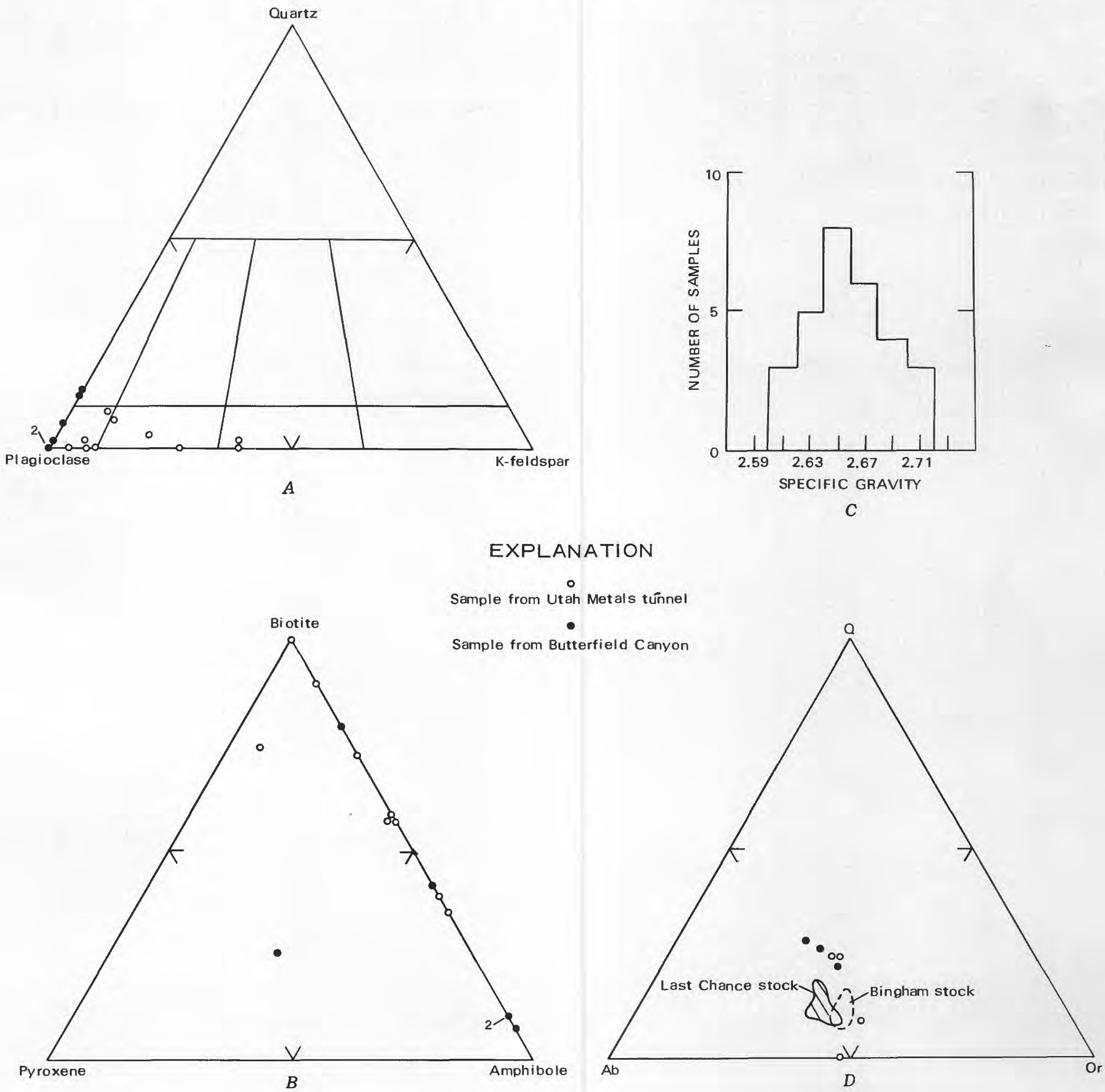


FIGURE 29.—Samples of latitic dike rocks, *A*, *B*, Modal phenocryst mineral proportions. *C*, Variations in specific gravity. *D*, Normative salic mineral proportions.

29*D* are plotted below the composition fields for the stocks; these represent rocks containing appreciable phlogopite that is thought to have crystallized from a melt contaminated by assimilation of dolomitic sedimentary rocks (Moore, 1970b).

EXTRUSIVE IGNEOUS ROCKS

GENERAL FIELD RELATIONS

A sequence of largely latitic volcanic rocks bounds the main area of intrusive rocks at Bingham on the east and south. Descriptions of the volcanic sequence are based on preliminary mapping, on petrographic studies, and, to a greater extent than in the preceding sections, on the work of others, including Gilluly (1932), Smith (1961), and E. W. Tooker (unpub. map).

The most complete section of volcanic rocks is exposed about 5 miles southeast of the main Bingham district in that part of the western Traverse Mountains included in the Tickville Springs 7½ minute quadrangle (fig. 31): the preserved volcanic section in this area is about 3,000 feet thick. The eruptive rocks cover a surface of moderate relief underlain by gently folded Mississippian and Pennsylvanian sedimentary rocks. Because of uncertainties regarding the pre-volcanic topography, the order of eruption suggested in the following discussion is generalized.

Laharic breccias make up the basal unit in the volcanic section over much of the Tickville Springs quadrangle. West of Oak Springs Hollow, breccias appear to overlap a small exposure of extrusive nepheline basalt; field relations here are not clear.

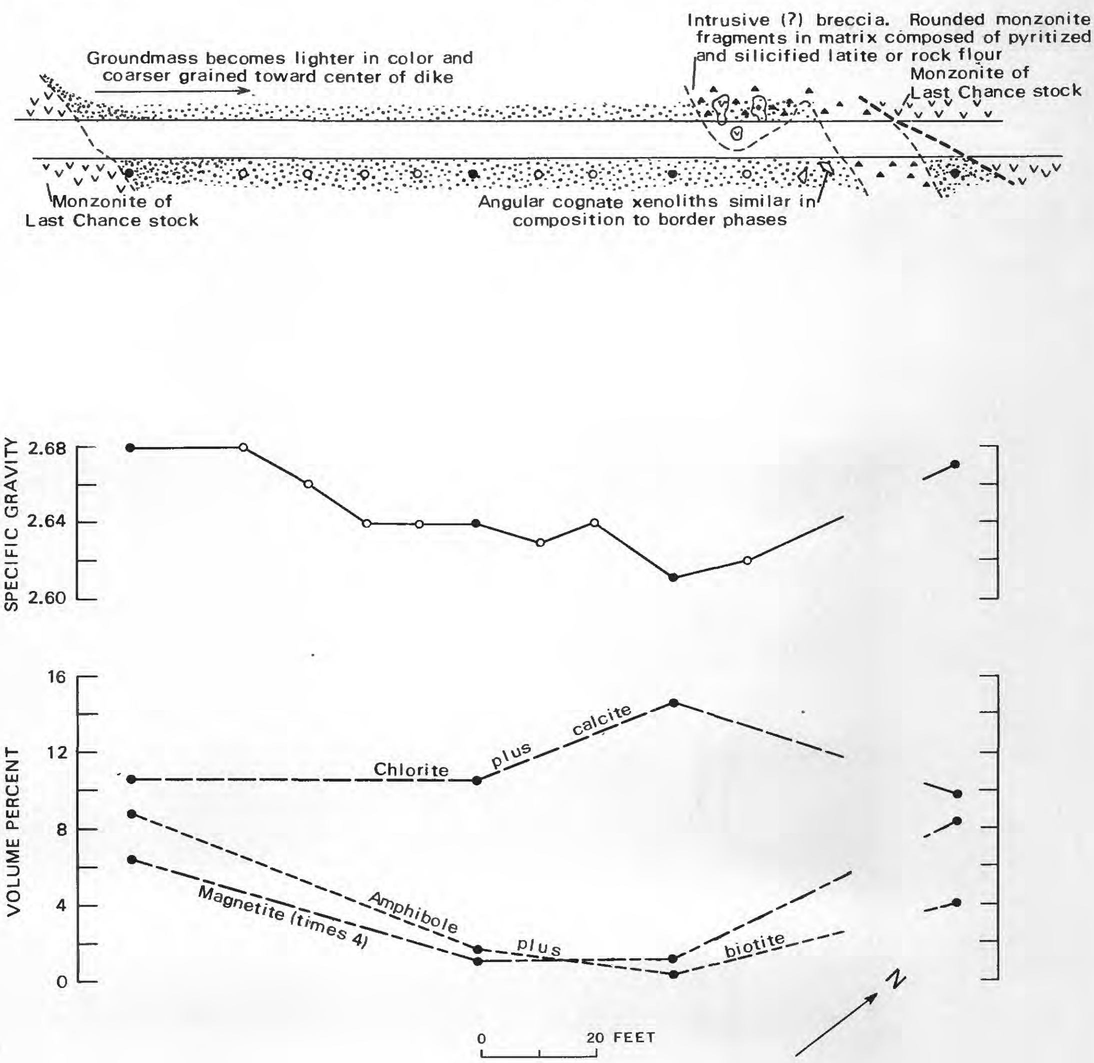


FIGURE 30.—Traverse across zoned latite porphyry dike in Utah Metals tunnel showing contrast in specific gravity and modal mineralogy between borders and center. Area located in figure 25.

The poorly stratified breccias reach a thickness of 1,500–2,000 feet in the Yellow Fork area and consist of subangular to rounded fragments ranging in size from several inches to several feet. (See Gilluly, 1932, plate 8.) The clasts are set in a matrix composed of lithic and crystal fragments. A wide variety of latitic and quartz latitic textural variants is included in the breccias, and hornblende-biotite latite is, perhaps, the most abundant. Interbedded with the breccias are thin and poorly indurated lenses of water-laid tuff, volcanic gravels, and crossbedded sands.

TABLE 8.—*Chemical data for latitic dike rocks*

[Chemical analyses by rapid methods by U.S. Geological Survey Analytical Laboratories under the direction of Leonard Shapiro. Semiquantitative spectrographic analyses by Chris Heropoulos, U.S. Geological Survey. Results are expressed in parts per million to the nearest number in the series 10,000, 7,000, 5,000, 3,000, 2,000, 1,500, 1,000, etc.; these numbers represent approximate midpoints of group data on a geometric scale. The precision of a reported value is approximately plus or minus one interval about 68 percent of the time or two intervals 95 percent of the time. Elements looked for but not found: Ag, As, Au, Bi, Cd, Eu, Hf, Hg, In, P, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn. Samples from table 7]

	Samples from Utah Metals tunnel					Samples from surface south and east of Bingham stock			
	80	81	87	89	Average	94	95	97	Average
				Chemical analyses (weight percent)					
SiO_2	60.2	57.6	59.8	57.4	58.7	61.5	64.5	61.8	62.6
Al_2O_3	13.0	13.4	14.5	14.1	13.8	15.4	15.7	14.6	15.2
Fe_2O_3	3.0	1.7	1.5	1.5	1.9	4.4	3.1	2.8	3.4
FeO	1.9	3.0	3.0	2.3	2.6	1.1	1.4	2.1	1.5
MgO	3.4	5.2	4.1	5.3	4.5	2.0	1.6	3.7	2.4
CaO	4.2	5.8	4.7	5.6	5.1	3.6	3.8	4.1	3.6
Na_2O	3.4	3.2	3.2	4.0	3.4	3.4	3.8	3.3	3.5
K_2O	4.5	5.2	3.9	5.3	4.1	4.5	3.3	3.5	3.8
H_2O	2.04	1.10	2.08	1.70	1.73	2.40	1.50	2.34	2.08
TiO_2	.51	.54	.51	.59	.54	.75	.60	.63	.66
CO_2	2.8	2.2	2.2	1.2	2.1	.11	<.05	.15	.09
P_2O_5	.34	.42	.35	.45	.39	.42	.42	.67	.50
MnO	.10	.12	.11	.10	.11	.07	.15	.11	.11
S	1.50	<.05	<.05	<.05	.38	<.05	<.05	<.05	<.05
Total	100	99	100	100		100	100	100	
				Spectrographic analyses (parts per million)					
B	---	---	---	15	---	10	---	---	---
Ba	1,500	1,500	1,500	1,500	---	5,000	2,000	3,000	---
Be	5	7	5	5	---	5	2	2	---
Ce	150	200	150	200	---	300	150	150	---
Co	15	20	15	20	---	20	15	20	---
Cr	70	150	100	200	---	150	50	300	---
Cu	70	100	70	100	---	100	30	50	---
Ga	15	15	15	15	---	30	20	20	---
La	100	100	100	100	---	200	70	100	---
Mo	7	7	5	3	---	3	2	---	---
Nb	15	15	15	20	---	15	15	15	---
Nd	---	70	70	70	---	150	---	70	---
Ni	100	200	100	150	---	100	30	70	---
Pb	70	20	20	70	---	100	30	70	---
Sc	10	15	10	15	---	20	15	20	---
Sr	1,500	1,500	1,500	1,500	---	1,500	1,000	1,000	---
V	100	100	100	150	---	200	200	200	---
Y	20	20	20	20	---	30	20	20	---
Yb	2	2	2	2	---	3	2	2	---
Zr	300	200	200	300	---	300	200	200	---
				Norms (weight percent)					
Q	17.6	5.7	15.4	0.2	9.7	15.6	20.5	17.0	17.7
or	26.4	30.9	23.1	31.5	28.0	26.7	19.5	20.7	22.3
ab	28.5	27.2	27.1	34.0	29.2	28.9	32.2	28.0	29.7
an	.9	6.9	7.1	4.9	5.0	13.5	16.1	14.7	14.8
wo	---	2.2	---	5.2	1.8	.4	---	.1	.2
en	8.4	13.0	10.2	13.3	11.2	5.0	4.0	9.2	6.1
fs	---	3.5	3.6	2.2	2.3	---	---	.7	.2
mt	---	2.5	2.2	2.2	1.7	1.6	3.3	4.1	3.0
hm	3.0	---	---	---	.7	3.3	.9	---	1.4
il	.7	1.0	1.0	1.1	1.0	1.4	1.1	1.2	1.2
ap	.8	1.0	.8	1.1	.9	1.0	1.0	1.6	1.2
pr	2.8	---	---	---	.07	---	---	---	---
cc	6.3	5.0	5.0	2.7	4.8	.3	---	.3	.2
C	2.2	---	2.4	---	1.2	---	---	---	---

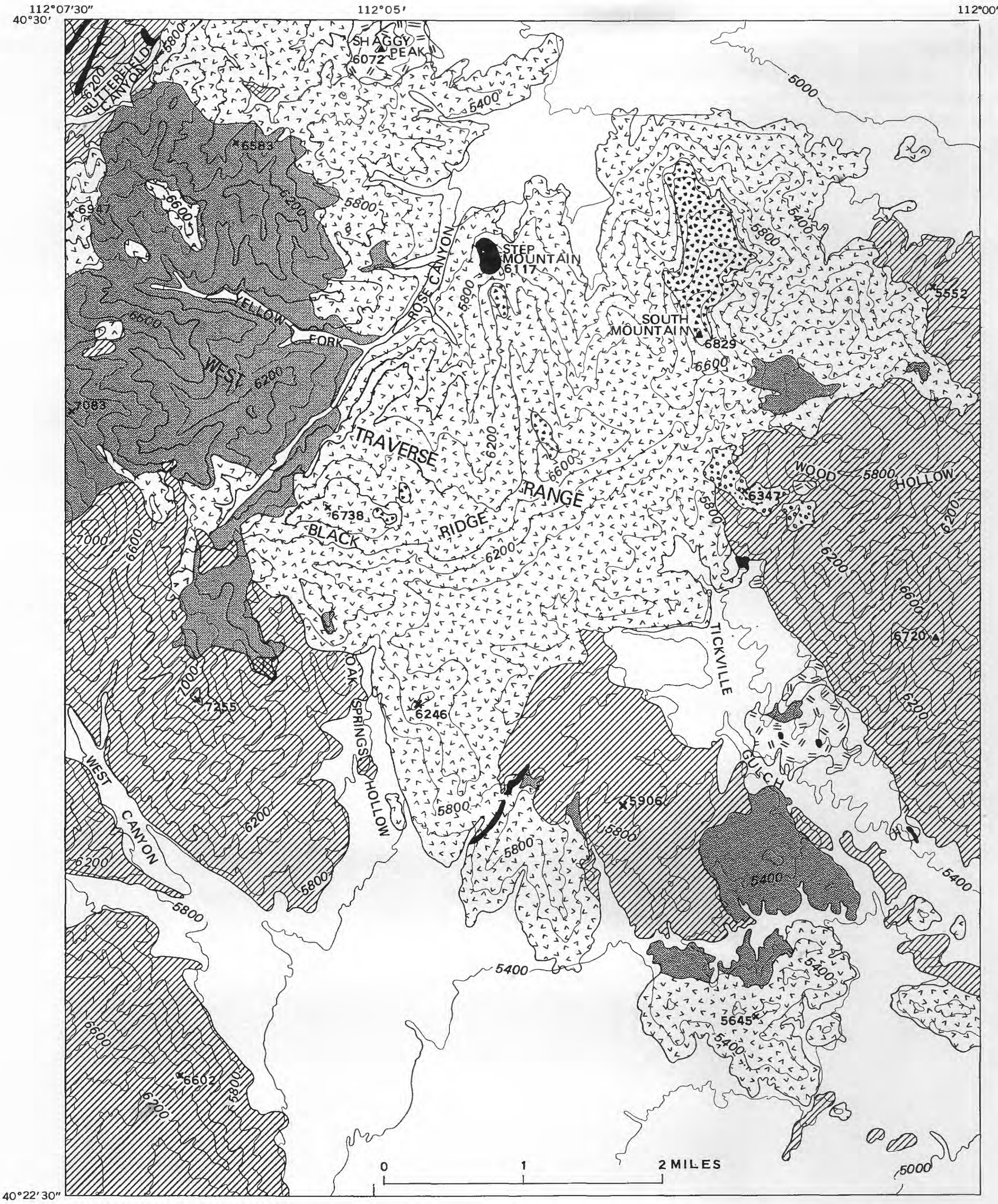
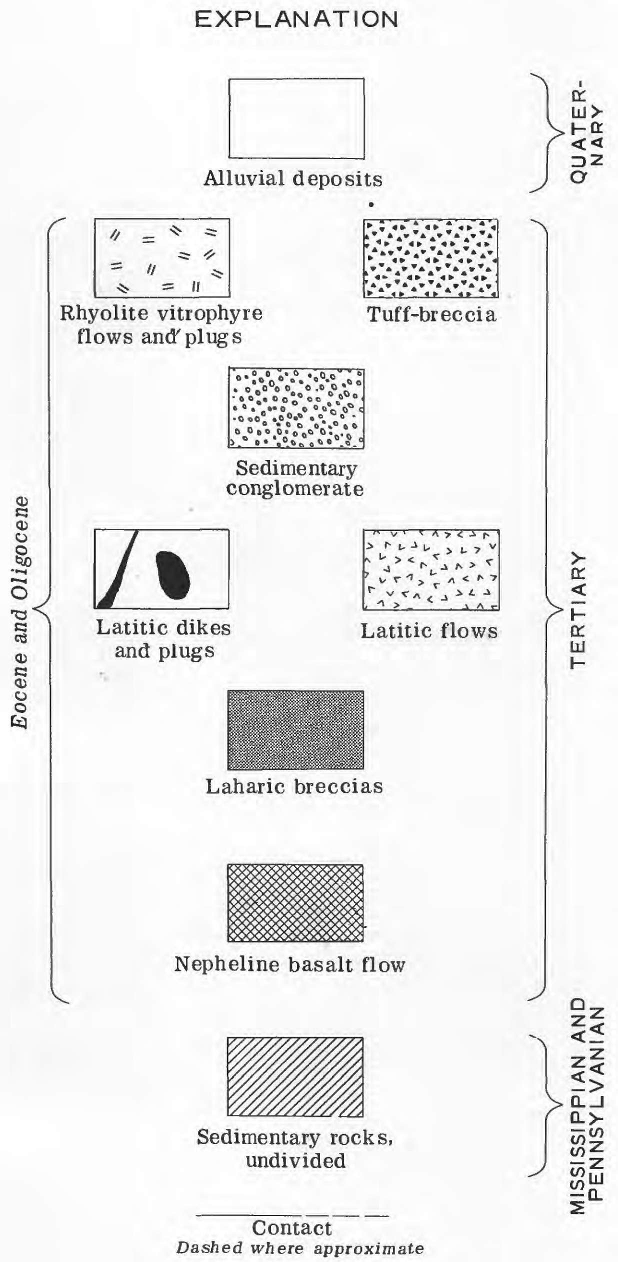


Figure 31.—Generalized geologic map of Tickville Springs 7½-minute quadrangle; area located in figure 1.



East of Rose Canyon, the breccias are overlain by a series of lenticular latitic flows with a minimum aggregate thickness of about 800 feet. Isolated exposures of the breccia are sufficiently common near the outcrop limits of the flows to suggest that the two were originally coextensive. The flows are predominantly hornblende-biotite latites. Less abundant variants include augite-biotite latite and hornblende-biotite quartz latite.

Near the head of Wood Hollow, in the east-central part of the Tickville Springs quadrangle, a small tongue of silica-cemented conglomerate several hundred feet thick rests with angular unconformity upon Pennsylvanian sedimentary rocks and overlaps flows representing the local base of the volcanic section. The conglomerate, contrary to Gilluly's description (1932, p. 39), contains no volcanic detritus but rather is composed of subrounded fragments of dark-gray limestone and buff to reddish-tan quartzite averaging less than a centimeter in diameter. White silty lenses are interbedded with the coarser clastics. From this exposure alone the conglomerate can be said only to postdate the basal part of the flow series. Evidence for an intravolcanic age follows.

Sizeable bodies of rhyolite occur in two areas within the Tickville Springs quadrangle. Extrusive rhyolite vitrophyre and rhyolite vitrophyre breccia are exposed over an area of approximately 1 square mile east of lower Tickville Gulch. These glassy rocks display fluidal structures resulting from viscous flowage and are finely color banded in pale shades of green, pink, and tan. Abundant milky plagioclase phenocrysts and scattered biotite plates are the only identifiable minerals in hand specimens. Locally intense silicification has produced a chalky nondescript altered facies. Two small silicified rhyolite breccia plugs in the Wood Hollow area may have fed the Tickville flows.

A larger, unbrecciated rhyolite plug underlies Shaggy Peak and intrudes the latite flow series. The plug is composed mainly of a dark-gray vitrophyric rhyolite crowded with resorbed and fragmented phenocrysts of quartz, plagioclase, sanidine, and biotite. A discontinuous border facies is composed of phenocryst-poor microcrystalline rhyolite that may represent a devitrified chilled zone.

Near the center of the largest rhyolite outcrop area east of Tickville Gulch (fig. 31), a 20–30-foot section of interbedded conglomerate and sandstone is exposed at the head of a minor tributary. The conglomerate is in sharp angular unconformity with subjacent Pennsylvanian rocks and is overlain by rhyolite breccia. The conglomerate consists entirely of limestone and quartzite clasts, some as much as 4–6 inches across, in a siliceous matrix. These coarse clastics are tentatively correlated with the thicker section exposed near the head of Wood Hollow, and exceptionally clear field relations show that they are older than the rhyolite.

Between the head of Rose Canyon and South Mountain, patches of a monolithologic latite tuff-breccia are preserved as a capping over the flow series. In the South Mountain area the tuff-breccia has a minimum thickness of 600 feet. This distinctive rock consists of angular to subrounded fragments of dark-gray hornblende-biotite latite in a porous matrix of reddish-brown tuffaceous material and finely comminuted latite. Its topographic position suggests that the breccia is one of the youngest units in the volcanic sequence.

Locally the eruptive rocks of the Tickville Springs quadrangle are intruded by latitic dikes and plugs. Similar dikes intrude Pennsylvanian sedimentary rocks northeast of Butterfield Canyon. The largest intrusion, an oval plug with a pronounced subhorizontal jointing in the border zone, underlies Step Mountain. A small "dioritic" plug, discussed in some detail by Gilluly (1932, p. 55–7), intrudes the flows near the head of Tickville Gulch. A narrow latite dike intrudes flows and a small breccia plug about 1 mile east of Oak Springs Hollow. Finally, several dark hornblende latite dikes and plugs intrude the rhyolites east of Tickville Gulch.

The volcanic history may be briefly summarized. Fragmental latitic rocks, including laharic breccias and interbedded tuffs, accumulated to a thickness of several thousand feet early in the volcanic episode and were followed by a series of lenticular latitic flows representing a period of more quiescent eruptive conditions. An erosion interval of unknown duration was followed by eruption of rhyolitic vitrophyres and a latite tuff-breccia whose relative age is uncertain. Small plugs or dikes of latitic and rhyolitic composition were emplaced during the later stages of the volcanic cycle. Because no large volcanic necks have been recognized in the Tickville Springs area, it is thought (Gilluly, 1932, p. 65) that the flows were fed by these intrusions and others not yet exposed by erosion.

PETROGRAPHY

In keeping with the generalized discussion of occurrence and areal distribution of volcanic rocks in the Bingham area, only a brief treatment of their typical lithologic features will be included here. The reader is referred to Gilluly's report (1932) for detailed petrographic descriptions of representative rock types in the volcanic sequence.

As a group, the volcanic rocks have porphyritic-aphanitic texture. Some glass is present in the groundmass of about half the latitic rocks, whereas glass or devitrified glass predominates in the rhyolitic rocks. Individual latitic flows differ most obviously in the size and abundance of milky white plagioclase phenocrysts; a typical flow rock contains 20–25 volume percent of plagioclase phenocrysts averaging 1–2 mm in length. Other less common variants are either crowded with relatively large plagioclase phenocrysts (fig. 32*B*) or are phenocryst poor (fig. 32*C*). Potassium feldspar phenocrysts were not observed in the latites but are present in sparse amounts in the rhyolites. Likewise, megascopic quartz phenocrysts were observed only in the rhyolitic rocks (figs. 32*D, E*).

With regard to mafic minerals, hornblende predominates over biotite in more than two-thirds of the latite flows and all the dike rocks. Pyroxene (augite and hypersthene) is the major mafic mineral in a few samples, whereas only biotite is present in the rhyolites.

MODAL DATA

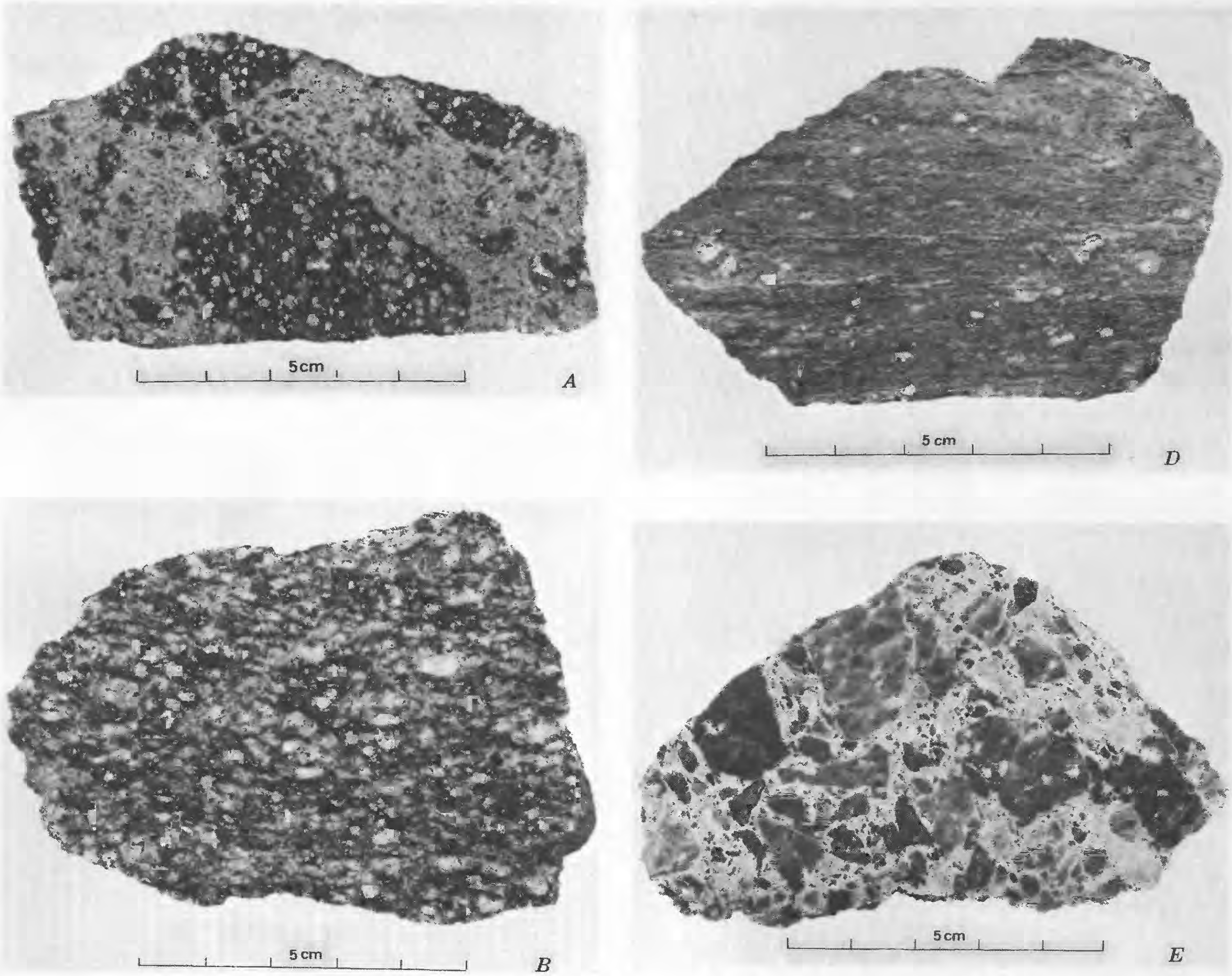
Modal abundances of phenocryst minerals from a wide variety of rock types in the volcanic sequence are summarized in table 9. As in the case of texturally similar latitic dike rocks from the Utah Metals tunnel and Butterfield Canyon, groundmass mineral quantities could not be accurately determined. Consequently, a total figure is reported for the percentage of groundmass in each sample. The extrusive rocks, compared with the Utah Metals dikes, differ mainly in the absence of K-feldspar phenocrysts and in the preponderance of hornblende-rich mafic mineral assemblages (figs. 33*A, B*). The rhyolite plugs and flows are readily distinguished from the latitic rocks on the basis of the abundance of quartz and biotite phenocrysts.

Specific gravity values for the volcanic rocks, shown in the frequency histogram of figure 33*C*, are uniformly lower than those for any other igneous rock types in the Bingham area. Differences in median values between the rhyolites ($\sim$2.35) and latites ($\sim$2.55) are presumably an index of rock composition. Greater porosity or vesicularity is a likely explanation for the lower specific gravities of the latitic extrusive rocks compared with those for latitic dikes from the main Bingham district (median value $\sim$ 2.65).

CHEMICAL DATA

Chemical compositions of volcanic rocks in the Tickville Springs quadrangle (table 10) are similar to those of other igneous rock types in the Bingham area. Compositional similarities are greatest between the latitic flows and dikes from the Utah Metals tunnel and Butterfield Canyon (table 8). Measured differences in phenocryst mineral proportions apparently affect the whole-rock compositions less than do similarities in salic mineral proportions in the groundmass.

If chemical and normative data for the volcanic rocks are included, it can be shown that alkali



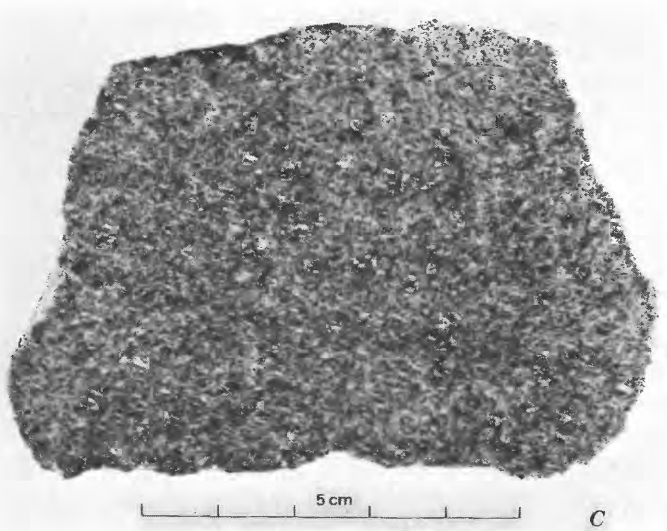


FIGURE 32.—Volcanic rocks in Tickville Springs quadrangle. *A*, Monolithologic hornblende-pyroxene latite tuff-breccia. Texture of dark fragments is typical of most flows in volcanic series. Sample locality one-quarter mile south of Step Mountain. *B*, Hornblende-biotite latite flow crowded with large flow-oriented plagioclase phenocrysts. Sample from east-central edge of Tickville Springs quadrangle. *C*, Fine-grained pyroxene-biotite latite flow. Sample locality near head of Rose Canyon. *D*, Laminated rhyolite vitrophyre flow with sparse plagioclase phenocrysts. Sample locality east of Tickville Gulch. *E*. Monolithologic rhyolite vitrophyre breccia containing medium- to dark-green fragments in pale-pink matrix. Sample locality east of Tickville Gulch.

ratios are remarkably uniform for all igneous rocks in the Bingham area. The latitic extrusions show the same slight enrichment in silica compared to the larger intrusions as did the Utah Metal dikes. This enrichment is even more pronounced in the rhyolites (fig. 33*D*).

TABLE 9.—*Modes, in volume percent, of latitic and rhyolitic volcanic rocks*

Sample	Phenocrysts						Groundmass	Specific gravity
	Quartz	K-feldspar	Plagioclase	Pyroxene	Biotite	Amphibole		
				Latitic rocks				
124	---	---	35	---	---	---	54	2.52
125	---	---	23	4	1	7	65	2.49
126	4	---	28	---	5	5	58	2.46
127	5	---	26	---	2	---	67	2.31
128	2	---	30	---	5	7	56	2.44
129	3	---	15	---	3	1	78	2.40
130	1	---	23	---	4	7	65	2.48
131 (dike)	1	---	21	---	3	10	65	2.52
132	1	---	30	---	4	8	57	2.54
133	---	---	23	2	1	8	66	2.52
134 (dike)	---	---	18	1	---	12	69	2.52
136 (dike)	---	---	15	---	1	11	73	2.55
140	---	---	24	6	5	5	60	2.53
141	---	---	5	---	4	12	79	2.47
142	---	---	9	---	3	8	80	2.30
143	---	---	11	---	1	10	78	2.37
144	---	---	26	6	1	1	66	2.54
145	---	---	27	2	1	6	64	2.51
146	---	---	20	8	1	3	68	2.62
147	---	---	20	1	1	8	70	2.46
148	---	---	19	2	2	5	72	2.60
149	---	---	17	2	1	8	72	2.52
150 (dike)	---	---	22	1	2	10	65	2.42
151	---	---	27	12	---	---	61	2.58
152	---	---	28	9	---	---	63	2.63
153	2	---	28	---	3	5	62	2.53
154	---	---	38	2	2	9	49	2.54
155	---	---	27	6	---	4	63	2.60
156	---	---	40	---	3	7	50	2.50
157	---	---	19	1	1	17	62	2.52
158	---	---	13	1	---	21	65	2.58
159	---	---	29	4	4	4	59	2.43
Average	<1	---	23	2	2	7	65	2.50
				Rhyolitic rocks				
104 (plug)	15	7	8	---	2	---	68	2.27
105	---	1	1	---	---	---	98	2.24
106 (plug)	11	8	10	---	2	---	69	2.44
135	1	---	5	---	1	---	93	2.25
137	---	---	3	---	1	---	96	2.36
138	4	1	4	---	1	---	90	2.33
139 (plug)	3	---	5	---	---	---	92	2.44
Average	5	2	5	---	1	---	87	2.33

SUMMARY OF COMPOSITIONAL TRENDS FOR THE IGNEOUS ROCKS

The compositional characteristics of the Bingham igneous rocks will be summarized now, before more speculative aspects of the magmatic history are considered. General intermediate or monzonite-latitic affinities of the Bingham suite have been frequently mentioned. In detail, however, systematic compositional variations between rock types are noted which must be accounted for in any proposed petrologic model.

MODAL VARIATIONS

A satisfactory comparison of rock compositions based on modal mineral abundances is limited to phases of the Bingham and Last Chance stocks. Figure 24*A* shows that fields for felsic mineral proportions of these rocks overlap slightly, but in general, monzonites from the Bingham stock have relatively higher alkali feldspar to plagioclase ratios, although modal quartz contents for the two stocks are about equal. The data of tables 1 and 5 indicate an inverse relationship between the proportions of clinopyroxene and amphibole in samples from both stocks. Another characteristic compositional feature is the systematic relationship between felsic and mafic mineral quantities, illustrated in figure 34, where modal percentages of pyroxene are plotted against the sum of K-feldspar plus quartz. The weak negative correlation for samples from the Last Chance stock is attributed to compositional inhomogeneities existing at the time of magma emplacement. A stronger negative correlation for the composite Bingham stock is clearly a function of rock type and reflects differences in cooling rate as well as differences in bulk composition (or volatile content) between the equigranular and porphyritic phases.

CHEMICAL VARIATIONS

Because mineral percentages in the fine-grained groundmass fraction of the latitic dikes and volcanic rocks cannot be specified modally, compositional comparisons of these rocks with the coarser grained intrusions must be based on chemical and normative data. In this section some of the more widely used chemical variation diagrams will be used to establish a uniform and inclusive compara-

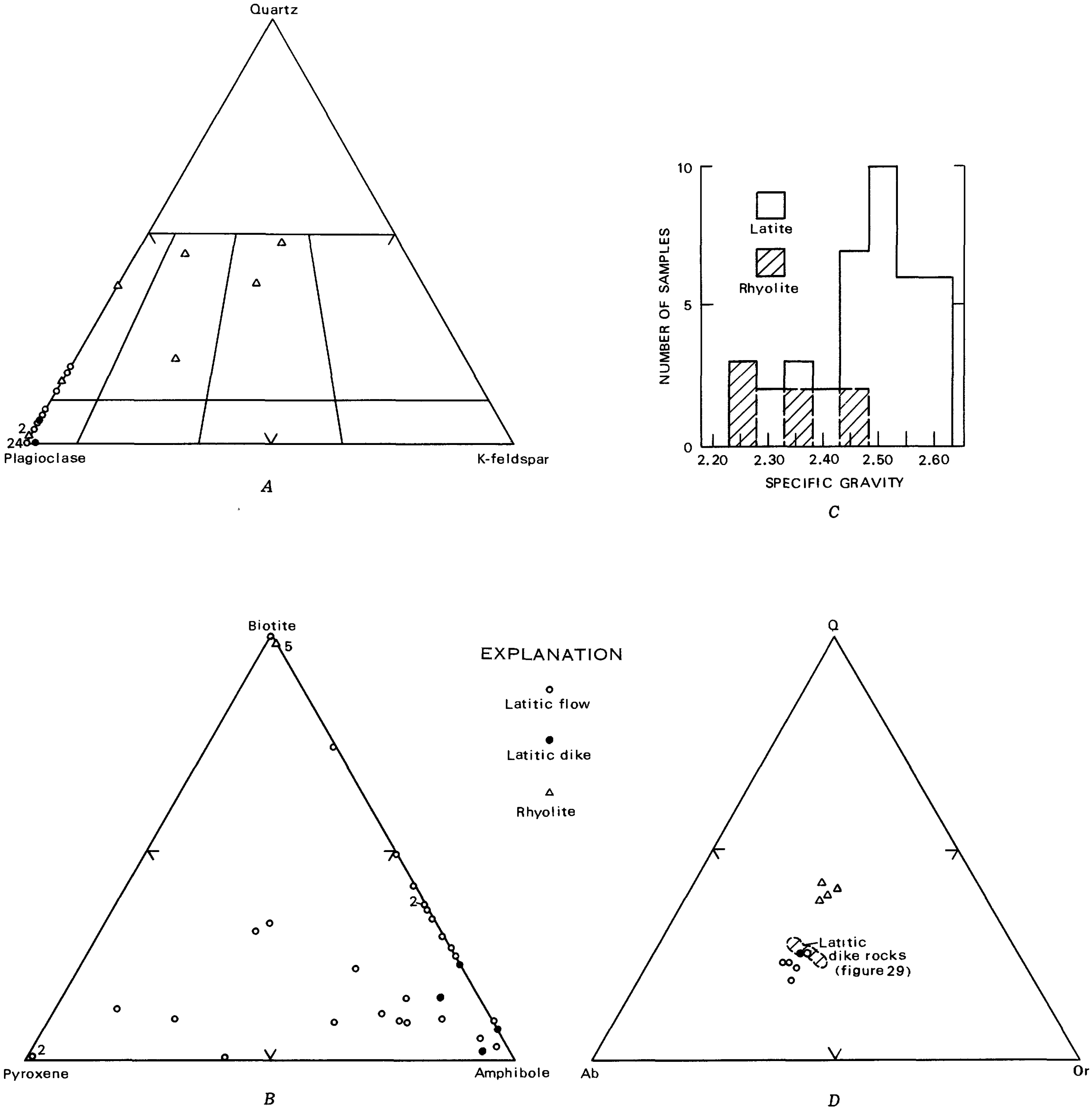


FIGURE 33.—Samples of volcanic rocks from Tickville Springs quadrangle. *A*, *B*, Modal phenocryst mineral proportions. *C*, Variations in specific gravity. *D*, Normative salic mineral proportions.

TABLE 10.—*Chemical data for latitic and rhyolitic volcanic rocks*

[Chemical analyses by rapid methods by U.S. Geological Survey Analytical Laboratories under the direction of Leonard Shapiro. Semiquantitative spectrographic analyses by Chris Heropoulos, U.S. Geological Survey. Results are expressed in parts per million to the nearest number in the series 10,000, 7,000, 5,000, 3,000, 2,000, 1,500, 1,000, etc.; these numbers represent approximate midpoints of group data on a geometric scale. The precision of a reported value is approximately plus or minus one interval about 68 percent of the time or two intervals 95 percent of the time. Spectrographic analyses columns under word "Average" report median values. Elements looked for but not found: Ag, As, Au, Bi, Cd, Eu, Hf, Hg, In, P, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn. Samples from table 9 except 68–TS–29]

	Latitic rocks								Rhyolitic rocks				
	125	136	146	147	151	155	159	Average	105	106	137	68–TS–29	Average
Chemical analyses (weight percent)													
SiO_2	60.4	63.1	59.1	60.9	61.8	61.2	62.1	61.2	74.9	73.7	74.4	72.4	73.9
Al_2O_3	16.5	16.0	16.4	16.1	16.7	16.4	16.4	16.4	13.0	12.9	14.2	14.0	13.5
Fe_2O_3	3.2	2.2	3.0	3.8	1.9	3.7	3.0	3.0	.35	.77	--	--	.28
FeO	2.2	1.8	2.7	1.2	3.2	1.8	1.8	2.1	.20	.48	.65	.60	.48
MgO	3.0	2.1	3.2	2.2	2.2	2.7	2.0	2.5	.10	.25	.07	.14	.14
CaO	5.0	4.1	5.4	4.8	4.7	4.7	4.1	4.7	1.1	1.3	.67	.79	.97
Na_2O	3.6	3.6	3.5	3.7	3.7	3.7	3.5	3.5	3.7	3.5	3.4	3.1	3.4
K_2O	2.9	3.6	3.3	3.5	3.1	3.2	3.7	3.3	4.4	4.3	4.0	4.5	4.3
H_2O	1.93	2.09	1.71	1.64	1.10	1.10	2.12	1.67	.95	2.46	2.26	4.11	2.45
TiO_2	.79	.77	.91	.77	.84	.84	.75	.81	.05	.17	.16	.12	.12
CO_2	$<.05$	$<.05$	$<.05$	.28	$<.05$	$<.05$	$<.05$	$<.05$	.14	$<.05$	$<.05$	$<.05$	$<.05$
P_2O_5	.34	.31	.44	.37	.36	.39	.39	.37	.29	.06	.06	.05	.12
MnO	.14	.12	.16	.15	.14	.13	.12	.14	.07	.04	.07	.12	.08
Total	100	100	100	99	100	100	100	99	99	100	100	100	
Spectrographic analyses (parts per million)													
B	--	10	--	--	--	--	--	--	70	20	20	15	--
Ba	2,000	2,000	3,000	2,000	2,000	3,000	3,000	2,000	200	700	3,000	2,000	--
Be	--	--	--	1	--	--	1	--	10	2	--	2	--
Ce	200	150	200	200	150	200	200	200	--	--	--	--	--
Co	20	10	20	15	15	15	10	15	3	5	--	1	--
Cr	100	30	200	30	30	30	20	30	7	2	5	10	--
Cu	30	50	70	70	50	70	30	50	30	15	30	20	--
Ga	30	20	20	30	30	30	30	30	--	--	--	--	--
La	100	100	150	150	100	150	150	150	--	--	30	30	--
Mo	5	5	5	5	3	5	5	5	--	--	3	5	--
Nb	15	10	20	20	15	15	15	15	30	15	20	20	--
Nd	70	--	100	100	100	70	100	100	--	--	--	--	--
Ni	50	20	70	20	20	30	15	20	5	5	--	--	--
Pb	30	50	30	50	50	50	70	50	150	30	70	50	--
Sc	15	7	20	10	10	15	10	10	7	--	3	--	--
Sr	1,000	1,500	1,500	1,500	1,500	1,500	1,500	1,500	30	300	300	200	--
V	150	100	150	100	100	100	70	100	7	15	--	--	--
Y	20	15	20	20	20	20	20	20	50	15	15	15	--
Yb	2	2	2	2	2	2	2	2	5	2	2	2	--
Zr	150	200	300	200	200	200	300	200	100	70	100	70	--
Norms (weight percent)													
Q	14.5	17.5	11.5	14.9	14.9	14.9	16.9	15.0	35.4	33.9	37.5	34.9	35.4
or	17.1	21.3	19.5	20.8	18.4	18.9	21.9	19.7	26.2	25.4	23.7	2[illegible].6	25.5
ab	30.5	30.5	29.7	31.5	31.4	31.4	29.6	30.7	31.5	29.6	28.8	2[illegible].3	29.0
an	20.3	16.9	19.3	17.1	19.9	18.7	17.8	18.6	2.7	6.1	2.9	3.6	3.8
wo	1.0	.6	1.9	1.1	.5	.9	--	.9	--	--	--	--	--
en	7.5	5.2	8.0	5.5	5.5	6.7	5.0	6.2	.3	.6	.2	.3	.4
fs	.4	.4	1.3	--	3.2	--	--	.8	.1	.1	1.1	1.1	.6
mt	4.6	3.2	4.4	2.1	2.8	3.8	4.0	3.6	.5	1.1	--	--	.4
hm	--	--	--	2.3	--	1.1	.2	.5	--	--	--	--	--
il	1.5	1.5	1.7	1.5	1.6	1.6	1.4	1.5	.1	.3	.3	.2	.2
ap	.8	.7	1.0	.9	.9	.9	.9	.9	.7	.1	.1	.1	.2
cc	--	--	--	.6	--	--	--	.1	.3	--	--	--	--
C	--	--	--	--	--	--	.1	--	1.2	.3	3.2	2.7	1.9

tive framework for the igneous rocks at Bingham. The data for these diagrams are taken from tables 2, 6, 8, and 10.

A conventional means of describing the "degree of alkalinity" of a given rock suite is the alkali-lime index of Peacock (1931). The Peacock index is defined as the silica content in weight percentage for which total alkalis equal CaO. Figure 35 shows that the Bingham suite has alkali-calcic affinities. Silica contents for all rocks but the rhyolites range between narrow limits of 57–65 weight percent, and some extrapolation is required to establish the point of intersection; so, these rocks are perhaps best described as "chemically intermediate," without attempting further qualification.

Chemical characteristics of the Bingham igneous rocks are conveniently summarized by means of the variation diagram shown in figure 36, in which weight percentages of the major oxides are plotted against the sum of normative quartz plus orthoclase plus albite—the differentiation index of Thornton and Tuttle (1960). This index was chosen as a coordinate for plotting in preference to silica percentages in order to expand the trend lines graphically as well as to position the various rock types in the salic femic series. Normal negative correlations are noted for alumina and the femic oxides. The alkalis show little variation but with increasing differentiation index actually increase with silica in terms of molecular proportions.

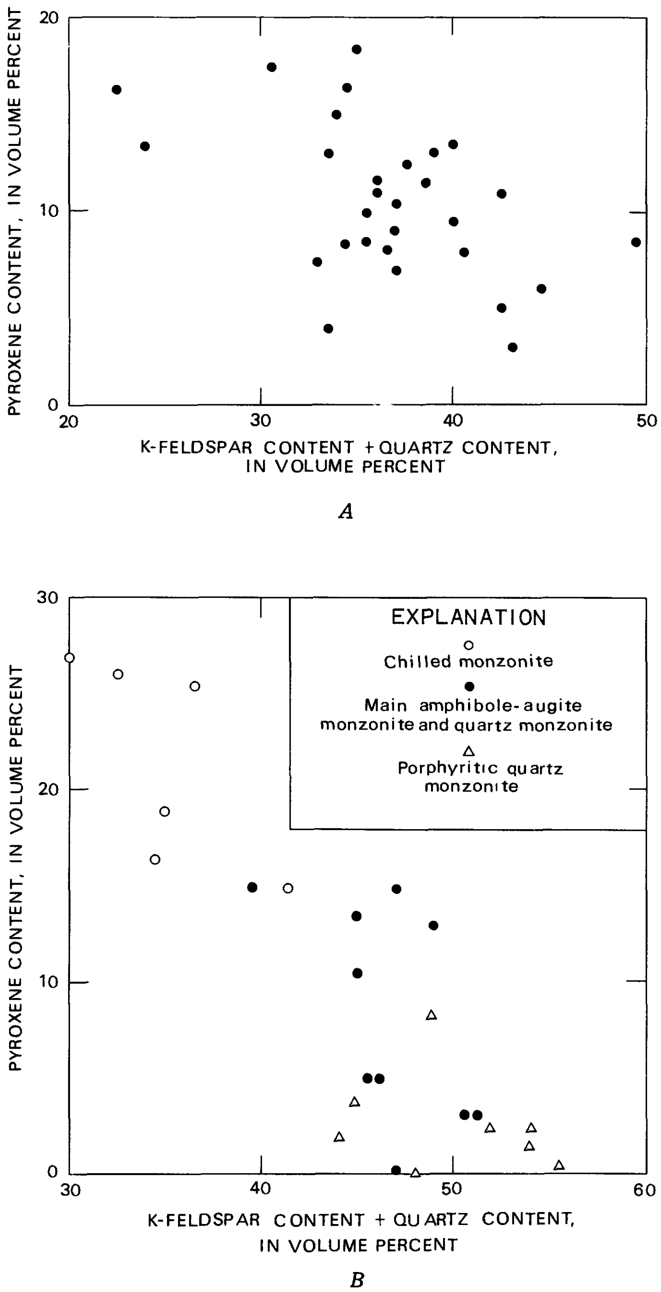


FIGURE 34.—Variations between selected modal minerals. *A*, Last Chance stock; *B*, Bingham stock.

A word of caution is in order regarding the interpretation of variation diagrams of any sort. Because the sum of oxide constituents in a rock analysis is constant, large increases in one oxide require at least a proportionate decrease in the sum of the remaining oxides. This "closure effect" is discussed qualitatively by Krauskopf (1967, p. 398–399), and a simple data transformation designed to reduce such spurious correlation is presented by Chayes (1967). Variation diagrams may be used as in figure 36 to demonstrate that members of a given suite of rocks are chemically related, but a more rigorous statistical treatment is required if finer distinctions are sought.

A final point concerns the shift in proportions of salic minerals for the various igneous rock types in the Bingham area, illustrated in the normative quartz-orthoclase-albite triangular diagram of figure 37*A*. Composition fields for the latitic volcanic rocks and dikes show slight to moderate enrichment in normative quartz compared with the Last Chance and Bingham monzonites; predictably, the rhyolites are even more siliceous. This trend is not apparent from a comparison of modal mineral proportions (fig. 37*B*) and must result from increasing quartz contents in the modally indeterminate groundmass fraction of the porphyritic-aphanitic rocks.

RADIOMETRIC AGES OF IGNEOUS ROCKS IN THE BINGHAM AREA

It was noted in the "Introduction" that igneous rocks in the Bingham area are middle Tertiary in age. This general age assignment was first suggested by Boutwell (1905). Subsequently Gilluly (1932) concluded, through a succession of analogies with structural and stratigraphic features in other areas in eastern Utah, that the age of volcanism at Bingham was late Eocene or Oligocene. Results of two recent studies (Moore and others, 1968; Moore and Lanphere, 1971), which will be reviewed here, confirm the middle Tertiary age of magmatism at Bingham and indicate, furthermore, that compositions of the major intrusive rock types are apparently a function of age.

Magmatism at Bingham spanned a period of about 8 m.y. (million years) from latest Eocene to middle Oligocene time (table 11). Radiometric ages suggest that the Last Chance stock is the oldest intrusion and was followed, in sequence, by the granitoid and porphyritic phases of the Bingham stock, latitic dikes, and the Shaggy Peak rhyolite plug. Statistical methods may be used to show that mean ages of the intrusive rock units differ significantly at the 95-percent confidence level (M. L. Silberman, oral commun., 1971), but only in the case of the latitic dikes compared with the Last Chance and Bingham stocks are field relations adequate to confirm the radiometric age sequence. It should be noted that the age sequence generally parallels the trend in rock compositions discussed in the previous section: the intrusive rocks become increasingly

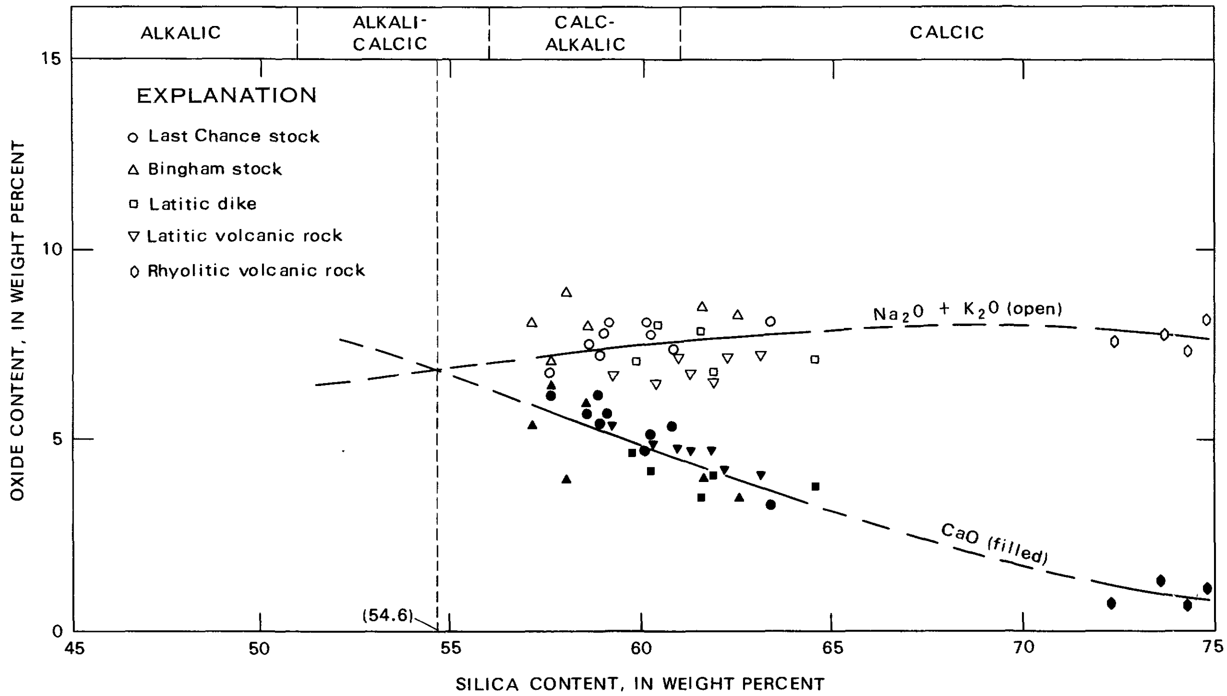


FIGURE 35.—Weight percentage of combined alkalis (K_2O+Na_2O) and CaO plotted against weight percentage of SiO_2 for samples of igneous rocks in the Bingham area.

TABLE 11.—*Potassium-argon radiometric ages for biotites from igneous rocks in the Bingham area*

[Adapted from table 3 of Moore and others, 1968]

Rock units and number of samples	*Mean age, millions of years*
Intrusive rocks:	
Last Chance stock (3)	38.6
Southeast margin of Bingham stock (3)	37.6
Latitic dikes from Utah metals and Bingham haulage tunnels (2)	37.3
Shaggy Peak rhyolite plug, Tickville Springs quadrangle (2)	33.0
Volcanic rocks:	
Rhyolite vitrophyre, Tickville Springs quadrangle (1)	31.2
Latite tuff-breccia of South Mountain, Tickville Springs quandrangle (1)	30.7

silicic or potassic or both with decreasing apparent age. (See Moore and others, 1968, fig. 3.)

Another aspect of the magmatic history at Bingham, and one of indirect economic significance, is the age of plutonism relative to volcanism. A sequential reconstruction suggests that flows near the base of the volcanic sequence may be about as old as the monzonitic stocks. Previously unpublished dates for the two youngest units in the volcanic sequence (table 11) indicate that volcanism continued after emplacement of the major intrusive bodies, but the dates only provide a lower age limit of about 31 m.y. for the main latitic flow series. Similarly, the 33-m.y. date for the Shaggy Peak plug provides a minimum age for the latitic flows that the rhyolite plug intrudes. An even older age is indicated for the latitic flows and agglomerates at the portal of the Bingham haulage tunnel that are intruded by a quartz latite porphyry dike dated at 36.9 m.y. (Moore and others, 1968). This result is consistent with the 38.8-m.y. age reported by Armstrong (1970) for an extrusive "biotite-hornblende andesite porphyry" sampled at the surface about one-half mile west of the portal.

Radiometric ages, and field relations in general, suggest that plutonism and volcanism at Bingham were broadly contemporaneous phases of a single magmatic episode. As Gilluly (1969) noted, "there must have been a monzonitic magma active at depth to furnish the latitic lavas that were being erupted to the surface. This magma may well have acted very differently at points only a few miles apart." Periodic and local venting of the shallow intrusive bodies apparently fed the latitic flows; conversely, hypabyssal dikes were intruded into earlier eruptive rocks at various times during the magmatic episode. Both processes are commonly associated

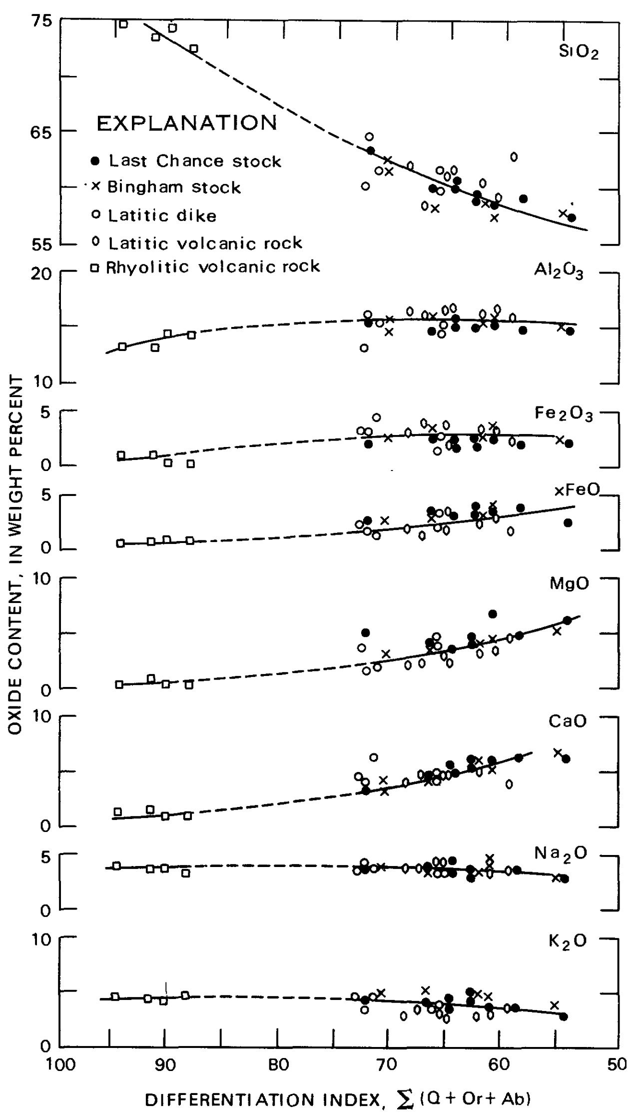


FIGURE 36.—Weight percentage of common oxides plotted against differentiation index of Thornton and Tuttle (1960). Index is defined as sum of normative quartz plus orthoclase plus albite.

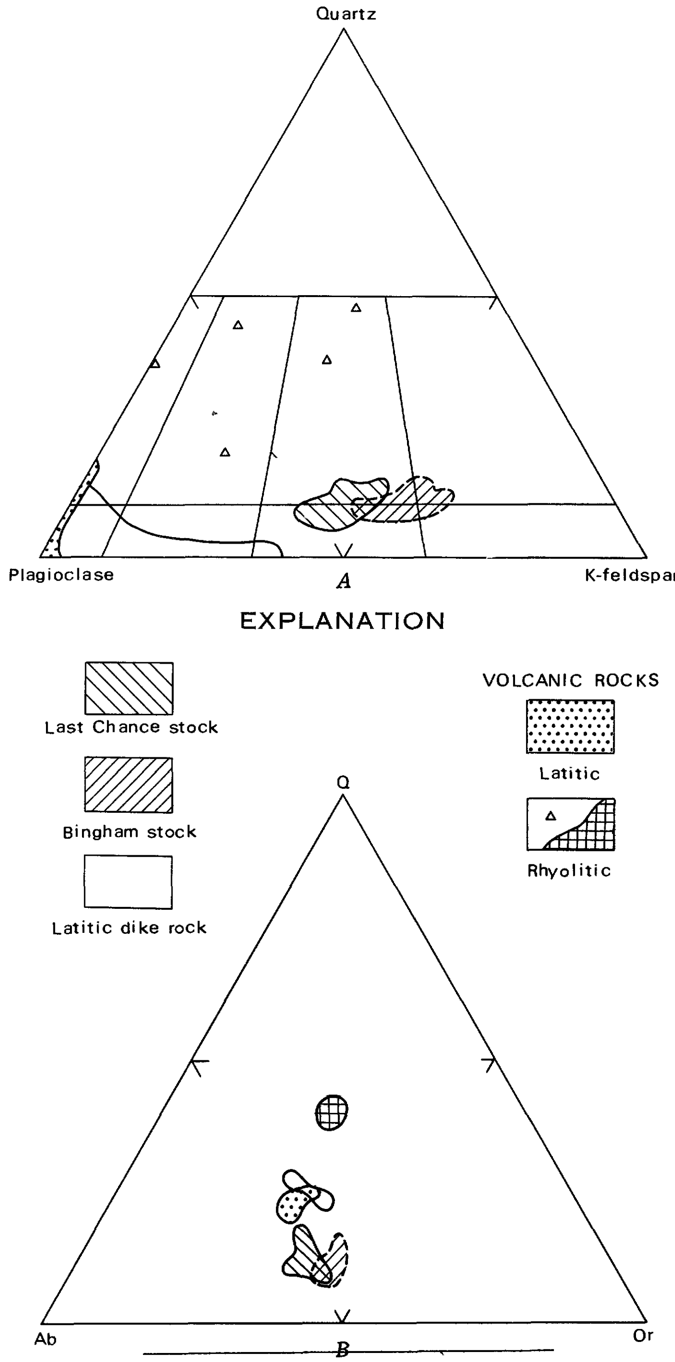


FIGURE 37.—Samples of igneous rocks in the Bingham area. *A*, Modal felsic mineral proportions. *B*, Normative salic mineral proportions.

with epizonal igneous complexes of the Bingham type.

Two other middle Tertiary magmatic centers with related base-metal mineralization are recognized in north-central Utah. Laughlin, Lovering, and Mauger (1969) showed that volcanic and plutonic rocks in the Tintic area, about 50 miles due south of Bingham, are of Oligocene and Miocene age. Igneous rocks from the Park City–Little Cottonwood mining area of the Wasatch Mountains, about 25 miles east of Bingham, are Oligocene in age (Crittenden and Kistler, 1966; Armstrong, 1970). Thus middle Tertiary epizonal magmatism is a feature of regional significance in the easternmost Basin and Range province of Utah and must be considered fully in models of crustal evolution for the Western United States. (See Armstrong and others, 1969; Armstrong, 1970.)

HISTORY OF EMPLACEMENT AND CRYSTALLIZATION

In an important review paper, Buddington (1959) classified the level of emplacement of granitic plutons in the crust in terms of a series of temperature-depth or "intensity" zones. The scheme is broadly analogous to and draws upon many of the same lines of evidence as Lindgren's (1933) temperature-depth classification of ore deposits. Buddington presumed that most Tertiary plutons now exposed were emplaced in the "epizone" of the earth's crust (a depth generally less than 4 miles), because the subsequent time has been too short to permit deep erosion.

Accordingly, Buddington described characteristics of Tertiary intrusions useful as criteria for recognizing epizonal plutons of older ages. It would be an exercise in circular reasoning to use these characteristics as supporting evidence in assigning the Bingham igneous complex to the epizone, but they can be used to summarize major structural and compositional features. Thus, the typical epizonal Tertiary pluton, as represented in this report by the Bingham stock (1) is largely or wholly discordant to the country rock, with part of the wall controlled by preintrusive faults (see Peters and others, 1966), (2) is of composite character with earlier members showing chill zones against the country rock, (3) lacks distinct lineation or foliation, even locally in the border facies, (4) is closely related to volcanic rocks, in large part, of comparable composition, (5) is emplaced in country rock that is unmetamorphosed outside the contact metamorphic zone, and (6) is cut by a set of late-stage porphyritic-aphanitic dikes.

These features of epizonal magmatism provide the framework for a reconstruction of the igneous history at Bingham. In this section, inferences concerning the physical environment during the magmatic episode will be drawn both from descriptive material discussed previously and from pertinent experimental studies.

As a first approximation to the depth of cover at the time of monzonitic plutonism, Gilluly (1946) suggested a figure of between 3,000 and 10,000 feet for the Bingham stock, as well as for texturally similar stocks at Tintic and San Francisco, Utah. In the Tintic and San Francisco district, the monzonitic plutons are clearly intrusive into the bases of their own volcanic piles, but at Bingham this relationship cannot be established directly. (See Gilluly, 1932.) A comparable upper limit (7,500± 1,000 feet), however, is obtained by reconstructing the Pennsylvanian and Permian stratigraphic section in the upper plate of the Midas thrust fault above the youngest units intruded by the Last Chance and Bingham stocks (Tooker and Roberts, 1970; E. W. Tooker, oral commun., 1971). This figure must be regarded as a maximum depth of cover because the extent of preemplacement erosion and topographic dissection following thrust movement is not known.

Estimates of load pressures based on a depth of cover of 7,500 feet range from about 250 bars under hydrostatic conditions to 650 bars under lithostatic conditions, assuming an average rock density of 2.6 grams per cubic centimeter. These limiting load pressures may be valid only for the earliest stages of plutonism. If forces exerted by the advancing magma were sufficient to produce doming or upward displacement of fault-bounded blocks of roof rock, accelerated erosion may have rapidly removed the sedimentary cover.

The foregoing estimates may be compared for consistency with calculated water pressures (here equated with total pressures) necessary to stabilize biotites of differing composition in two phases of the Bingham intrusive complex. (See Moore, 1970a.) The general approach and equations used were developed by Wones and Eugster (1965) from results of experiments showing that f_{H_2O} $-T$ conditions at specified f_{O_2} may be calculated for a biotite of known composition coexisting with K-feldspar and magnetite. The methods of calculation are illustrated in recent reports by Dodge, Smith, and Mays (1969) and Putman and Alfors (1969).

The Last Chance stock, an early monzonitic intrusive phase, contains coexisting biotite ($KFe_3AlSi_3O_{10}[OH]_2 \cong 32$ atom percent), K-feldspar ($Or_{bulk} \cong 74$ mole percent), and magnetite (assumed to be the pure end member). With minimum water pressures and temperatures limited by the solidus curve for a water-saturated melt of intermediate composition, water pressures necessary for crystallization of the biotite range from about 200 bars at 900°C to 1,600 bars at 750°C. The higher value, although plausible in terms of Wones and Eugster's experimental studies, is appreciably greater than the lithostatic load pressure of 650 bars calculated from depth-of-cover considerations. In fact, there is no structural evidence to suggest a fluid overpressure during the crystallization of the Last Chance stock; so, P_{load} probably exceeded P_{fluid} early in the magmatic episode.

These conditions may be contrasted with those during the terminal stages of intrusive activity by considering the field relations and lithology of latitic dikes that cut the Last Chance and Bingham stocks.

As noted previously, minor pebble dikes and an intrusive breccia are closely associated with the latitic intrusives in the Utah Metals tunnel, and some of the dikes show a zonal distribution of deuteric alteration minerals. These features suggest that the latitic melts became fluid saturated during crystallization and that fluid overpressures were released with explosive force at a later stage in the cooling history. A minimum P_{H_2O} of about 1,500 bars at 750°C was calculated for the stable coexistence of an unusual phlogopite-actinolite assemblage in one of the dike rocks (Moore, 1970b). Again, the calculated P_{H_2O} exceeds the estimated initial lithostatic load pressure, but in this instance the results may be interpreted consistently with structural evidence for explosive venting.

Additional evidence for separation of a fluid phase in the later stages of intrusive activity was presented recently by Wilson (1969), who described a small plug composed of "vesicular porphyritic quartz monzonite" that he believed "represents a highly fluid, low viscosity crystal mush that intruded much cooler, previously mineralized granite." According to Wilson, the fluid, which "separated from the silicate portion of the magma" to form the vesicles, contained 15 percent by volume of chalcopyrite, quartz, and apatite.

Although the plug was not studied in the Utah Copper pit, two hand samples were kindly provided by R. L. Nielsen of the Kennecott Copper Corporation. In thin section the rock appears to be typical quartz latite porphyry—the youngest intrusive phase of the composite Bingham stock. Sericitized plagioclase, resorbed quartz phenocrysts as much as 2 cm long, and pseudomorphic aggregates of magnesium-rich biotite are set in a felted quartz-orthoclase groundmass. The rock contains numerous small (2–5 mm) cavities that are variably rounded and a few that are elongate, as much as 2 cm long and somewhat angular; the cavities are coated with tiny terminated quartz crystals or quartz encrusted with chalcopyrite.

As Wilson suggested, the cavities (or miaroles) may indeed represent vapor bubbles that separated during crystallization of the plug. This example, unique in the writer's experience at Bingham, is compelling evidence for late-stage separation of magmatic fluids. Furthermore, the preservation of a miarolitic texture in the plug suggests that confining pressures were at least temporarily greater than pressures generated by separation of the fluids.

The enrichment of hydrous fluids in the younger intrusive phases at Bingham is inferred to be a further consequence of the differentiation processes that led to increasingly silicic and potassic bulk compositions. However, the concentration of volatiles, as opposed to the progressive changes in bulk composition, was probably not a unidirectional trend; that is, the magma system may have reached saturation with respect to dissolved volatiles more than once during the crystallization history. The latest period of fluid saturation occurred at the time of latite dike emplacement. An earlier release of volatiles may have accompanied the crystallization of the main porphyritic host rock.

The porphyritic phase of the Bingham stock is characterized by centimeter-size pink orthoclase and sericitized plagioclase phenocrysts together with aggregates of finely crystalline magnesian biotite set in a microgranular or aplitic orthoclase-quartz groundmass; the average grain size of the groundmass is about 0.1 mm. The distinctive drop-like groundmass texture may have resulted from a sudden release of fluids during or after emplacement. This "pressure quench" mechanism, proposed originally by Jahns and Tuttle (1963), was invoked recently by Fournier (1967) and Nielsen (1968) to account for similar textures in the ore porphyries at Ely, Nev., and Santa Rita, N. Mex. The sudden release of fluids may also account for the intimate shattering of the porphyry and older intrusive host rocks in the copper ore body.

Field observations additionally suggest that the Bingham stock was "wetter" than the Last Chance stock at the time of emplacement. It will be recalled that the Last Chance contact metamorphic aureole consists largely of wollastonite-quartz-diopside hornfels resulting primarily from isochemical recrystallization of calcareous sedimentary rocks. The same rocks in the Bingham contact aureole, on the other hand, are replaced by irregular bodies of massive red grossularite with specularite and tremolite; quartzites adjacent to the stock are variably replaced by K-feldspar. These rocks are products of metasomatic reactions, and presumably, aqueous fluids derived from a water-saturated magma transferred magnesium, iron, aluminum, and potassium into the contact zone.

In considering the mode of emplacement for igneous rocks associated with porphyry copper deposits, Stringham (1966) noted the predominance of "passive" intrusive bodies, that is discordant intrusives that have not disturbed the pre-emplacement attitudes of the surrounding rocks. This term appropriately describes the structural character of the Last Chance and Bingham stocks. Only in the case of the younger latitic dikes do field relations suggest forcible intrusion.

Lowell and Guilbert (1970) concurred with Stringham, suggesting that "replacement, stoping, and assimilation were more important processes than * * * forceful intrusion" in the emplacement of porphyry copper stocks and that "both lateral and vertical petrologic zoning might be more common than has been recognized." They recognized that extensive stoping and assimilation are inconsistent with the rapid loss of heat associated with "extremely shallow" emplacement but suggested that "moderately shallow environments may be indicated." A test of these suggestions in the Bingham district is provided by structural and petrographic features of the Last Chance stock that, although not the locus of disseminated copper mineralization, shared an epizonal intrusive environment similar to that of the Bingham stock.

At the present level of exposure the Last Chance stock contains few large sedimentary blocks; those that do occur are found near the margins of the stock on upper levels of the U.S. mine (less than 1,500 ft below the surface). Local contact brecciation and stoping has occurred on a small scale (figs. 4, 5), but generally, contacts between intrusive rocks and wallrocks are sharply discordant, with no evidence for intrusive deformation.

The paucity of large xenoliths would not rule out the possibility of a forcible process of emplacement for the Last Chance stock if, for example, it could be shown that the engulfed blocks had settled and had been subsequently destroyed by assimilation. Partly digested blocks occur locally near the borders of the stock, and in these areas the enclosing monzonite has been contaminated, as noted earlier. However, no isolated volumes of contaminated monzonite, that is relict indications of completely reacted xenoliths, have been found within the main mass of the stock. Moreover, variations in chemical composition are small over the 2,400-foot vertical section accessible in the U.S. mine (table 2). In short, no positive evidence is available to suggest that reactive assimilation played an important role in the later stages of emplacement of the Last Chance stock. Block stoping and assimilation may have been relatively more important at greater depths in the magma chamber, where both viscosities and rates of heat loss were lower.

If the importance of shouldering aside and assimilating wallrocks during intrusion is discounted, at least at the present level of exposure, another explanation must be sought. One such possibility would be the vertical displacement and concomitant erosion of fault-bounded blocks of roof rock during emplacement of the intrusive complex. A similar hypothesis was proposed recently by Tabor and Crowder (1969) for the Cloudy Pass batholith in Washington. Although basically a forcible process, lifting the roof would require minimal deformation or stoping of the intruded rock and would be facilitated by a relatively thin cover. In support of this suggestion, Tooker (1971) presented structural evidence indicating that initial movement on high-angle northeast-trending faults in the district occurred prior to the period of magmatism. Also, Peters, James, and Field (1966) noted that "the detailed outlines of the Bingham and Last Chance stocks are clearly related to fold and fault structures in the Oquirrh Mountains." The specific controlling structures, however, have apparently been obliterated by subsequent erosion and unroofing of the stocks. Earlier faulting may have established zones of weakness that controlled subsequent emplacement of the intrusions. A serious objection to the vertical displacement model is raised by the total absence of megascopically foliated platy minerals in both stocks. Absence of internal structures may indicate that the uppermost parts of the magma columns had nearly crystallized before reaching levels presently exposed by erosion.

Speculations regarding the history of emplacement and crystallization of the Bingham igneous complex are summarized as follows:

1. The magmatic episodes commenced with emplacement of the Last Chance augite-biotite monzonite stock about 38 m.y. ago. Vertical displacement of previously faulted Pennsylvanian and Permian roof rocks with an aggregate thickness of probably less than 7,500 feet made room for the stock. Lithostatic load pressures (650 bars maximum) were not exceeded by fluid pressures generated during crystallization of the stock.
2. The granitoid and porphyritic phases of the Bingham stock were emplaced in close succession about 1 m.y. after crystallization of the Last Chance stock. Rocks from margins of the younger stock are also monzonitic and, in part, are unaltered equivalents of host rocks in the disseminated copper ore body. Systematic increases in the proportions of K-feldspar to plagioclase and hornblende to clinopyroxene are attributed to progressive differentiation of a single source magma.
3. Subsequent tapping of the magma reservoir led to the forcible emplacement of a series of more siliceous latite dikes that cut both stocks. Sud-

den release of hydrous fluids during crystallization resulted in contact brecciation and the formation of related pebble dikes. Venting of the latitic dikes through roof rocks thinned by uplift and erosion may have supplied fragmental debris to laharic breccias near the base of the volcanic series.

4. Latitic volcanism continued after release of fluids with the accumulation of at least 800 feet of lenticular flows overlying the breccias. Petrographic and chemical similarities suggest a common source for the latitic dikes and volcanic rocks.

5. Intrusive activity in the Bingham area terminated about 31 m.y. ago, following base-metal mineralization in the district (Moore and Lanphere, 1971). The last stage of activity consisted of local emplacement of rhyolite vitrophyre plugs into the older volcanic rocks. The genetic relationship between the latites and rhyolites is tenuous at best, but in view of their close age relations (table 11), a comagmatic origin is probable.

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