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General Geology of the Bingham Mine, Bingham Canyon, Utah

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Abstract

This report describes the general geology of the Bingham mine and presents a 1 : 9,600 scale detailed mine geology map. Important new contributions shown on this map include (1) a prealteration monzonitic classification of igneous rock, (2) the Ohio Copper dike in Copper Notch, (3) the Alice W. dike extending into the porphyry phases in Carr Fork, (4) reinterpretation of gradational granite porphyry as a zone of hybridization around quartz monzonite porphyry, surrounded by a zone of recrystallization, (5) more detailed mapping of small calcareous sandstone and limestone beds, and (6) the delineation of subsidiary folds related to the Bingham syncline.

Six major igneous phases of the Bingham stock intrude folded sedimentary rocks of the Butterfield Peaks and Bingham Mine formations. The folding, along with left-lateral, northeast tear faults, accompanied thrusting. Early equigranular phases are quartz poor compared to the later porphyry phases; both are intermediate in composition. Stocks are emplaced mainly into the Apex fold which is interpreted as a second-order fold on the southwest limb of the Bingham syncline. Hydrothermal alteration and mineralization is genetically related to the quartz monzonite porphyry, the major porphyry phase, based on zone patterns around the top of the intrusion. Later, normal, northwest faulting cut the intrusions and is related to Basin and Range tectonics.

Introduction

The Bingham porphyry deposit, an important source of copper, molybdenum, gold, silver, and other by-products, is located in the central Oquirrh Mountains, 32 km southwest of Salt Lake City, Utah. The geology of the orebody has received much attention, both economic and academic, over the past 70 years. The primary purpose of this paper is to present the general geologic setting of Bingham based on current knowledge and interpretation. Swensen provided the section on sedimentary rocks in this paper; Lanier and Reid wrote the section on intrusive rocks; John and Lanier wrote the section on structure; Lanier, Caddey, Reid, and Bard contributed to the section on alteration and mineralization.

Figure 1 is the first detailed map of Bingham to be published. It covers an area slightly larger than the open-pit mine, approximately 900 hectares, with vertical relief of 850 m. Most of the geology in Figure 1 is the result of surface mapping in the mine from 1971 to 1975; and other sources used in the compilation are acknowledged on the index map. An earlier version of this map at a scale of 1 : 4,800 and a district geologic map covering 26,000 hectares at a scale of 1 : 24,000 are presented in Bray and Wilson (1975, plates 1 and 2).

Figure 1 is different from previous unpublished geologic maps of the mine prepared in 1962 and 1969, and from published geologic maps by Keith and Boutwell (1904, 1918), Stringham (1953), Bray (1967), and Moore (1973a). The chief differences include: (1) the equigranular phases of the Bingham and Last Chance stocks interpreted as a single intrusion which has undergone hydrothermal alteration in the Bingham stock, (2) several latite porphyry dikes in Carr Fork and the Ohio Copper dike distinguished for the first time, (3) the hybrid quartz monzonite porphyry and recrystallized monzonite representing a reinterpretation of the "gradational granite porphyry" of Bray (1967, 1969), and (4) the geometry of folding on the southwest limb of the Bingham syncline shown in greater detail.

The mine mapping procedure is based on photogrammetric methods (McCarter, 1976) in which geologic contacts are plotted in the field on large-scale horizontal terrestrial photographs of the pit wall and later transferred to a topographic base map at a scale of 1 : 2,400. The topography shown in Figure 1 is compiled from mine maps prepared during several mapping seasons. Original topography lying beneath the mine dumps is used for the base map outside the open pit.

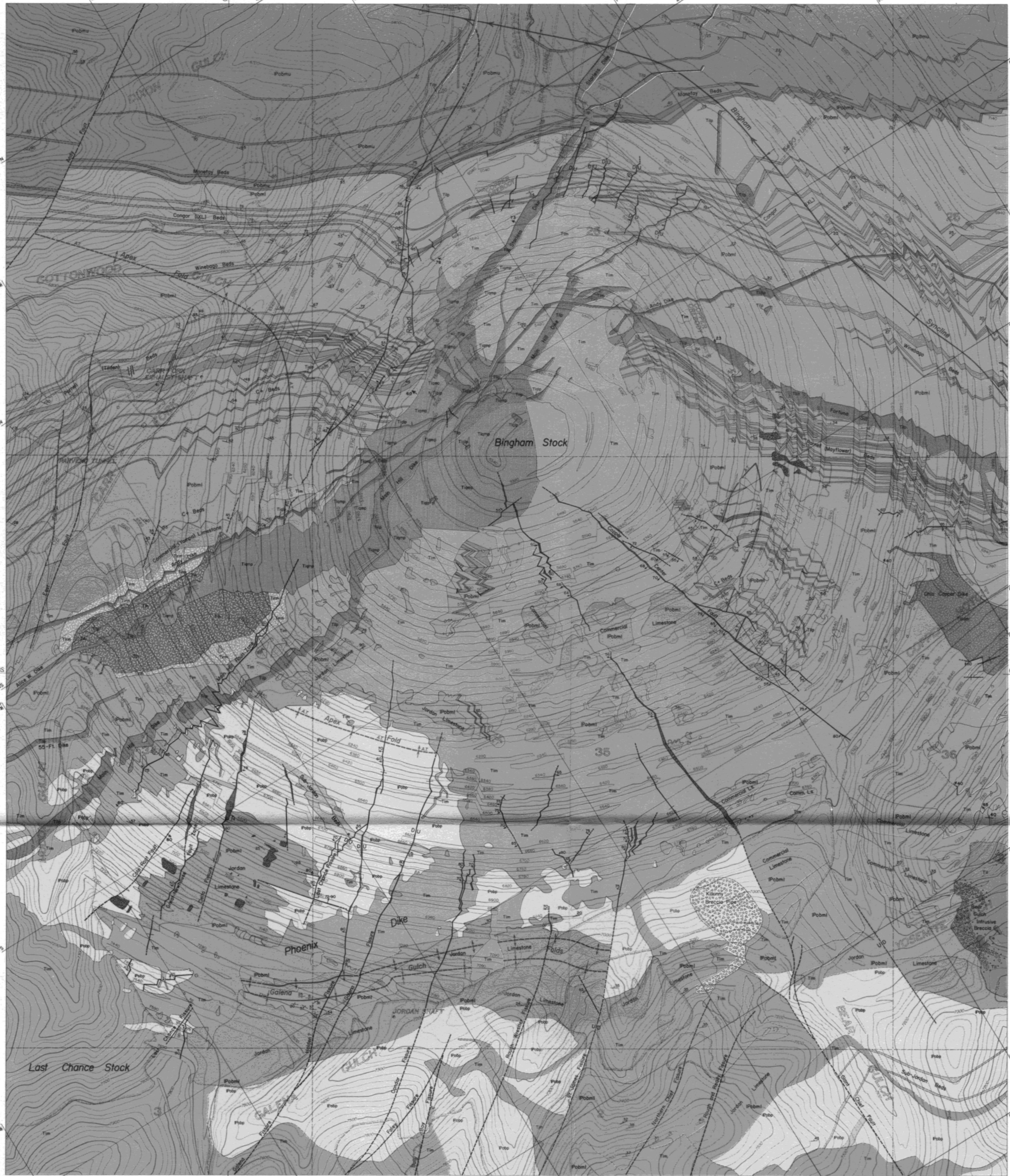
Sedimentary Rocks

Sedimentary rocks exposed within the immediate mine area include parts of the Butterfield Peaks Formation and the overlying Bingham Mine Formation of the Oquirrh Group, Pennsylvanian System. The descriptions of the lithologic units in the following discussion are based on unaltered rock.

Fig. 1

GEOLOGIC MAP OF THE BINGHAM MINE

Bingham Canyon
Utah



Igneous Rocks

TERTIARY
Eocene

Quartz Latite Porphyry (Tiqlp)

Andy dike and related small apophyses. Medium gray and light green. Hornblende-biotite quartz latite porphyry. Hornblende altered to phlogopite and chlorite. Late stage mineralization contains chalcopyrite and pyrite. Distinguished from other latite dikes by the presence of abundant quartz phenocrysts and higher percent groundmass which contains abundant mafics.

Latite Porphyry (Tilp)

Fortuna Sill, Main Hill, Starless, 55-Foot, and Alice W. dikes and related apophyses. Light to medium gray. Hornblende-augite-biotite quartz latite porphyry. Ferromags altered to phlogopite and chlorite in pit area. Plagioclase altered to clay and sericite. Contains ore grade mineralization of chalcopyrite and bornite with associated pyrite.

Recrystallized Monzonite (Tirm)

Recrystallized monzonite aureole around hybrid quartz monzonite porphyry. Distinguished from monzonite by much coarser grain size.

Hybrid Quartz Monzonite Porphyry (Tih)

Assimilated monzonite at top of quartz monzonite porphyry. Medium gray. Amphibole-biotite quartz monzonite porphyry. Amphibole altered to biotite, plagioclase altered to clay and sericite. Contains ore grade mineralization of chalcopyrite with associated pyrite.

Quartz Monzonite Porphyry (Tiqmp)

Bingham stock. Light gray. Amphibole-biotite quartz monzonite porphyry. Amphibole altered to phlogopite and quartz, plagioclase to sericite and clay. Contains pyrite, chalcopyrite, bornite, and molybdenite. There are no unaltered exposures. Center of hydrothermal alteration.

Syenodiorite (Tis)

Small dikes intruding Bear Gulch intrusive. Medium gray. Amphibole-biotite syenodiorite. Plagioclase and amphibole altered to clay. Abundant disseminated pyrite.

Latite (Til)

Bear Gulch intrusive "breccia". Buff to light gray. Amphibole-biotite quartz latite porphyry. Contains subrounded to angular quartzite and intrusive fragments generally located near contacts. Amphibole, biotite, and plagioclase locally altered mainly to clay. Disseminated pyrite common. Age uncertain within intrusive sequence.

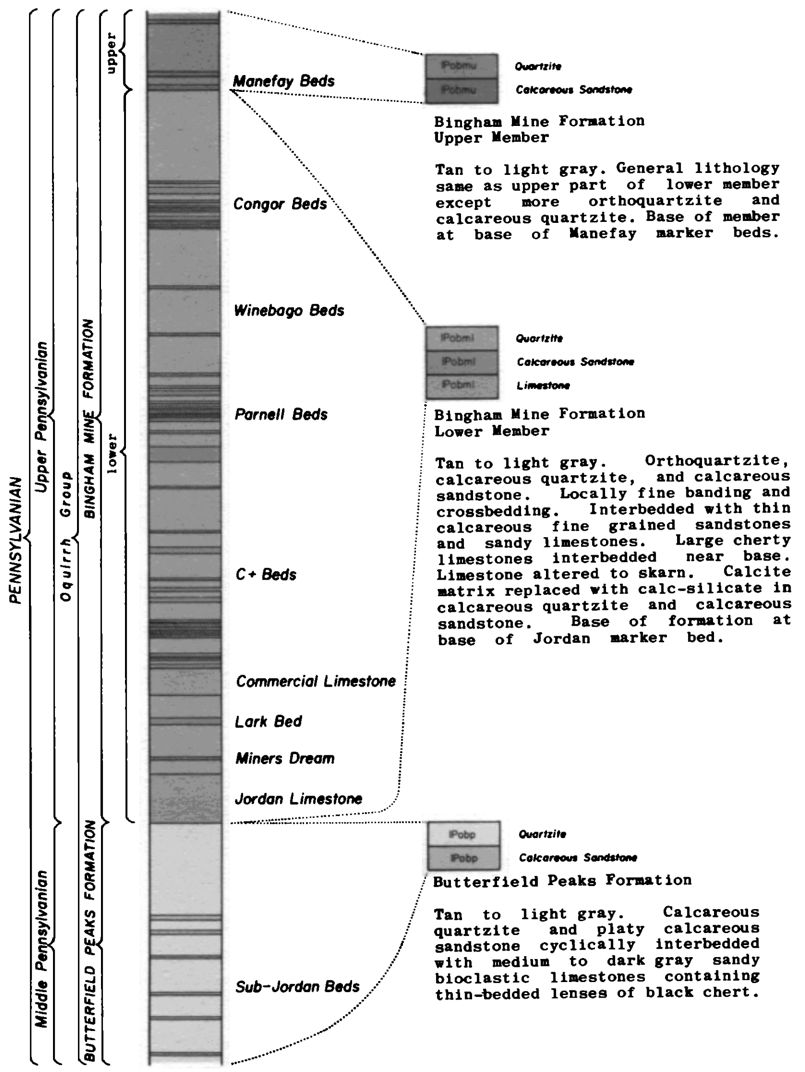
Porphyritic Quartz Monzonite (Tipqm)

Ohio Copper dike. Medium gray to greenish gray. Porphyritic amphibole-biotite quartz monzonite. Pale pink orthoclase and white plagioclase phenocrysts in a phaneritic granitoid groundmass. Disseminated primary magnetite. Pyrite occurs in veins. Late distinct phase of monzonite.

Monzonite (Tim)

Bingham and Last Chance stocks. Medium to dark gray. Augite-actinolite-biotite monzonite. Augite replaced with actinolite, chlorite, phlogopite, and quartz. Plagioclase replaced with orthoclase. Magnetite replaced with pyrite, chalcopyrite, and bornite. Molybdenite occurs in veins. Main sulfide host.

Sedimentary Rocks



Bingham Mine Formation Upper Member

Tan to light gray. General lithology same as upper part of lower member except more orthoquartzite and calcareous quartzite. Base of member at base of Manefay marker beds.

Bingham Mine Formation Lower Member

Tan to light gray. Orthoquartzite, calcareous quartzite, and calcareous sandstone. Locally fine banding and crossbedding. Interbedded with thin calcareous fine grained sandstones and sandy limestones. Large cherty limestones interbedded near base. Limestone altered to skarn. Calcite matrix replaced with calc-silicate in calcareous quartzite and calcareous sandstone. Base of formation at base of Jordan marker bed.

Butterfield Peaks Formation

Tan to light gray. Calcareous quartzite and platy calcareous sandstone cyclically interbedded with medium to dark gray sandy bioclastic limestones containing thin-bedded lenses of black chert.

Symbols

Portal of adit

Shaft

Mine contours (5940, TOE, CREST)

Dump fill

Stope fill

Contact, showing dip

Fault, showing dip and relative movement

Gouge or breccia zone

Kilkinny breccia pipe

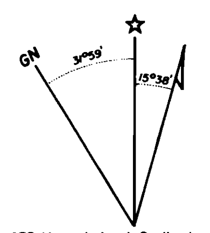
Strike and dip of beds: inclined, overturned, vertical

Syncline, showing trace of axial plane and direction of plunge; dashed where approximately located (Bingham & Galena Gulch synclines)

Anticline, showing trace of axial plane; dashed where approximately located (Galena Gulch anticline)

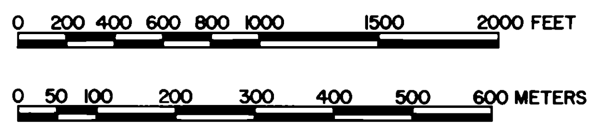
Axial trace of roll folds (Keith, 1905); dashed where approximately located (Apex & Rood folds)

Copper orebody outline



1975 Magnetic North Declination

SCALE 1:9600



Mine level intervals 40 & 50 feet

Contour interval outside open pit mine 25 feet

Mine topography from Utah Copper Division Pits and Levels maps 1970 to 1975

Pre-dump topography surveyed 1899-1900

Peripheral topography plotted 1954

US Land Office Township & Range section lines plotted in halftone

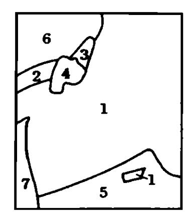
2000 foot grid based on KCC Mine coordinate system

KCC District grid 00 point can be located using halftone tick marks on map border

Kennecott Copper Corporation
Utah Copper Division
Geology Department

Wilbur H. Smith, Division Geologist

1978



INDEX TO SOURCES

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2 Atkinson, W.W., Jr., 1976, Surface geology of a portion of the Carr Fork area: The Anaconda Company unpublished map.
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Compiled by George Lanier
Drafted by Steve Richardson

The *Butterfield Peaks Formation* (IPobp) represents the oldest geologic unit in the mine area, with exposures confined to the southwestern and southern portions of the mine. Rocks of this formation consist predominantly of feldspathic orthoquartzite and calcareous quartzite. Four to six arenaceous limestone and calcareous sandstone interbeds are locally argillaceous, silty, cherty, and fossiliferous; these units are identified as the Sub-Jordan beds in Figure 1 and, with a few exceptions, are not ore bearing (Rubright and Hart, 1968).

Rocks of the *Bingham Mine Formation* overlie those of the Butterfield Peaks Formation and are subdivided into a lower and upper member. The lower member (IPobml) includes the Jordan and Commercial limestone beds which are the most important sedimentary ore hosts in the district and are also the most important stratigraphic marker beds in the Bingham Mine Formation. The beds consist of argillaceous, silty, cherty, and locally fossiliferous limestone. The section between the Jordan and Commercial is largely orthoquartzite, but two thin, discontinuous, calcareous marker beds are recognized, the Miners Dream and the Lark. Both beds are known chiefly from drill holes and underground workings, and both have produced ore.

A section of primarily quartzite overlies the Commercial limestone and extends to the base of the upper member. This rock generally consists of feldspathic orthoquartzite and calcareous quartzite. Interbedded in the quartzite, along with other indistinct, thin, carbonate-rich units, are four "groups" of thin arenaceous limestone and calcareous sandstone beds. These groups can make relatively useful stratigraphic markers and are, in ascending order above the Commercial, C+, Parnell, Winebago, and Congor. The stratigraphic position, number of beds, and approximate thickness of the beds are shown in Figure 1. The marker beds above the Commercial consist primarily of arenaceous limestone and calcareous sandstone with varying argillaceous, silty, and feldspathic portions. Calcareous sandstone is the dominant lithology, and all beds are listed as calcareous sandstone in the explanation of Figure 1. Ore-grade copper mineralization extends 800 m horizontally from the quartz monzonite porphyry in some of these calcareous beds.

The upper member (IPobmu) of the Bingham Mine Formation is predominantly quartzite, having significantly fewer limestone and sandstone beds than the lower member. The lithology of both the quartzite and carbonate rock is essentially the same as those previously described for the lower member. The lower part is exposed along the northern edge of the mine. The Manefay beds mark the base of this member and consist of two or three arenaceous limestone and calcareous sandstone beds.

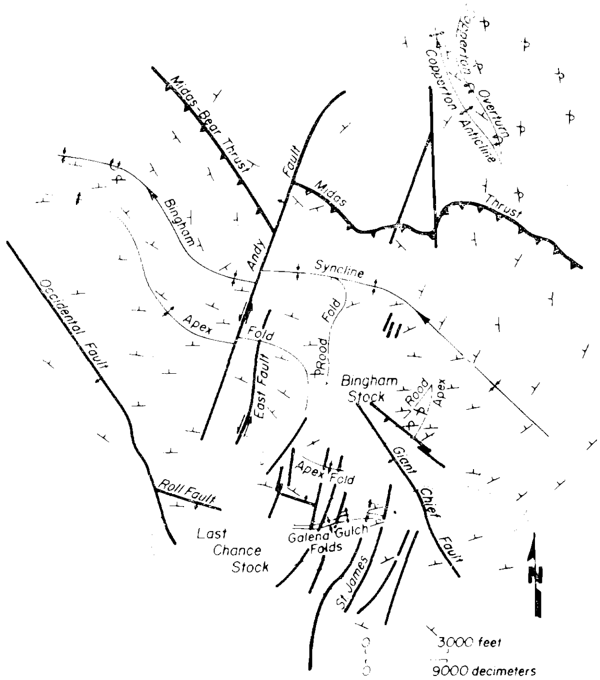

FIG. 2. Structural map of the Bingham area.

Structure

Folds

Structural elements of the Bingham district are shown in Figure 2. Folding generally conforms to regional patterns in the southern part of the Oquirrh Mountains and is characterized by large, generally open, asymmetrical anticlines and synclines which strike northwest. Within the district, northeast anticlinal limbs steepen, locally overturn, and fold axes strike more westerly. The Bingham syncline, defined originally by Keith (1905) as a broad open fold below the mouth of Carr Fork, is the dominant fold in the mine with two significant second-order folds on the southern limb: the Apex and Rood folds. The axis of the Bingham syncline strikes N 60° W and plunges 12° NW (James et al., 1961). The fold is broad and poorly defined in the mine but is more tightly folded to the northwest where the Rood fold and Bingham syncline converge. The northeast limb is truncated by the Midas thrust, and igneous rocks and related sulfide mineralization occur in the southwest limb.

The Apex and Rood folds, similar to the roll folds described by Keith (1905), occur on the southwest limb of the Bingham syncline. The axial trace of the Apex fold, an anticlinal structure, is approximately located in Figure 1 and generally trends east as it enters the mine from Cottonwood Gulch, bends south because of topography, and is cut and offset at the Bingham stock, possibly due to dilation. Both limbs dip north (except where the north limb is overturned), the south limb at 20° to 40° and the north limb at 60° to overturned. The Apex fold is described by Atkinson (1975) in Carr Fork as an "overturned anticline, the axial plane of which strikes approximately due east and dips 50° south."

The Rood fold, a synclinal structure, is defined where the steeply dipping strata of the north limb of the Apex fold return to a dip of 20° to 40° to the north on the north side of the mine. The axial planes of the Rood and Apex folds are roughly horizontal in the mine but converge 60 m from the northwest to the southeast side. This decrease in amplitude is in part due to an increase in the degree of overturning. The Apex and Rood folds appear to die out on the surface southeast of the mine.

A small anticline and syncline, the Galena Gulch folds, may be considered third-order folds on the southern limb of the Bingham syncline and are responsible for the duplication of Jordan limestone in Galena Gulch.

Faults

Faults, fractures, and joints are more abundant in the Bingham district than elsewhere in the Oquirrh Range. Boutwell (1905) documents the broken nature of the rocks with emphasis on the prominent northerly trend of most faults. He noted that faults trending in a northeast direction contain more economic mineralization than those trending northwest. Farmin (1933) discusses Basin and Range faulting. James et al. (1961) emphasize thrust faulting and also discuss major fault systems of the district. Rubright and Hart (1968) summarize the fault systems and their age relationships. Atkinson and Einaudi (1978) also discuss faulting in the Carr Fork area and its control on igneous intrusion and mineralization.

Age relationships of the faults are complex, with displacement along many having several periods and directions of movement. The results of two directions of compressional force are observed in the district, one from the southwest resulting in the northwest-trending folds of the southern Oquirrh Mountains and the Midas thrust (Fig. 2), and the other from the north resulting in the east-trending folds of the northern Oquirrh Mountains and the North Oquirrh thrust which is located 6 km north of the mine. The age relationships of the two compressional episodes are uncertain. The most recent stress was tension related to Basin and Range faulting.

The oldest faults in the district are the west- to northwest-striking normal faults (Rubright and Hart, 1968) which have been obscured by subsequent folding and faulting. The Roll (South) fault (Fig. 2), the best documented of the set, projects into the Phoenix dike and is not exposed on the 1955–77 mine surface. Two unnamed faults with this trend offset the Jordan limestone on the southwest side of the mine.

Northeast-trending left-lateral faulting in the rocks of the lower plate of the Midas thrust is older than or contemporaneous with thrust faulting. Strike-slip displacement on the northeast-trending faults roughly correlates with the eastward decrease in amplitude of the Bingham syncline, suggesting a close relationship between folding and faulting. The Main Hill, East, and Andy faults, in the upper plate of the Midas thrust, are somewhat parallel to this trend.

The Midas fault was first recognized in the Lark mine in the early 1940s and named the North fault; it was independently discovered on the surface north of the open pit in the 1950s. Although the Midas is not exposed in the area covered by Figure 1, related bedding-plane slippage along the top and bottom of calcareous sandstone beds is a common type of faulting on the east side of the mine and is in part responsible for the discontinuous nature of some of the smaller calcareous beds. Drag folds in quartzite adjacent to the limestone beds attest to this faulting.

The productive north-northeast-trending faults have been mined for lead and zinc southwest of the open pit over vertical distances of nearly 1,500 m. In Figure 1 northeast-trending faults south of the pit are projected from underground workings. Most dip steeply west and, with the exception of three larger faults, the Great, Delta, and Main Hill, have relatively minor displacement. Significant movement is preintrusion left-lateral strike-slip based on underground offset of north-dipping limestone beds and the south-dipping Midas thrust. Gouge zones along the strike of these faults in the Phoenix dike and possibly the Bingham stock suggest later, minor normal movement.

The northwest fault set includes the Giant Chief and Copper Center faults. These faults form wide gouge and breccia zones in monzonite, suggesting that important movement is postintrusion. This is the youngest significant set in the mine and may be related to northwest-trending Basin and Range faulting. Weak mineralization on the northwest-trending structures indicated that this fault set was relatively impermeable during mineralization or that it postdates the main period of mineralization.

Small, wavy to planar faults with 2- to 15-cm gouge fillings are abundant in intrusive rock in the mine. These faults have less than 5 m vertical displacement where observed and can rarely be correlated over more than three levels. Powdered and fragmental sulfides in gouge indicate postmineral fault movement. However, faulting probably occurred along premineralization fractures. This faulting may be related to recurrent movement along preintrusion faults, to isostatic rebound due to erosion and later mining, and to seisms related to mine blasting.

Structural controls on the emplacement of intrusions

Control of the emplacement of the main intrusive bodies at Bingham has been previously described by James et al. (1961) as dilation in the Bingham horst between the Occidental and Bear faults at the intersection of the northeast and northwest fault sets (Fig. 2). However, recent findings show only minor dilation occurred with intrusive emplacement. The Bear fault is now believed to be a continuation of the Midas thrust. The effect of northwest faults, such as the Bear, on the shape of the intrusion is limited to minor irregularities on the west and south sides of the stock. Local structural controls are discussed by James et al. (1961) and Peters et al. (1966). Tooker (1971) and Moore (1973b) discuss the importance of northwest-trending regional folds on intrusion and ore deposition.

The intersection of northeast-trending faults with the Copperton anticline beneath the Midas thrust is now interpreted as the major emplacement control of the Bingham stock. Recent drilling shows that the north and east edges of the Bingham stock are controlled by the location of limestone beds in the Copperton anticline (Fig. 2). Control of the shape of the intrusion by limestone beds is clearly demonstrated at the surface in Carr Fork where the Commercial limestone forms part of the northwest contact of the stock.

Igneous Rocks

The Bingham mine is centered on a composite, hydrothermally altered and mineralized pluton, first referred to as the Bingham stock by Butler (1920). The stock was earlier described as the Bingham laccolith (Boutwell, 1905; and Beeson, 1917) and later as the Utah Copper Stock. The Bingham and Last Chance stocks and nearby plutons in Butterfield Canyon are similar in texture and composition, and are connected by dikes suggesting that the surficially separated rock masses may converge at depth forming one stock. In general, the intrusions are discordant with irregular outline.

The Bingham stock is an epizonal intrusion having a maximum cover thickness of 2,300 ± 300 m (Moore, 1973a). Some of the phases apparently vented, forming the volcanic pile to the east of the range. This relationship is substantiated by the proximity of intrusive and extrusive rocks, similarities in their compositions, and radiometric age dates (Moore, 1973a).

Equigranular phases of the Last Chance and Bingham stocks were mainly emplaced passively by stoping and assimilation (Willden, 1952), whereas porphyry phases were forcefully intruded (Bray, 1967).

The age of the several phases of the Bingham and Last Chance stocks range from 39.8 ± 0.4 to 38.8 ± 0.4 m.y. (Warnaars et al., 1978). Crosscutting relationships are consistent with available radiometric ages, showing older equigranular phases to be cut by younger porphyry phases. The relative age of the six main intrusive phases is shown in Table 1 and is based mainly on field relationships.

The major intrusive phases in the Bingham stock are monzonite and quartz monzonite in composition based on modal data. All the intrusions are chemically intermediate; SiO_2 ranges between 57 and 65 percent (Moore, 1973a). Although this chemical classification is probably shared by all phases, a striking contrast exists in the quartz content between equigranular and younger porphyry phases. The contrast is shown by Moore (1973a) to exist for normative quartz. Based on quartz abundance, the intrusive phases can be divided into two distinct groups, quartz rich and quartz poor, whose characteristics are summarized in Table 1.

Monzonite (Tim) is the most common rock type exposed in the Bingham stock and is an important sulfide host rock for the porphyry copper deposit. Except for small latitic dikes it is the only igneous rock type recognized in the Last Chance stock. The Bingham monzonite was emplaced mainly by magmatic stoping and assimilation and is probably the oldest phase. Interpretation of radiometric age dates by Warnaars et al. (1978) yields a late Eocene age of 39.8 ± 0.4 m.y.

Stringham (1953) classified the equigranular phase of the Bingham stock as granite, but his samples represent K-silicate altered rock. The phase was termed "dark porphyry" by Butler (1920) and monzonite by Boutwell (1905).

Unaltered monzonite is dark gray, fine grained (0.5 mm), and equigranular. Locally 1 to 2 percent feldspar phenocrysts may be present. The composition of unaltered Bingham monzonite is probably the same as the monzonite of the Last Chance stock, augite-amphibole-biotite monzonite (Lanier et al., 1978). Modal analyses of the Last Chance stock (Moore, 1973a) show that K-feldspar (30%) is about the same as plagioclase (33%). Quartz averages 7 percent, giving a quartz to felsic constitu-

TABLE 1. Summary of Intrusive Phases, Bingham Mine

		Quartz-poor	Quartz-rich
Phases:	Youngest		Quartz latite porphyry dikes (Tiqlp) Latite porphyry dikes (Tilp)
		Recrystallized monzonite (Tirm)	
			Hybrid quartz monzonite porphyry (Tih) Quartz monzonite porphyry (Tiqmp) Bear Gulch latite (Til)
		Porphyritic quartz monzonite (Tipqm), Ohio Copper dike	
	Oldest	Monzonite (Tim): Phoenix dike, Bingham and Last Chance stocks	
Composition		Monzonite and latite, quartz less than 10 vol %	Quartz monzonite and quartz latite, quartz greater than 20 vol %
Color		Dark gray	Light to medium gray
Texture		Equigranular to porphyritic	Porphyry
Form		Small stocks and related apophyses	Dikes, sills, and small apophyses
Emplacement		Stoping and assimilation	Forceful injection
Relative age		Pre-quartz-rich phases	Post-quartz-poor phases

ent ratio of 0.1 which is borderline between monzonite and quartz monzonite. The monzonite classification is preferred at Bingham because it emphasizes the contrast in quartz abundance between equigranular and porphyritic phases and is more consistent with the presence of augite which averages 11 percent of the rock. Uralitic amphibole (7%), biotite (8%), magnetite (2%), and accessory minerals (2%) make up the remainder of the rock. Small areas of contaminated igneous rock that occur near contacts with sedimentary rocks are included with monzonite in Figure 1.

The *Ohio Copper Dike* (Tipqm) is a 150- by 300-m, northwest-trending, rectangular intrusion that crops out in Copper Notch in the southeast part of the mine. The dike plunges 55° to the northwest. The rock is greenish gray and porphyritic with an equigranular phaneritic groundmass that is similar in composition and texture to the surrounding monzonite. On the mine surface, the dike mainly intrudes porphyritic, endomorphically altered monzonite in contact with quartzite. The two intrusive phases are megascopically similar in appearance and difficult to distinguish. When sharp contacts are absent, the dike boundary is defined on the change in abundance of plagioclase phenocrysts from less than 5 percent in monzonite to greater than 10 percent in the dike with an accompanying increase in pale pink orthoclase phenocrysts. W. H. Smith originally delineated and named the Ohio Copper dike from drill hole intercepts (pers. commun.). Moore (1973a) mapped and classified the dike as porphyritic amphibole quartz monzonite in the Mascotte tunnel and Ohio Copper 500 levels. Based on composition and texture, the dike is more closely related to equigranular monzonite than to porphyry phases of the Bingham stock.

The *Bear Gulch latite* (Til) forms a 400- by 600-m intrusion located in Yosemite Notch near the southeast edge of the mine. Abundant fragments of quartzite and latite near the perimeter form intrusive breccia. The latite is buff colored, mostly porphyritic but locally microcrystalline, with 0.05 mm groundmass and sparse 0.5 mm phenocrysts. Subrounded quartzite fragments and possible latite autoliths (1 to 7 cm) occur in the igneous matrix. Rounding of fragments is probably due to assimilation.

Microscopic examination shows that orthoclase is slightly more abundant than plagioclase; quartz ranges from 10 to 15 percent; nearly colorless, nonpleochroic phlogopite(?) makes up 5 percent; and aggregates of clay, sericite, quartz, and pyrite replacing ferromagnesian phenocrysts make up 10 percent. Pyrite is also common as discrete disseminated grains. Phenocrysts are subhedral and consist of ferromagnesian replacement aggregates, phlogopite(?), and some plagioclase which occur in subparallel alignment. Groundmass orthoclase and plagioclase have a tendency to separate into flow bands parallel to phenocrysts.

The Bear Gulch latite is in general compositionally related to other phases in the mine, although the relative age is unknown. Quartz abundance is intermediate between that of major porphyry and equigranular phases. The intrusion is classed with younger phases (Table 1) because of texture, color, and forceful emplacement. Two small syenodiorite dikes (Tis), possibly the most basic rock in the mine, cut the Bear Gulch intrusion near the southwest border.

Quartz monzonite porphyry (Tiqmp) is the major porphyry intrusion in the Bingham stock and areally coincides with the center of mineralization in the Bingham mining district. This phase forms a thick northeast-trending dike which dips northwest. The widest portion is 400 m and occurs in the bottom of the mine. The intrusion has been referred to as light porphyry (Butler, 1920), granite porphyry (Stringham, 1953; Bray, 1967, 1969), aplite porphyry (Moore and Czamanske, 1973; Moore and Nash, 1974), and quartz monzonite porphyry (Moore and Czamanske, 1973).

Exposures not overprinted by silicification and sericitic alteration reveal a coarse-grained porphyry with more than 50 percent phenocrysts of argillized feldspar and large phlogopitized amphibole in an aphanitic groundmass. The prealteration modal composition of this porphyry is estimated at 32 percent plagioclase, 32 percent orthoclase, 23 percent quartz, and 14 percent mafic and accessory minerals. The rock was probably a hornblende-biotite quartz monzonite. Modal plagioclase is represented mainly by (1) clay-sericite aggregates replacing plagioclase, (2) remnant plagioclase, (3) orthoclase replacing plagioclase, and (4) minor epidote and calcite. Phlogopite, orthoclase, quartz, some apatite, and sulfides replace amphibole. Relict magmatic phlogopitic mica with sagenetic rutile makes up a small percentage of the rock. The mode of quartz monzonite porphyry is approximate because of the difficulty in distinguishing the products of alteration from primary minerals and because of the difficulty in measuring actual proportions of groundmass and phenocrysts.

Hybrid quartz monzonite porphyry (Tih) is interpreted as a product of assimilation of monzonite near the top of the parent quartz monzonite porphyry. The rock, originally described as gradational granite porphyry by Bray (1967), asymmetrically surrounds and overlies the westward-plunging quartz monzonite porphyry dike in Carr Fork. The underlying quartz monzonite porphyry displays sharp contacts with monzonite along the lower sides suggesting forceful intrusion. Upward migration of the porphyry stopped and the overlying monzonite was assimilated. Modal data from Bray support the hybrid interpretation. The abundances of quartz, 13 percent, and brown mica, 14 percent, are compositionally between monzonite and quartz monzonite porphyry, suggesting mixing of the two phases.

The contact between the hybrid porphyry and quartz monzonite porphyry is abrupt, often less than one meter. Compared to the quartz monzonite porphyry, the hybrid rock is megascopically darker gray because of abundant phlogopite and has a more pronounced aphanitic groundmass containing small phlogopite flakes.

Recrystallized monzonite (Tirm) probably formed as a result of pyrometamorphism of monzonite at the hybrid quartz monzonite porphyry contact and forms a shell around the hybrid rock. This unit is compositionally similar to monzonite and retains the equigranular texture of the monzonite but is much coarser grained. Abundant aggregates of dark brown biotite make up 25 to 40 percent of the rock and impart a distinctive spotted appearance. Although both hybrid and recrystallized rock are altered, the two rock types have relatively uniform lithologies and can be consistently separated in the field.

Latite porphyry (Tilp) forms the Main Hill dike, Starless dike, Fortuna sill, and several other tabular bodies which comprise a 6,000-m-long swarm of northeast-trending dikes and sills which pass through the northwest margin of the Bingham stock. Latite porphyry dikes in Carr Fork are described by Bray (1969) and Moore (1970, 1973a).

The dikes are light to medium gray and have an unaltered amphibole-biotite quartz latite composition. In general, the phenocryst assemblage is principally 2.5 mm plagioclase grains with minor orthoclase, biotite, amphibole, and small, rare, partially resorbed quartz grains. The groundmass is composed of 0.02 to 0.08 mm quartz and orthoclase grains which form one-half to two-thirds of the rock.

These dikes show some textural and compositional variability. Bray (1969) describes three groundmass textural and compositional variants in Carr Fork; similar variations also exist for dikes on the east side of the mine. Some textural differences are probably related to cooling environment, while compositional variation suggests emplacement of dikes during different magmatic surges.

The main emplacement control for the dikes appears to be the northeast-trending, left-lateral faults in the lower plate of the Midas thrust.

Quartz latite porphyry (Tiqlp) forms narrow dikes, less than 10 m wide, and other irregular and discontinuous bodies. The most extensive of these is the Andy dike which is 4 m wide and trends northeast. Small apophyses near the bottom of the mine are less altered, mineralized, and fractured than their wall rocks and may be the youngest igneous rocks in the Bingham stock. Exposures of these dikes were first described as a separate rock unit by Stringham (1953). Wilson (1978) describes an unusual vesicular dike of this composition in the southeast part of the mine.

Unaltered quartz latite porphyry is medium gray or green and is typically composed of 25 percent feldspar phenocrysts (2–30 mm), 8 percent quartz

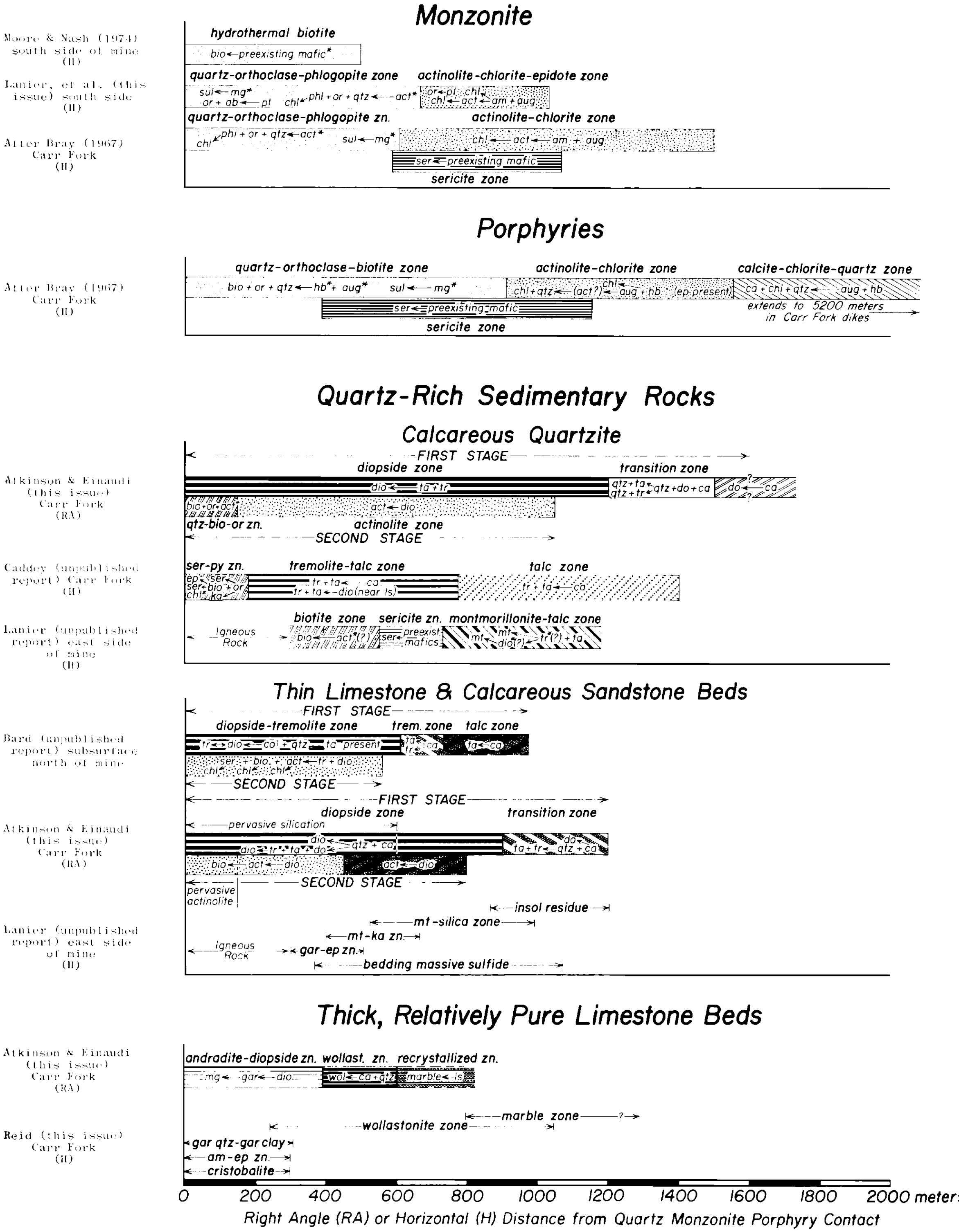

FIG. 3. Hydrothermal alteration mineral zoning in igneous and sedimentary rocks, Bingham mine.

Mineral abbreviations: ab–albite, act–actinolite, am–amphibole, aug–augite, bio–biotite, ca–calcite, chl–chlorite, dio–diopside, do–dolomite, ep–epidote, gar–garnet, hb–hornblende, ka–kaolinite, ls–limestone, mg–magnetite, mt–montmorillonoid, or–orthoclase, pl–plagioclase, py–pyrite, qtz–quartz, ser–sericite, tr–tremolite, wol–wollastonite, zn.–zone.

Arrows indicate sequential order of mineral formation. *–mineral not present within zone.

phenocrysts (3–6 mm), and 6 percent biotite phenocrysts (2 mm), with the remainder groundmass (0.05 mm) of the same minerals (Bray, 1969). Mafic laths in the groundmass commonly show subparallel alignment in the Andy dike. Common quartz phenocrysts, abundant groundmass, and abundant mafics in the groundmass are the distinguishing features of these dikes.

Kilkinny Breccia Pipe

The Kilkinny breccia pipe has been discussed by Peacock (1948), James et al. (1961), Rubright and Hart (1968), and Smith (1975). The pipe is located near the southeast edge of the Bingham stock and is roughly elliptical, elongate in a northwest direction. Underground workings indicate that the breccia pipe dips steeply to the southwest. Another smaller area of breccia observed underground, approximately 120 m southwest of the main pipe, may be related to the Kilkinny. The Kilkinny is largely surrounded by sedimentary rock but extends into intrusive rock to the south.

The pipe is mainly composed of hydrothermally altered quartzite, limestone, and, less commonly, monzonite fragments ranging in size from 2 cm to over 2 m. The matrix surrounding the breccia fragments is mainly composed of quartz powder and small quartzite fragments presumably derived from attrition of sedimentary rocks during brecciation.

The Kilkinny pipe is younger than the emplacement of the Bingham monzonite and older than mineralization based on the occurrence of pyrite reported in underground workings. Observations on the Kilkinny breccia pipe are consistent with the "collapse breccia model" of Norton and Cathles (1973).

Hydrothermal Alteration

The current interpretation of the premineralization geology of the Bingham mine was described in the preceding section. The products of mineralization and alteration are summarized in this section and at greater length by other authors in this issue of *Economic Geology* and other publications.

Hydrothermal alteration in part is zoned around and genetically related to the top of the quartz monzonite porphyry. The hollow-domed shape of the Bingham orebody with vertically extending roots is similar to the three-dimensional shape of the San Manuel-Kalamazoo deposit (Lowell and Guilbert, 1970). Concentricity of zoning is not attained because of rock-type variation and greater structural control of fluid movement along northeast-trending faults in the north half of the deposit. Tilting of the ore shell approximately 17° east from vertical resulted from Basin and Range faulting.

Extremely abundant planar fractures occur in all rock types in the orebody. These fractures increased permeability for altering hydrothermal fluids and provided open space for copper-iron sulfide deposition and quartz-molybdenite veining. Fracturing was a postconsolidation, premineralization event, and the abundance of fractures is spatially zoned with sulfides around the quartz monzonite porphyry (John, 1978).

A quantitative measure of planar fracture intensity can be expressed by fragment size. On the present mine surface, in potassically altered rock, fragments bounded by premineral fractures range from 1 to 15 cm. Angles between fracture planes are generally 90 degrees and less.

Silicate alteration is summarized in Figure 3, and the areal distribution of mineral zones in igneous rocks is shown in Figure 4. In Figure 3, important alteration products are grouped into mineralogical zones and paragenesis is given with arrows; equilibrium assemblages are not implied. Zoning is described using either horizontal or right-angle distances to the contact of the quartz monzonite porphyry. Alteration effects are discussed in terms of four principal lithologies: (1) monzonite, (2) porphyries including quartz latite porphyry, quartz monzonite porphyry, and hybrid quartz monzonite porphyry, (3) quartz-rich sedimentary rocks including calcareous quartzite and thin sandy limestone and calcareous sandstone beds, and (4) thick, relatively pure limestone beds.

Alteration in monzonite

Data from Moore and Nash (1974), Bray (1967), and Lanier et al. (1978) are used to summarize mineral zoning in monzonite. Three zones are recognized with the following alteration mineral associations: (1) quartz-orthoclase-phlogopite, (2) sericite-quartz, and (3) actinolite-chlorite-epidote. In the former zone, ferromagnesian replacement aggregates are made up mainly of phlogopite, quartz, orthoclase, pyrite, and chalcopyrite. Phlogopite is locally altered to chlorite. Plagioclase is replaced by orthoclase, and disseminated sulfides probably replace magnetite. This mineral association occurs closest to the quartz monzonite porphyry and is typical of K-silicate alteration (Creasey, 1959).

Sericitic alteration partially or totally replaces all earlier formed minerals except quartz and orthoclase with quartz and sericite. However, even in the area of strong sericite development, sericitic alteration is controlled by fractures and faults, and the sericite occurs in selvages around quartz-pyrite veinlets and around gouge-filled faults. The sericite zone is best developed on the west side of the mine in Carr Fork where selvages locally coalesce (Fig. 4). Sericite

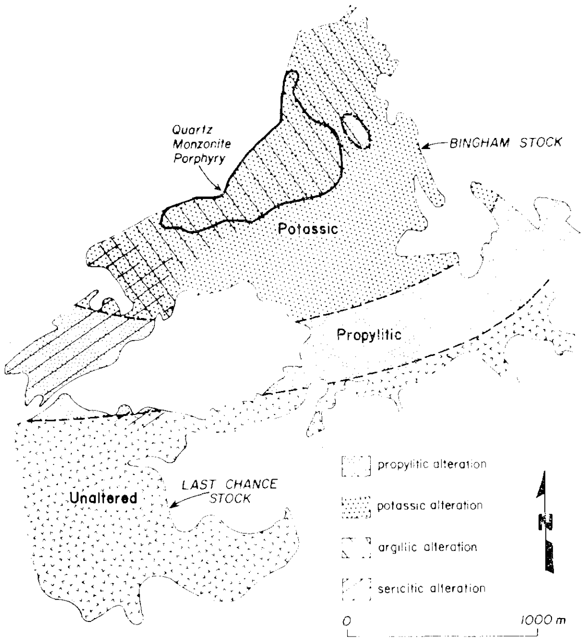

FIG. 4. Plan map showing generalized distribution of silicate alteration zones in igneous rocks at Bingham.

veinlets decrease to the south and east where they are almost nonexistent. The zone occurs between and overprints the potassic zone and the propylitic zone.

In the propylitic zone, which surrounds the potassic zone, actinolite replaces magmatic augite. Actinolite, augite, and biotite are replaced by disseminated and vein-controlled chlorite. Epidote is common and can occur along veins and is disseminated with actinolite. Orthoclase incipiently replaces plagioclase.

Alteration in porphyries

Data for the discussion of quartz-rich porphyry phases mainly come from Bray (1967), Moore and Nash (1974), and unpublished reports. Four zones are recognized with the following alteration mineral associations: (1) quartz-orthoclase-phlogopite (biotite), (2) sericite-quartz, (3) actinolite-chlorite-(epidote), and (4) calcite-chlorite-quartz.

Quartz monzonite porphyry is included with the quartz latite porphyry dikes, and on the surface lies totally within the zone of potassic alteration. The mineral associations in this zone are very similar to that described for monzonite except for two important differences: (1) mafic replacement products make up a smaller percentage of the rock because of a lower magmatic mafic content, and (2) plagioclase is only weakly altered to orthoclase with pervasive clay and sericite the most important alteration products. Moore and Nash (1974) described the clay-sericite alteration as "sericitic alteration" resulting from moderate to strong hydrolytic alteration (Hemley and Jones, 1964). The zones of sericitic and propylitic alteration are similar to the same zones in monzonite.

The mineral association calcite-chlorite-quartz appears to be unique to latite dikes. Calcite, chlorite, and lesser amounts of quartz replace preexisting mafics. Calcite also replaces, to a lesser extent, plagioclase. Bray (1967) considers the alteration to be related to sulfide-associated hydrothermal fluids. If that interpretation is correct, the zone can be considered an outer propylitic zone. Moore (1973a), noting the absence of this type of alteration in monzonite bordering the dikes, suggests that the rock was "altered by a hydrous CO_2-bearing fluid that separated from the melt during crystallization." This type of alteration does extend well beyond alteration described for other igneous and sedimentary rock, and the Carr Fork dikes intrude thick carbonate beds favoring the latter interpretation.

Three stages of hydrothermal alteration are recognized which formed the alteration zoning in igneous rocks, early hydrous, Mg and K metasomatism, and late hydrous. The early hydrous stage involved the formation of actinolite by the hydrolytic alteration of augite. Potassium was added with the incipient formation of orthoclase which replaced plagioclase. Magmatic magnetite was stable during the early stage. Magnesium and K metasomatism was superimposed on the early hydrous stage and involved the formation of phlogopite which replaced actinolite and continued development of orthoclase. The addition of iron and copper in disseminated sulfides is part of this stage based on the close spatial relationship of phlogopite and sulfides. Late hydrous alteration was superimposed on both earlier stages and involved at least three substages: (1) chloritic alteration of phlogopite in the potassic zone and chloritic alteration of biotite, augite, and actinolite in the propylitic zone, (2) sericitic alteration around quartz-pyrite veinlets, and (3) pervasive, intermediate argillic alteration consisting mainly of a montmorillonoid and sericite selectively replacing plagioclase.

The strong sericitic alteration occurs mainly on the west side of the mine (Fig. 4) and is distinct from the pervasive argillic alteration which is distributed mainly with porphyry phases. Both alteration types appear to be related to the northeast fault trend defined by latite dikes; however, sericitic alteration is also controlled by fracturing and distance from the quartz monzonite porphyry. Temporal relationships of late hydrous substages are uncertain.

Alteration in quartz-rich sedimentary rocks

Atkinson and Einaudi (1978) describe three stages of alteration in calcareous quartzite and thin calcareous sandstone and limestone beds. The first, Mg metasomatism, involved the formation of an early diopside zone and an outer transition zone which contains talc-tremolite assemblages. The second involved Fe metasomatism which overprinted actinolite and biotite on the diopside zone. Copper and iron sulfide mineralization accompanied second-stage alteration. Hydrous alteration, the third stage, overprinted second-stage assemblages and included mainly chloritic, sericitic, and argillic alteration mineral assemblages. Argillic alteration is extremely intense on the east side of the mine (Fig. 3). This pervasive clay alteration of the sedimentary rocks may be a continuation of the strong argillic alteration in igneous rocks in the northern half of the mine and is probably controlled by bedding planes.

Data used to summarize mineral zoning in *calcareous quartzite* are from Atkinson and Einaudi (1978), Caddey, and Lanier. Interpretation of mineral zoning is mainly from Atkinson and Einaudi (1978) for the remainder of the discussions on altered sedimentary rock. In calcareous quartzite, silicate mineral assemblages occur mainly in the site of calcium carbonate cement interstitial to primary detrital quartz grains. This is also true for the thin, calcareous beds discussed later. Mineral zoning in calcareous quartzite resembles zoning described for intrusive rock with a centrally located quartz-biotite-orthoclase zone, a sericite zone, and an actinolite zone. These zones were superimposed on diopsidic quartzite during the main period of sulfide deposition.

Quartzite within the quartz-biotite-orthoclase zone occurs as ore on the lower levels of the mine. The rock is brown from megascopically visible medium brown mica. Quartz grains are often enlarged due to recrystallization. Biotite replaces actinolite which is not present within the zone; orthoclase is a minor phase. A sericite zone is reported on the east and west sides and sericite is also reported underground north of the mine. Sericitic alteration pervades the rock and overprints earlier biotite alteration. Actinolite replaces diopside in the actinolite zone.

Mineral zonation data for *thin limestone and calcareous sandstone beds* are from Atkinson and Einaudi (1978), Bard, and Lanier. Mineral assemblages occurring in these thin beds are almost identical to calcareous quartzite assemblages. The main difference is that zoning is telescoped in toward the quartz monzonite porphyry. Zones are characterized as actinolite, diopside-actinolite, and talc-tremolite.

Alteration in thick, relatively pure limestone

The Commercial and Jordan limestones fall into the category of thick, relatively pure limestone. Data from Atkinson and Einaudi (1978) and Reid are used to summarize mineral zoning. Two main zones are recognized: a garnet zone occurring nearer the quartz monzonite porphyry, and an outer wollastonite zone. Black, recrystallized limestone occurs beyond the wollastonite zone. The garnet zone contains garnet, diopside, and magnetite (mainly at depth) as primary minerals with clay, quartz, opal (mainly near the surface), and actinolite. Ore-grade copper mineralization is associated with this zone. The wollastonite zone contains wollastonite and diopside with accessory idocrase, andradite, and sulfide.

Three stages of alteration occur in limestone: early metamorphism, Fe metasomatism, and late hydrous. Early metamorphism, time-equivalent to early magnesium metasomatism in quartzite, resulted in early barren wollastonite-diopside assemblages. Iron metasomatism formed garnet, magnetite, and sulfides. Some garnet formed in the first stages, and the phase is considered transitional between early and main stages. Ore-grade Cu mineralization accompanied Fe metasomatism. Late hydrous alteration replaced earlier stage assemblages and formed epidote, chlorite, montmorillonoids, sericite, talc, and possibly opal.

Discussion

Hydrothermal alteration formed mineral zones around the quartz monzonite porphyry which were mainly controlled by the bulk composition of the unaltered rocks and distance from the porphyry. Alteration of intrusive rock is characterized by an inner quartz-orthoclase-phlogopite zone and an outer actinolite-chlorite-epidote zone. Calcareous sedimentary rocks are zoned with an inner quartz-biotite-orthoclase zone (well developed in calcareous quartzite but weakly developed or absent in thin calcareous sandstone and limestone beds), an actinolite zone, a diopside zone, and an outer talc-tremolite zone. Thick limestone beds have an inner garnet zone with an outer wollastonite zone. Sericitic and argillic alteration was superimposed on rock in the northern half of the orebody.

Three stages of alteration are recognized in igneous and sedimentary rocks. Magnesium and K metasomatism in igneous rocks formed the quartz-orthoclase-phlogopite mineral associations, and is time equivalent to Fe metasomatism in sedimentary rocks which formed garnet in limestone and actinolite and biotite in calcareous sediment. Sulfide mineralization accompanied this main stage. The late hydrous alteration is time equivalent in both sedimentary and igneous rocks and overprinted main-stage alteration with chloritic, argillic, and sericitic alteration. Early hydrous alteration occurred in igneous rocks and formed actinolite and some orthoclase; however, the early Mg metasomatism in sedimentary rock, forming diopside, tremolite, and talc, appears to be absent in igneous rock.

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