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Petrology of the Ryan Canyon Stock
Mineral County, Nevada

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

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The Ryan Canyon stock is a small quartz monzonite porphyry intrusion that crops out in the Ryan Canyon area of the Gillis Range, Mineral County, Nevada. This stock is elongate northwest-southeast and has maximum exposed dimensions of about 4 miles by \( \frac{1}{2} \) mile. Although relatively fresh rocks have been observed along the northwest margin of this stock, the original composition and textures of a major portion of the intrusion have been modified by late magmatic autometamorphism and subsequent hydrothermal and supergene alteration. Of particular interest is the unusual hornfels-textured quartz, andalusite, orthoclase, and pyrite alteration assemblage (andalusite hornfels facies) present in the Ryan Canyon stock and some of the small satellite bodies.

In the proposed alteration model, the andalusite hornfels facies rocks formed by autometamorphism that occurred during late stage crystallization of the magma. Excess alumina, derived from the destruction of plagioclase and biotite, combined with silica to form the stable aluminum silicate, andalusite. The critical factor responsible for the andalusite-bearing alteration assemblage appears to be the high sulfur activity in the magma, which is reflected by the ubiquitous presence of pyrite in the intrusion. The source for both the sulfur and the quartz monzonite magma is believed to be a strongly fractionated parent magma that gave rise to a hybrid quartz monzonite by physical mixing of the differentiated felsic and cumulus fractions. After the stock was emplaced, parts of the intrusion suffered deuteric
alteration that is characterized by a quartz and coarse muscovite alteration assemblage. Late stage sericitization and supergene alteration have affected the stock only slightly.
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PETROLOGY OF THE RYAN CANYON STOCK, MINERAL COUNTY, NEVADA

INTRODUCTION

Ryan Canyon is a major drainage on the southwest flank of the Gillis Range, a northwest trending mountain range in central Mineral County, Nevada. The mouth of the canyon is located about eight miles northeast of Hawthorne; it can be easily reached via a county road that extends from Hawthorne through Ryan Canyon to Rawhide. Rock units exposed in the canyon range in age from Late Triassic through Quaternary and include a small Late Cretaceous stock that is termed the Ryan Canyon stock in this report. The petrology of this stock is the principal concern of the present investigation; however, the surrounding area was examined and mapped to provide information on the local structure and geological setting. The actual area that was mapped is shown in Figure 1.

The Ryan Canyon stock was selected for study because it is one of the few igneous bodies known to the author that contains the alteration assemblage andalusite, quartz, orthoclase, and pyrite. The only other locality in the United States where a similar alteration assemblage has been described is in the Beaver Lake Mountains, Utah (Butler, 1913; Barosh, 1960). However, the published reports pertaining to that area do not contain detailed descriptions of the alteration, nor do they attempt to explain its origin. Therefore, the purpose of the present investigation was to describe and interpret the unusual occurrence of andalusite in the Ryan Canyon stock.
FIGURE 1. Index map of Nevada showing the location of Ryan Canyon and present area of investigation.
METHODS OF STUDY

Field work for this study was conducted in the summer of 1973 and spring of 1974, during which time 33 days were spent in mapping and sampling the Ryan Canyon area. Geologic mapping was done on aerial photographs at an approximate scale of 1:12,000 and then transferred to a 1:12,000 scale topographic base map using an optical pantograph. The base map was obtained by photographically enlarging a segment of the U.S. Geological Survey Hawthorne, Nevada, 15' topographic quadrangle. In conjunction with the mapping, over 350 rock samples were examined in thin section to assist in the correlation of rock units and to provide petrographic data on the Ryan Canyon stock. An additional sample was collected from the Ryan Canyon stock for isotopic age dating.

The fifteen chemical analyses presented in this report are from selected rock samples that are as nearly representative as possible of the major rock units and the altered Ryan Canyon stock. Most of the major-element oxides were determined by X-ray fluorescence using unfused, pelletized rock powders. Water was determined gravimetrically by fusion and adsorption in a moisture trap, while alumina and sulfur were determined by outside laboratories using AC spark emission spectrography and an ignition-titration process, respectively. Bulk rock densities used to compute gains and losses were measured using an air comparison pycnometer.

Considerable emphasis was placed on petrographic work during investigation of the Ryan Canyon stock. The various alteration products
observed in thin section were identified by optical methods and X-ray diffraction techniques. Rock modes were determined by point counting thin sections using a mechanical stage. In certain instances, staining with sodium cobaltinitrite was required to distinguish between the alkali feldspars. Plagioclase compositions were estimated by the Michel-Levy method. In addition to the petrographic work, a limited number of high temperature experiments were conducted to help define the geologic conditions under which the andalusite-bearing alteration assemblage could be produced. These experiments were done in cold-seal, externally heated pressure vessels using standard procedures for buffering the sulfur and oxygen fugacities. Results from both the petrographic and experimental work were used to define the chemical reactions and explain the origin of the observed alteration assemblage.

GEOLoGY OF THE RYAN CANYON AREA

Stratigraphy and Lithology

Gold Range Formation (Upper Triassic and Lower Jurassic)

Metamorphosed volcanic and coarse clastic rocks, together with rare interbedded impure limestone, crop out over a major portion of the mapped area forming rugged, angular outcrops and blocky talus slopes. These rocks are the oldest rocks that are exposed in the Ryan Canyon area, and they are tentatively correlated with the Gold Range Formation described and named by R. L. Nielsen (1964). In the central Excelsior Mountains, the type locality for the Gold Range Formation,
this formation is about 13,000 to 15,000 feet thick (Nielsen, 1964). In the present mapped area, however, neither the top nor bottom of the formation is exposed, and recent tectonic complications make measurement of the exposed thickness impractical.

In general, the Gold Range Formation is characterized by a highly variable lithology and by rapid lateral changes in the thickness of individual units. No attempt was made to completely define the local stratigraphy of the formation, but field work indicates that it is predominantly graywacke and volcaniclastic breccia with subordinate andesite flows. Phrydacite and rhyolite flows, as well as tuffaceous sandstone, arkose, and impure limestone beds, were noted, although these units together represent only a small fraction of the exposed stratigraphic section. The only basalt flow found in the formation occurs at the base of the Gillis Range in Sections 22 and 27. Thin sections show that the flow was a vesicular olivine basalt that has undergone thermal metamorphism and subsequent severe hydrothermal alteration to a cordierite- and andalusite-bearing rock. The only reason this unit was mapped separately is because it appears to be significant in localizing the few small corundum and andalusite deposits that occur in the Ryan Canyon area.

In thin section, the majority of samples are granoblastic-polygonal textured hornfels that contain quartz, biotite, calcic plagioclase, and microcline. Most of the original rock structures are preserved. Adjacent to intrusive contacts, biotite is locally replaced by hornblende and, occasionally, by anthophyllite in response to the higher temperatures near the intrusion. The originally impure limestone beds
have been altered to calc-silicate hornfels, and the arkosic units, to slightly schistose hornfels.

No identifiable fossils were found in the Gold Range Formation at Ryan Canyon, but fossils found by Muller and Ferguson (1939) in equivalent rocks at a locality seven miles northwest of the present mapped area were identified as early Middle Triassic in age. A re-interpretation of the fossil evidence by N. L. Silberling (Silberling and Roberts, 1962) suggested a Middle to Late Triassic age, and fossils collected more recently from the upper part of the formation indicate an Early Jurassic age (Nielsen, 1964). This evidence, plus the fact that the formation is in part equivalent to the Luning Formation, led Nielsen to conclude that the Gold Range Formation is Late Triassic to Early Jurassic in age.

Luning Formation (Upper Triassic)

Metamorphosed carbonaceous limestone of the Luning Formation occurs as small, isolated exposures at the crest of the Gillis Range along the Ryan Canyon road, at the extreme north central portion of the mapped area, and in Sections 14 and 15. In the mapped area, the Luning Formation consists of thick- to thin-beded marble with at least one thin bed of black shale. The maximum exposed thickness of this formation is only a few hundred feet, and neither the top nor bottom of the formation is exposed.

The age of the Luning Formation has been well established from fossil evidence as being Late Triassic (Muller and Ferguson, 1939), the same age as the lower portion of the Gold Range Formation. Work
done by Nielson (1964) showed that these two formations interfinger, and he concluded that they represent different facies deposited in the same early Mesozoic depositional basin. Although the contact relations between the Gold Range and Luning Formations are poorly exposed in the present mapped area, there is no evidence to indicate that a major thrust fault separates the two formations as proposed by Ferguson and Muller (1949). In the Garfield Hills and Pilot Mountains, which lie to the south of the Gillis Range, the contact between the Luning and Gold Range Formations was found to be conformable (Nielsen, 1964), and the same relationship is thought to exist in the Ryan Canyon area.

Granodiorite (Cretaceous?)

Massive, dark-gray granodiorite crops out along the southwest flank of the Gillis Range as an exposed segment of a larger stock(?) and in the central portion of the mapped area as small scattered bodies. On close examination, it is apparent that the dark color is due to an abundance of mafic minerals. Typically, these intrusions are coarse-grained, but grade to medium-grained toward the contact with older rocks. The latter texture is particularly well developed in the smaller intrusive bodies. These igneous rocks, which are broadly termed granodiorite, actually exhibit a range of compositions from quartz diorite to granodiorite; available data, however, were insufficient to indicate any systematic variation of composition with geographic distribution.

In thin section, one typical granodiorite sample consisted of
plagioclase (47%), biotite (19%), quartz (11%), hornblende (11%),
and orthoclase (8%). Magnetite, apatite, sphene, and zircon are common
accessory minerals. Allanite and hematite are present, but are rare.
The most abundant secondary minerals are epidote, chlorite, and
sericite; actinolite, minor calcite, and traces of rutile were found
in some samples. The most common rock texture is hypidiomorphic-
granular, but the coarse-grained rocks tend to be xenomorphic-granular.

Plagioclase in the coarse-grained granodiorite is unzoned to
weakly zoned soda andesine, whereas the medium-grained rocks contain
progressively zoned crystals with calcic andesine cores and narrow
oligoclase rims. Pervasive saussuritization of the plagioclase is a
characteristic feature observed in all thin sections. Locally, the
plagioclase is replaced by fresh "chessboard" albite which, in turn,
is partly replaced by orthoclase. Extensive alteration of the plagioclase
to alkali feldspar was observed only in samples from the granodiorite in Sections 21, 22, and 23.

Quartz, all of which is slightly strained, occurs both as
vermicular intergrowths with feldspar and as irregular granular
aggregates. Orthoclase most commonly occurs intergrown with quartz,
but it also forms irregular replacement patches within plagioclase.
Hornblende appears to have been the only mafic mineral originally
present in the granodiorite, but it is now largely replaced by dark
brown to green biotite. Locally, both mafic minerals are replaced by
chlorite, and the hornblende by epidote. In extensively albitized
samples, biotite is not present and the hornblende is completely
replaced by actinolite.
These granodiorite bodies are the oldest plutonic rocks exposed in the Ryan Canyon area. From contact relations, the age can be bracketed as younger than the Gold Range Formation and older than the quartz monzonite porphyry dikes and the Ryan Canyon stock. This evidence places the time of intrusion within the interval from Early Jurassic to Late Cretaceous. Although there is no direct evidence to more closely establish the age of the granodiorite, dating of the major plutonic activity in west-central Nevada (Evernden and Kistler, 1970) suggests that it is at least Early Cretaceous age.

Biotite quartz monzonite and related porphyry intrusions (Cretaceous)

Part of a small biotite quartz monzonite stock is exposed in the extreme northwest portion of the mapped area. This intrusion is a massive, light-gray, medium-grained rock that exhibits a slight porphyritic texture near the margin. In thin section, the quartz monzonite consists of quartz (32%), andesine (35%), potassic feldspar (22%), and biotite (9%). Magnetite, apatite, sphene, zircon, and allanite are common accessory minerals that occur with secondary epidote and traces of calcite and sericite. In general, the rock exhibits a hypidiomorphic-seriate texture.

Plagioclase forms subhedral crystals that are weakly zoned with compositions ranging from about An35 at the core to about An30 at the rim. Slightly more calcic plagioclases were noted from the porphyritic margin of the stock with compositions as high as An42. Moderate to weak saussuritization of the plagioclase crystals is common, and a few grains are partly replaced by a more sodic plagioclase, particu-
larly along late quartz veinlets. The potassic feldspar is predominantly perthitic orthoclase, although microcline is present. Quartz is characteristically strained and usually occurs as anhedral grains interstitial to the feldspars. The biotite is dark brown and mostly fresh, but locally, it is replaced by pennine. Late magmatic biotite together with fine aggregates of quartz and magnetite often form pseudomorphs after hornblende.

Small, irregular bodies and tabular dikes of quartz monzonite porphyry occur scattered along the base of the Gillis Range in the southern portion of the mapped area. Since these rocks are mineralogically and chemically similar to the biotite quartz monzonite, they are considered to be either finer-grained equivalents of the main stock or closely related igneous bodies. In thin section, the quartz monzonite porphyry consists of sodic oligoclase and rare quartz phenocrysts in a matrix of granophyric quartz and alkali feldspar. The oligoclase phenocrysts are weakly saussuritized and partly replaced by orthoclase plus quartz. Hornblende is replaced by biotite which, in turn, is extensively chloritized. Magnetite, apatite, sphene, and zircon occur as accessory minerals. Secondary minerals are epidote, calcite, chlorite, rutile, and sericite that are products of weak hydrothermal alteration associated with occasional late quartz-calcite veinlets.

The age of the biotite quartz monzonite is not precisely known, but crosscutting relations indicate that it is younger than both the Gold Range Formation and granodiorite. At the present erosional level,
the quartz monzonite is not in contact with the Late Cretaceous leucogranite pluton exposed in the Ryan Canyon area. However, faults that cut the quartz monzonite porphyry bodies terminate against the leucogranite pluton, indicating that the latter igneous body is younger. This evidence, in conjunction with regional dating of plutonic activity, suggests an Early Cretaceous age for the biotite quartz monzonite stock and related porphyry intrusions.

Leucogranite (Upper Cretaceous)

Leucogranite crops out along the western margin of the mapped area and in the central portion of Section 8. These outcrops mark the western terminus of a large pluton that extends for nine miles along the crest of the Gillis Range. Typically, the leucogranite is a massive, light-pink, medium- to coarse-grained rock that forms prominent bouldery outcrops and hummocky grus slopes. In hand specimen, this rock exhibits pink orthoclase crystals up to 10 mm., but more commonly less than 5 mm., in the largest dimension together with quartz and subordinate white plagioclase. Finer-grained but mineralogically identical rocks occur in Sections 22 and 27. These smaller intrusions undoubtedly are aplitic equivalents of the leucogranite. Pink orthoclase and the almost total absence of mafic minerals serve to distinguish the leucogranite from other granitic rocks in the Ryan Canyon area.

In thin section, the leucogranite consists of perthitic orthoclase (49%), oligoclase (15%), quartz (35%), and biotite plus hornblende (1%). Sphene, magnetite, apatite, and zircon occur as accessory
minerals together with traces of epidote, sericite, and hematite. The rock texture is hypidiomorphic-seriate, although in some samples it approaches equigranular. Formerly, this rock unit was termed albite granite (Ross, 1961), but it should be more properly classified as leucogranite.

The orthoclase forms large subhedral Carlsbad-twinned crystals that have exsolved to microperthite in which the potassic feldspar lamellae have inverted partly to microcline and the albite lamellae remain untwinned. Quartz and plagioclase occur interstitial to the orthoclase. The quartz is strained and often contains poikilitic inclusions of feldspar or accessory minerals. The plagioclase is weakly zoned oligoclase that exhibits albite and, rarely, pericline twinning. The zoning is progressive, and the core to rim composition difference rarely exceeds $An_5$. Most of these grains are fresh, but occasionally the cores are weakly replaced by epidote and sericite. Dark-brown biotite and green hornblende occur together in the rock, but biotite is greatly predominant. Both minerals, often, are partly replaced by pennine.

K-Ar age dates published by Evernden and Kistler (1970) indicate that the leucogranite at Ryan Canyon is Late Cretaceous (89.1 to 90.2 m.y. - no standard deviation is given). This intrusion was found only in contact with the Triassic metamorphic rocks and the Ryan Canyon stock. Crosscutting relations clearly indicate that the leucogranite is younger than the former but older than the latter. In addition, structural evidence indicates that it is younger than the biotite quartz monzonite and related porphyry rocks that are exposed.
in the western portion of the mapped area.

Ryan Canyon quartz monzonite porphyry (Late Cretaceous)

A small quartz monzonite porphyry stock crops out in approximately the center of the mapped area. This stock is elongate in a northwest-southeast direction and has maximum exposed dimensions of about 4 miles by ½ mile. The extreme southeast end, which is not shown on Plate 1, extends approximately 2,000 feet beyond the present mapped area where it narrows and terminates against the leucogranite pluton. The exposed intrusion occurs as irregular, discontinuous bodies that are thought to interconnect at depth. In part, the discontinuous nature is due to displacement along post-intrusion faults. Related dikes and other smaller intrusive masses, identical in composition, are exposed for some distance on either side of the main stock. Although quartz monzonite porphyry is the principal rock type, porphyritic quartz latite and porphyritic rhyolite are present. The former occurs as a chilled marginal facies of the main stock, while the latter forms a small satellitic body lying to the north. The stock and related satellitic bodies have been termed the Ryan Canyon quartz monzonite porphyry in this report.

In outcrop, the quartz monzonite porphyry is a well-fractured porphyritic rock that contains plagioclase and minor quartz phenocrysts set in a dense, aphanitic matrix. Locally, country rock xenoliths and lithic fragments are abundant in the intrusion, particularly near the intrusive margin. Pyrite is ubiquitous to the rock, occurring as disseminated euhedral crystals in the groundmass. By volume, the pyrite
content ranges from $1\frac{1}{2}$ to 3 percent, but averages about 2 percent. On fresh surfaces, the rock is light-gray to white, however weathered samples are a distinct reddish brown due to the oxidation of pyrite. Throughout much of the exposed intrusion, including many of the satellitic bodies, the original mineralogy and textures have been modified or obliterated by late magmatic autometamorphism and subsequent hydrothermal and suprategene alteration. The mineralogy, textures, and alteration are described in a later portion of this report under "Petrography of the Ryan Canyon Stock".

The Ryan Canyon stock intrudes rocks of the Gold Range and Luning Formations, as well as the granodiorite, biotite quartz monzonite, and leucogranite. Contacts with the country rock are discordant, and tend to be sharp and irregular with vertical to steep inward dips. Drilling near the southeast end indicates that the intrusion narrows at depth, possibly narrowing to a dike-like mass. Along the contact, flow structures are locally well developed and in one area the contact is brecciated (Figure 2). Strong fracturing within the stock appears to be entirely random and is interpreted as fragmentation produced by cooling and contraction of the stock. There is no stockwork veining associated with the fractures.

During the present study, a K-Ar age of 89.2 ± 3.4 m.y. (Late Cretaceous) was obtained from an altered sample of the Ryan Canyon quartz monzonite porphyry. The date was determined for muscovite separated from an unweathered sample. This age is virtually identical to the age determined for the leucogranite; however, field evidence demonstrates that the Ryan Canyon intrusion is younger, i.e. fragments
FIGURE 2. Contact breccia exposed along the northwest margin of the Ryan Canyon stock in the W § Section 5.
of the leucogranite were observed in the quartz monzonite porphyry. The close proximity in time and space of these two intrusions strongly suggests that they are genetically related.

Older alluvial gravels (Miocene)

Five small areas of older gravels occur near the crest of the Gillis Range. Two such areas are overlain by small hornblende dacite flows. These deposits were delimited on the geology map, but they were not examined in detail. It was noted, however, that cobbles of leucogranite are abundant in the gravels and that the northernmost exposure contains boulders of ash-flow tuff. These gravels are out of topographic accord with the present basin levels and appear to be remnants of an older alluvial surface that formed before the range reached its present elevation. Correlation of these gravels with the inception of Basin and Range faulting and with volcanic rocks of known age indicates a Miocene age for the gravel deposits.

Hornblende dacite (Miocene)

Small flows and feeder dikes of hornblende dacite are exposed in the northern portion of the mapped area. Although the phenocryst mineralogy suggests that the rock is an andesite, chemical data indicate that it is intermediate in composition between andesite and dacite (Table 2, Sample 4-5). These extrusive rocks are composed of euhedral hornblende phenocrysts (5%), plagioclase (23%), magnetite (4%), hematite (2%), and traces of apatite in a groundmass of glass and plagioclase (?) microlites. The plagioclase crystals, which exhibit
a continuous size range up to \( \frac{1}{2} \text{ cm} \), in length, are progressively zoned labradorite with andesine rims. The rock texture is pilotaxitic. A few partly resorbed lithic fragments were noted in the rock, but it does not appear to be extensively contaminated.

Flows of the hornblende dacite were found to overlie patches of older alluvium that locally contain cobbles of welded tuff. These cobbles were presumably derived from ash-flow sheets in the northern Gillis Range or the Gabbs Valley Range that have been dated as late Oligocene to early Miocene (23 and 22 m.y., M. L. Silberman, unpublished data). At Ryan Canyon, the hornblende dacite flows postdate the inception of Basin and Range faulting which started about 15 to 17 m.y. ago in the west-central Great Basin (Noble, 1972). Therefore, they must be post-early Miocene and, probably, are middle or late Miocene age. These flows are comparable in age with other andesite flows in west-central Nevada that have been isotopically dated as Miocene (D. C. Noble, personal communication).

Andesite porphyry dikes of uncertain age

Andesite porphyry dikes are locally abundant cutting the granodiorite near the mouth of Ryan Canyon; only a few are shown on the geologic map. These dikes have intruded northwest trending fractures that parallel some of the Basin and Range faults. Most are only a few feet wide, but they can be as wide as 100 feet. These dikes consist of glomeroporphyritic andesine crystals in a pilotaxitic groundmass of sodic andesine or oligoclase with interstitial magnetite, hornblende and/or biotite, and minor quartz. Epidote occurs as an
abundant secondary mineral, particularly replacing hornblende. The age of the andesite porphyry dikes could not be determined except to note that they postdate the granodiorite intrusion.

Olivine basalt (Quaternary)

Vesicular olivine basalt crops out as isolated exposures aligned in a west-northwest direction near the mouth of Ryan Canyon. One specimen contained olivine phenocrysts in a hyalopilitic groundmass composed of calcic labradorite, olivine, and augite with interstitial glass. The glass contains numerous microlites and is dusted with opaque minerals and hematite. An approximate modal composition of the basalt is 50% plagioclase, 10% olivine, 10% augite, and 30% groundmass. These basalt outcrops appear to be a single flow that is interbedded with recent alluvial fans, suggesting a Quaternary age.

Younger alluvium (Quaternary)

A wide variety of sedimentary deposits were mapped together as younger alluvium. These include unconsolidated talus, conglomerate, gravel, and sand which form recent alluvial fans, talus slopes, terrace gravels, and arroyo deposits. The detrital material was entirely derived from local sources. No fossils were obtained to date these sediments, but a Quaternary age is indicated by their obvious connection with current processes of erosion and deposition.

Geologic Structure

The major structural features in the Ryan Canyon area are high-
angle normal faults of Mesozoic to Recent age; some appear to have significant lateral displacement. Arcuate shaped faults, generally convex to the east, are the oldest recognized structures, although most of these faults can be shown to have been involved in later periods of movement. Younger, approximately east-west trending range front faults are associated with recent uplift of the Gillis Range. As noted earlier, no evidence was found to support the contention that a major thrust fault separates rocks of the Gold Range and Luning Formations (Ferguson and Muller, 1949), at least in the Ryan Canyon area.

The most prominent faults are shown on the geologic map as the Ryan Canyon fault system and the Alpha and Beta faults. These faults show evidence of more than one episode of movement; the earliest apparent movement postdates the biotite quartz monzonite intrusion but predates the leucogranite intrusion. Hydrothermal solutions were channelled through the fractures subsequent to the earliest movement, producing pervasive argillic alteration and silicification. These faults were active again either during or prior to intrusion of the Ryan Canyon stock, since the previously altered rocks were brecciated and then intruded by dikes and small apophyses of the Ryan Canyon quartz monzonite porphyry. Later movement occurred only along the Ryan Canyon fault system, which transects the Ryan Canyon stock in the east half of Section 9, followed by intrusion of hornblende dacite dikes along the fault zone. Based on geometric relations and known rock ages, these arcuate faults were periodically active from Late Cretaceous through Miocene. Other less prominent faults and several secondary
structures may have been active during this same period.

The youngest faults in the area are the east-west trending range front faults that border the steep south flank of the Gillis Range. These structures form subparallel fault zones, most of which are covered by alluvial outwash from the range, that displace the valley several thousand feet down relative to the adjacent range. In places, recent alluvial deposits have been juxtaposed against Cretaceous and older rocks. Subsidiary faults related to the major structures trend approximately north-south and are exposed across recent alluvial fans near the mouth of Ryan Canyon. These faults appear to be caused by the flexure in the range front faults where they cross Ryan Canyon. The fact that many of the fault scarps are still evident in recent alluvial fans suggests that faulting and uplift are still active along the range front.

Other workers (Ferguson and Muller, 1949; Nielsen, 1964) found that Mesozoic rocks in nearby areas were deformed by folding and local thrust faulting during Jurassic orogenesis that preceded intrusion of the granitic rocks. There is insufficient data from the present study to indicate whether the metamorphic rocks of the Ryan Canyon area were affected by this regional deformation. It was noted, however, that rocks of the Luning and Gold Range Formations are strongly deformed near contacts with younger plutonic rocks. This deformation is mostly in the form of isoclinal folding and local fracturing along the igneous and metamorphic rock contacts. These structural features were produced by forceful intrusion of the igneous rocks into the surrounding wall rocks.
Several types of rock alteration are present in the Ryan Canyon area; these have been broadly grouped into six facies that can be recognized in the field. Two types, andalusite hornfels and quartz-muscovite alteration, are confined almost exclusively to the Ryan Canyon stock, and therefore, are discussed in detail under the section "Petrography of the Ryan Canyon Stock". Propylitic alteration is widespread throughout the mapped area and is so ubiquitous in the older rocks that it was not mapped. Silicification and argillitic alteration are significant, since they are closely associated with mineralization. These two alteration facies grade one into the other and are not entirely separable. The last alteration type, sericitic alteration, is unique in that it occurs with the andalusite and corundum deposits located at the base of the Gillis Range.

Propylitic alteration is described first because it is the most widespread, although not necessarily the earliest, alteration type. Generally, it is observed as quartz-epidote veins or as epidote clots in the Gold Range Formation as well as in the biotite quartz monzonite and granodiorite igneous rocks. Although most plagioclase-bearing rocks show some evidence of propylitic alteration, it is most strongly developed adjacent to quartz-epidote-chlorite veinlets. In thin section, plagioclase is partly replaced by epidote and sericite, biotite is chloritized, and hornblende is replaced by chlorite plus epidote. Calcite may be present in minor amounts, usually associated with quartz veinlets. Locally, sulfur has been introduced in the form
of pyrite that occurs within veinlets and disseminated sparingly through the rock. In all cases, the bulk chemistry of the rock appears to be relatively unchanged, although the mineralogy has changed to reflect weak hydrogen metasomatism (Meyer and Hemley, 1967). The age of propylitization does not appear to be everywhere the same, and there was probably more than one period of alteration.

Argillic alteration and silification are more restricted in areal extent and occur primarily along major fault zones in the central mapped area. As in the case of the propylitic alteration, silification and argillic alteration probably were not confined to a single hydrothermal event, although the major alteration pulse appears to have occurred within the interval between intrusion of the biotite quartz monzonite and leucogranite plutons. These two alteration types, which are gradational one into the other, represent hydrolytic leaching (Hemley and Jones, 1964) of differing intensities. Outward from the solution channelway, the rock passes from a quartz-sericite through a kaolinite-sericite alteration assemblage into fresh rock. Complete leaching of the alkali metals and calcium leads to an altered rock composed essentially of kaolinite plus quartz; with removal of even alumina, only quartz remains. In the Ryan Canyon area, these altered rocks are usually refractured or brecciated and contain late quartz and/or carbonate (calcite and dolomite) veins. Weak metallization, consisting of pyrite, chalcopyrite, and galena, is often associated with the veins. Locally, the earlier rock alteration is lacking and only the late quartz and carbonate veins are present as fracture fillings.
Intense sericitic alteration associated with shear zones occurs in the SE\(^2\) Section 22 and NE\(^2\) Section 27. A unique feature of this alteration facies is the presence of andalusite, corundum, diaspor, and pyrophyllite in the more intensely altered rocks. Locally, andalusite and corundum are sufficiently abundant to form mineable deposits. Samples that were examined during the present investigation show progressive alteration within the shear zones from cataclastically deformed metavolcanic rocks to an altered rock consisting of andalusite plus quartz with accessory rutile. Further alteration leads to the breakdown of andalusite and formation of corundum, diaspor, and pyrophyllite. Wall rocks adjacent to these shear zones have been altered to biotite-cordierite-quartz hornfels, and locally, the metavolcanic rocks are extensively replaced by quartz and tourmaline. Only the areas of sericitic alteration are shown on the geologic map.

A more detailed alteration study of this area was not attempted because a thesis dealing with the andalusite and corundum deposits in Section 27 is available (Klinger, 1952) and the interested reader is referred to that report.

Mineralization

Mineralization in the Ryan Canyon area is restricted to quartz fissure veins in the Gold Range Formation, the biotite quartz monzonite, and the granodiorite. Since the quartz veins do not extend into the Ryan Canyon stock or the leucogranite pluton, it is thought that the mineralization predates these intrusions. Published reports
(Vanderberg, 1937; Ross, 1961) indicate that the larger veins were prospected for precious metals; however, there has been no recorded production from this area. A list of minerals that have been identified in the fissure veins is given in Table 1. Of these minerals, quartz is the most abundant gangue mineral and chalcopyrite, the principal ore mineral. The only other metallic minerals noted were galena, pyrite, hematite, and rare native gold and cinnabar. In most veins, the sulfide minerals have been thoroughly oxidised to a depth of several feet and are replaced by a variety of secondary minerals, the most prevalent being hisingerite, hematite, malachite, and chrysocolla. Commonly observed gangue minerals, other than quartz, are calcite, garnet, and chlorite.

The extensive pyrite mineralization observed in the Ryan Canyon stock is not accompanied by economic mineralization. Field evidence indicates that the pyrite formed through sulfurization without introduction of ore metals. This fact is readily apparent from surface geochemical samples (see Figure 3) and drill core assays (see Plates 2, 3, and 4). Locally anomalous copper mineralization, usually observed as oxide copper staining, represents remobilization of copper from the wall rocks into the stock at the time of intrusion. The absence of economic mineralization associated with pyrite is a significant feature of this particular intrusion.

Geologic History

From regional studies, it has been reasonably established that
<table>
<thead>
<tr>
<th>Table 1. Minerals identified in the vein deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gangue minerals:</strong></td>
</tr>
<tr>
<td>Quartz</td>
</tr>
<tr>
<td>Calcite</td>
</tr>
<tr>
<td>Chlorite</td>
</tr>
<tr>
<td>Andradite</td>
</tr>
<tr>
<td>Grossularite</td>
</tr>
<tr>
<td>Hematite</td>
</tr>
<tr>
<td>Most abundant; present in all veins</td>
</tr>
<tr>
<td>Present in many veins</td>
</tr>
<tr>
<td>Locally abundant in a few veins</td>
</tr>
<tr>
<td>Minor</td>
</tr>
<tr>
<td><strong>Hypogene ore minerals:</strong></td>
</tr>
<tr>
<td>Chalcopryte</td>
</tr>
<tr>
<td>Pyrite</td>
</tr>
<tr>
<td>Galena</td>
</tr>
<tr>
<td>Native gold</td>
</tr>
<tr>
<td>Cinnabar</td>
</tr>
<tr>
<td>Abundant in all mineralized veins</td>
</tr>
<tr>
<td>Present in minor amounts</td>
</tr>
<tr>
<td>Extremely rare</td>
</tr>
<tr>
<td><strong>Supergene minerals:</strong></td>
</tr>
<tr>
<td>&quot;Limonite&quot;</td>
</tr>
<tr>
<td>Bornite</td>
</tr>
<tr>
<td>Hisingerite</td>
</tr>
<tr>
<td>Chrysocolla</td>
</tr>
<tr>
<td>Malachite</td>
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<tr>
<td>Anglesite</td>
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<tr>
<td>Cerussite</td>
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<tr>
<td>Mnorite</td>
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<tr>
<td>Azurite</td>
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<tr>
<td>Jarosite</td>
</tr>
<tr>
<td>Calcite</td>
</tr>
<tr>
<td>Chalcedony</td>
</tr>
<tr>
<td>Mottramite</td>
</tr>
<tr>
<td>Erichalcite</td>
</tr>
<tr>
<td>Common assemblage in oxide zone</td>
</tr>
<tr>
<td>Minor</td>
</tr>
<tr>
<td>Fracture coatings</td>
</tr>
<tr>
<td>Rare</td>
</tr>
</tbody>
</table>
FIGURES 3. Geochemical data from surface samples of the Ryan Canyon quartz monzonite porphyry and adjacent rocks (compiled from various sources).

ppm Cu  ppm Mo
<100  <50
100-200  50-50
>200  >50
the eastern portion of Mineral County, Nevada, was submerged beneath an epicontinental sea during the Triassic and Early Jurassic periods in what is termed the Luning Embayment (Ferguson and Muller, 1969; Nielsen, 1964). During this period, predominantly carbonate rocks were deposited along the eastern margin of the embayment, while the southern portion of the basin received clastic sediments and volcanic rocks from an island arc source to the west and southwest (Stanley et al., 1971). The transition zone between the volcanic and carbonate assemblages occurs in the present Ryan Canyon area where rocks of the two facies interfinger. By at least Early Cretaceous, rocks deposited in the Luning Embayment were emergent, probably in response to uplift that accompanied Jurassic and Cretaceous orogenesis (Silberling and Roberts, 1962). Folds and local thrust faults, which occurred during this orogeny, are evident in early Mesozoic rocks along the southern margin of the Luning Embayment. This deformation may not have extended as far north as the Ryan Canyon area, but if it did, such structures have been obscured by later deformation.

Beginning in Late Jurassic or Early Cretaceous, magmatic activity at Ryan Canyon commenced with intrusion of the quartz diorite and granodiorite rocks. This event was followed by intrusion of other igneous rocks in a magma series that became progressively more felsic with time. The Ryan Canyon quartz monzonite porphyry of Late Cretaceous age was the last intrusion in this series. This plutonic cycle was responsible for the thermal metamorphism and recurrent deformation that are evident in the early Mesozoic rocks. Widespread hydrothermal alteration and quartz veining that are related to this igneous activity
appear to have occurred during the time span between intrusion of the biotite quartz monzonite and leucogranite plutons. A younger alteration stage that is characterized by the andalusite-bearing mineral assemblage accompanied intrusion of the Ryan Canyon stock; this alteration is confined almost exclusively to the stock. There is insufficient data to determine the original thickness of cover over the presently exposed intrusive rocks at Ryan Canyon; however, Nielsen (1964) estimated that the maximum cover over exposed plutons in the Pilot Mountains was about 2.5 km, based on stratigraphic reconstructions. This estimate probably can be considered valid for the Ryan Canyon area as well.

High-angle faulting started 15 to 17 m.y. ago in the Basin and Range Province (Noble, 1972), and uplift in the Ryan Canyon area probably began at the same time. Contemporaneous with faulting, calc-alkaline and basaltic rocks were erupted in west-central Nevada. In the mapped area, this volcanic activity is reflected by andesite dikes and small hornblende dacite and olivine basalt flows that ascended along high-angle faults. As uplift progressed, alluvial material derived from the ancestral Gillis Range accumulated in the adjacent valleys and in topographic depressions within the range. Recent fault scarps along the range front and active erosion of older alluvial deposits indicate that faulting and uplift are continuing processes in the Ryan Canyon area.
Unaltered Quartz Monzonite Porphyry

Unaltered rocks from the Ryan Canyon intrusion are restricted in areal extent and are not typical of the main intrusive body. Relatively unaltered samples that were examined in thin section were obtained from the extreme northwest extension of the intrusion, principally along the north and northeast margins in Section 5. In this area, the magma was quenched against adjoining wall rocks, forming a chilled marginal facies that varies from a few feet to over two hundred feet in thickness. The rock is porphyritic quartz latite, but grades to quartz monzonite porphyry away from the contact. Within the chilled zone, flow structures are locally well developed, and in the W½ Section 5, the contact is brecciated. Axiolithic structures and micrographic groundmass textures, which were observed in thin section (Figure 4), indicate that these quenched rocks were partly glassy during emplacement and, later, were devitrified.

Microscopic examination reveals that rocks from the marginal facies contain euhedral sodic amphibole phenocrysts, occasional embayed beta quartz phenocrysts, and abundant lithic fragments in a microcrystalline matrix of quartz and feldspar. Biotite occurs as anhedral flakes scattered through the matrix and as aggregates with magnetite that are pseudomorphous after hornblende. Pyrite, magnetite, zircon, and muscovite are common accessory minerals together with minor rutile, apatite, and allanite. Jarosite, hematite, sericite, and rare chlorite
and epidote occur as secondary minerals.

Pyrite, which is ubiquitous in the Ryan Canyon quartz monzonite porphyry, occurs as disseminated euhedral grains that, often, are enclosed in aggregates of muscovite plus quartz. The apparent lack of replacement textures in these rocks, as well as other indirect evidence, indicates that the pyrite was synmagmatic in origin and was not introduced during a later hydrothermal event. In all of the samples that were examined, magnetite coexists with pyrite, occasionally forming intergrowths with the pyrite. Although the relative proportion of these two minerals varies, the combined content remains relatively constant between one and two percent. The fact that both minerals occur together indicates that the oxygen and sulfur fugacities in this portion of the stock were maintained near the univariant curve for the magnetite-pyrite equilibrium reaction.

Lithic fragments are abundant constituents in these rocks, with local concentrations approaching 25 volume percent. Wall rock inclusions predominate adjacent to the contact, but cognate xenoliths become relatively more abundant away from the contact. Strained and embayed alpha quartz fragments, which were observed in some samples, are allothetic crystals that are locally abundant and they are difficult to distinguish from the authigenic beta quartz phenocrysts. Within this zone, there is a general tendency for the lithic fragments to increase in abundance away from the contact, then reach a maximum and decrease. In comparison, rocks from the typical quartz monzonite porphyry contain few lithic fragments. Probably, cognate inclusions in the chilled zone were produced by movement of the magma after the
margin solidified, causing autobrecciation along the contact. The foreign inclusions were derived from the intruded wall rocks.

Although rocks from the chilled marginal zone appear fresh in hand specimen, they are not entirely unaffected by the alteration observed throughout the intrusion. Some plagioclase phenocrysts are partly replaced by clots of muscovite and quartz that formed during late magmatic crystallization. Quartz microveinlets, which contain albite, orthoclase, and muscovite (Figures 4 and 5) or biotite and magnetite, are approximately the same age. These veinlets are sparingly distributed through the chilled rocks and rarely exceed a few centimeters in length. Feeble replacement of plagioclase by sericite and epidote and of biotite by chlorite occurred slightly later, probably during deuteric alteration. There is no evidence in any samples for major chemical changes of the rocks due to late hydrothermal alteration.

As noted above, the marginal facies rocks, present in the northwest portion of the intrusion, grade to quartz monzonite porphyry away from the contact. This transition is marked by a regular change in the groundmass grain size, indicating a difference in cooling rate between the marginal porphyritic quartz latite rocks and the main quartz monzonite body. The mineralogy of both rock types is essentially the same, but there is a distinct difference in grain size. Hand samples of the quartz monzonite porphyry are light-gray to white on fresh surfaces, but weathered samples are dark maroon to reddish brown from oxidation of pyrite. The well developed porphyritic texture is not readily detectable except under close inspection, which reveals small
FIGURE 4. Photomicrographs showing well developed flow structures and "quenched" groundmass texture in the marginal chilled facies of the Ryan Canyon quartz monzonite porphyry. Micro-veinlets at the right margin formed during late magmatic crystallization. Lithic fragment (L), biotite and magnetite pseudomorph after hornblende (h), biotite (b). A, plane polarized light; B, crossed nicols.
FIGURE 5. Photomicrograph of quartz veinlet showing local concentration of albite. Albite (a), quartz (q). Crossed nicols.
plagioclase phenocrysts uniformly distributed through an aphanitic matrix. The most distinctive feature of this rock is the abundance of disseminated pyrite without visible stockwork veining.

A typical sample of quartz monzonite porphyry contains subhedral sodic andesine (15%) and embayed beta quartz (2%) phenocrysts in an equigranular groundmass containing quartz (33%), orthoclase (21%), plagioclase (17%), and biotite (5%). Accessory minerals, in order of decreasing abundance, are pyrite, muscovite, magnetite, rutile, apatite, and zircon. These minerals occur together with sericite and chlorite alteration products. Weathered samples contain jarosite and hematite, which form pseudomorphs after pyrite and coatings along fractures. The rock has a porphyritic texture with plagioclase phenocrysts as large as 5 mm, but averaging 2 mm, in a slightly granophyric groundmass (Figure 6).

The andesine phenocrysts are weakly zoned with a core to rim composition difference of about An2. They are present as either individual crystals or cumulophytic clusters. The groundmass plagioclase is unzoned and slightly more sodic in composition. Some phenocryst crystals are partly replaced by irregular patches of orthoclase or albite and occasional muscovite and quartz clots. Locally, the calcic feldspars are feebly sericitized as a result of late hydrothermal alteration.

Biotite occurs as small anhedral flakes in the groundmass and as coarse-grained, scalloped aggregates. Fresh crystals are pleochroic with $X = \text{light green to } Z = Y = \text{moderate reddish brown}$. Chloritization of biotite is common, and in more altered samples, biotite is replaced
FIGURE 6. Photomicrographs of relatively unaltered Ryan Canyon quartz monzonite porphyry showing the typical porphyritic texture. Biotite aggregate in upper right is completely replaced by sericite, fine rutile, and allophane. Jarosite occurs as pseudomorphs after pyrite and as fracture fillings. Plagioclase (p), sericite (s), jarosite (j), allophane (a). A, plane polarized light; B, crossed nicols.
by sericite with fine rutile distributed along the former cleavage planes. Magnetite, which is a minor constituent in the quartz monzonite facies, occurs in the biotite aggregates together with traces of zircon and corroded apatite.

Pyrite is considerably more abundant in these rocks than in the marginal facies and locally reaches three percent by volume. It is present as euhedral crystals in the groundmass and it, also, selectively replaces magnetite. Again, the pyrite appears to have formed during crystallization of the magma. The fact that pyrite was noted in rare healed quartz microveinlets indicates that iron and sulfur were mobile elements during late stages of magmatic crystallization.

A small satellitic intrusion, located ½ mile north of Section 4, appears to be genetically related to the Ryan Canyon intrusion, although it differs significantly in chemical composition. In outcrop it is a dense, aphanitic rock that weathers to a dull reddish brown color due to oxidation of sparse pyrite grains. Small feldspar crystals, biotite clusters, opaque minerals, and lithic fragments are present in the matrix. Flow structures are locally evident along the contact.

Microscopic examination reveals anhedral feldspar phenocrysts, as large as 3 mm. long, but averaging 1 mm., and small lithic fragments in a fine-grained groundmass of predominantly quartz, orthoclase, and oligoclase. The feldspar phenocrysts were originally calcic plagioclase, but have been replaced by albite which, in turn, is partly altered to orthoclase. The latter mineral forms patches
and perthitic intergrowths in the plagioclase. All of the phenocryst feldspars now have sutured borders. Biotite is present as small shredded flakes and as aggregates that are pseudomorphs after hornblende(?). Magnetite, apatite, rutile, zircon, sphene, and pyrite are minor accessory minerals. Chlorite and sericite are sparingly present as secondary minerals replacing biotite and plagioclase, respectively. The overall rock texture is porphyritic, but near the contact, devitrification textures were noted in quartz-orthoclase bands. Apparently, the margin was partly glassy at the time of intrusion, comparable to the marginal facies of the Ryan Canyon intrusion.

Field and petrographic work clearly demonstrate that this intrusion is younger than the leucogranite, and it is thought to be equivalent in age to the main Ryan Canyon intrusion. Textural and mineralogical similarities, particularly the occurrence of accessory pyrite, support the belief that the two intrusions are genetically related. Consequently, this unit was mapped as part of the Ryan Canyon quartz monzonite porphyry intrusion. Chemical data, however, indicate that this satellitic body is an alkali rhyolite (Table 2, Sample 33-J0) rather than quartz latite, as might be expected. The difference in composition, as compared with the Ryan Canyon quartz monzonite porphyry, is readily explained by the abundance of alkali feldspar phenocrysts rather than by any differences in the groundmass mineralogy, which appears to be identical. This point is significant in interpreting the origin of the Ryan Canyon intrusion and is discussed in a later portion of this report.
Alteration in the Ryan Canyon Stock

The original composition and textures of a major portion of the Ryan Canyon intrusion have been modified by late magmatic autometamorphism\(^1\). The resultant rocks comprise two major alteration facies that are characterized by quartz-muscovite and andalusite-orthoclase-quartz alteration products; both contain pyrite. The latter alteration assemblage represents the more advanced stage inasmuch as the original rock textures and minerals are completely destroyed. These two facies are gradational one into the other, and therefore, were divided in the field by the presence or absence of andalusite. Locally, late stage sericitization, represented by fine-grained muscovite, is superimposed on the above mineral assemblages, while weathering and supergene alteration have affected all of the exposed portions of the Ryan Canyon stock to some degree.

Typical samples containing the andalusite-orthoclase-quartz alteration assemblage (henceforth termed the andalusite hornfels facies rocks) predominantly consist of quartz (50%), orthoclase (30%), and andalusite (15%). Pyrite, rutile, and muscovite are common accessory minerals, while tourmaline and fibrolite were noted in some samples. These rocks have crystallized to a hornfels that commonly exhibits weak foliation parallel to the intrusive contacts. In outcrop, the hornfels appears fine-grained and equigranular, but actually is seriate

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1. The term autometamorphism, as used in this report, refers to a specific alteration process that is distinct from either deuteric or hydrothermal alteration.
textured with a locally well-developed polygonal quartz groundmass (Figure 7). The fact that wall rock inclusions observed along the intrusion margin are not recrystallized or altered suggests that the hornfels texture is a primary igneous feature and was not derived through a later metamorphic or hydrothermal event. Rare protoclastic textures observed in thin section support this conclusion, since post-magmatic recrystallization or alteration would have obliterated such features.

Microscopic examination reveals that quartz occurs as polygonal, often inclusion filled, groundmass crystals or as poikilitic inclusions in orthoclase and andalusite. Orthoclase forms anhedral, intergranular grains or large poikiloblastic crystals which commonly exhibit striations that appear to be submicroscopic exsolution lamellae of sodic feldspar. Pyrite and rutile are present in variable amounts as disseminated euhedral to anhedral grains in all samples of the andalusite hornfels. Rutile is rarely seen except under the microscope, but pyrite forms readily visible crystals up to 2 mm. across. Tourmaline occurs in quartz as rare tiny euhedral needles that may form radiating aggregates. Although muscovite is not a characteristic mineral in this assemblage, it is usually present in trace amounts replacing andalusite. Neither magnetite nor apatite were observed in these rocks.

Fibrolite is a common, but minor, constituent of the andalusite hornfels rocks found within the extreme southeast exposure of the stock. It is most abundant along the contact with the leucogranite where it locally reaches concentrations of one percent. The fibrolite was
FIGURE 7. Photomicrographs of the andalusite hornfels facies showing well developed granoblastic-polygonal texture in the quartz and orthoclase groundmass. High relief grains are poikiloblastic andalusite. Opaque minerals scattered throughout the slide are primarily rutile. A, plane polarized light; B, crossed nicols.
observed coexisting with andalusite (Figure 8), and since neither mineral replaces the other, it is assumed that the andalusite and fibrolite are in equilibrium. This fact places restrictions on the possible temperature of formation of the andalusite-orthoclase-quartz mineral assemblage. The minimum temperature is established at 620°C by the andalusite, sillimanite, and kyanite triple point (Richardson et al., 1969), and the maximum temperature is limited by the upper stability limit of andalusite, which could be as high as 850°C (Figure 9). However, pressure considerations, assuming a 2.5 km depth of cover, place the actual crystallization temperature in the 800°C range.

Based on the study of rocks collected from many localities within the Ryan Canyon stock, the transition from normal quartz monzonite porphyry to the andalusite hornfels rocks is gradational. Andalusite first appears replacing the plagioclase phenocrysts, where it forms irregular clots together with quartz (Figure 10). Incipient crystallization of andalusite is accompanied by destruction of biotite and simultaneous crystallization of rutile and pyrite. Increasing alternation intensity leads to complete replacement of plagioclase by quartz and poikiloblastic andalusite together with the formation of a nearly granoblastic-polygonal textured quartz and microcline groundmass. The appearance of striated orthoclase instead of microcline completes the transition into the typical hornfels rocks described above.

In contrast to the andalusite hornfels facies rocks, rocks of the fibrolite may form as a metastable phase below the sillimanite stability field in metamorphic reactions (Pitcher, 1965), however this possibility seems unlikely under magmatic conditions.
FIGURE B. Photomicrograph showing sillimanite coexisting with andalusite in a sample from the andalusite hornfels facies of the Ryan Canyon quartz monzonite porphyry. Opaque minerals are rutile. Plane polarized light.
FIGURE 9. Stability fields of andalusite, sillimanite, and kyanite as a function of temperature and pressure (Richardson et al., 1969). Curve II, beginning of melting curve for granite (Tuttle and Bowen, 1958); curve III, upper stability of muscovite plus quartz (Day, 1971); curve IV, upper stability of muscovite (Velde, 1966); curve V, upper stability of annite plus quartz (Eugster and Wones, 1962); curve VI, probable upper stability of biotite plus quartz (Turner, 1968).
FIGURE 9

The diagram shows the phase relationships between Kyanite, Sillimanite, and Andalusite as a function of temperature and pressure of water vapor ($P_{H_2O}$).

- **Kyanite** is indicated on the left side of the diagram.
- **Sillimanite** is on the right side.
- **Andalusite** is in the center.

The curves represent different phase transitions, with specific regions labeled I, II, III, IV, V, and VI.

The temperature scale is marked from 400°C to 1000°C on the x-axis, and the pressure scale for water vapor ($P_{H_2O}$) is marked from 0 to 10 Kbars on the y-axis.

The diagram includes notes such as "Granite stability" and "$P_{H_2O} = P_f"."
FIGURE 10. Photomicrographs showing andalusite replacing plagioclase in a sample of the Ryan Canyon quartz monzonite porphyry. Part of the plagioclase phenocryst has been replaced by orthoclase. The high relief mineral is andalusite that is intergrown with quartz and the opaque minerals are pyrite. Note muscovite starting to replace andalusite. A, plane polarized light; B, crossed nicols.
quartz-muscovite facies still exhibit a porphyritic texture inherited from the original quartz monzonite porphyry. On fresh surfaces, these rocks are light pink due to the abundance of groundmass orthoclase and absence of mafic minerals. Characteristic coarse muscovite books are visible throughout the rock. Plagioclase usually stands out as conspicuous white or clouded phenocrysts due to replacement by sericite and montmorillonite, although this alteration is distinctly younger than the quartz-muscovite alteration. Rare muscovite- and pyrite-bearing quartz microveinlets, which were not found in the andalusite hornfels rocks, were noted in some samples.

The quartz-muscovite facies rocks have essentially the same mineralogy as the fresh quartz monzonite porphyry with the exception that they contain coarse muscovite, which was identified as the 2M muscovite polymorph (see Appendix I), and recrystallized quartz. Commonly, the muscovite occurs as subhedral, sutured crystals that average ½ mm. across, intergrown with quartz and pyrite (Figure 11). The quartz forms crystalloblastic aggregates, authimorphic groundmass crystals, and irregular shaped megacrysts. These textural features, together with an increase in modal quartz, indicate widespread redistribution of silica. Two other minerals that were noted are barite\(^1\) and rare, small tourmaline needles.

Modal compositions of these rocks vary with alteration intensity, but in general, there is an increase in muscovite, quartz,

\(^{1}\) It should be noted that the celesian molecule liberated during destruction of the alkali feldspars will react with sulfur to form the relatively insoluble sulfate species, barite, in a sulfur-bearing system.
FIGURE 11. Photomicrographs showing coarse muscovite intergrown with quartz and pyrite. The opaque minerals are pyrite and the highly birefringent minerals are muscovite. The large clouded phenocryst is plagioclase that has been weakly replaced by montmorillonite. A, plane polarized light; B, crossed nicols.
FIGURE 11
pyrite, and rutile at the expense of biotite, plagioclase, and orthoclase. During progressive alteration of the quartz monzonite porphyry, biotite is selectively replaced by muscovite and pyrite. Titanium released during alteration of the biotite crystallizes first as fine rutile distributed along mica cleavage planes, but later recrystallizes to coarse, anhedral rutile. The destruction of biotite is usually accompanied by local recrystallization of the groundmass minerals. Continued muscovitization results in replacement of plagioclase and orthoclase, and ultimately leads to a rock containing only quartz and muscovite as the major mineral phases. The absence of apatite in these altered rocks suggests that it is unstable in this environment and that phosphate was removed from the system early in the alteration sequence.

As noted above, the quartz-muscovite facies rocks locally grade into rocks of the andalusite hornfels facies. Within the transition zone, muscovite selectively replaces andalusite. It first appears as rims on the andalusite, and eventually forms pseudomorphs after the andalusite. If plagioclase is present, it is replaced slightly later in the sequence, followed by replacement of orthoclase in the groundmass.

Late stage sericitization has further modified large areas of the Ryan Canyon stock, particularly those parts that are strongly fractured. Rocks from both the quartz-muscovite and andalusite hornfels facies, as well as the fresh quartz monzonite porphyry, seem to be equally affected. Quartz and sericite are essential minerals of this late stage alteration, which is characterized by extensive recry-
stallization or, in some places, complete destruction of the original rock. Montmorillonite, which replaces plagioclase, is a minor constituent of this assemblage. Commonly, sericite is observed replacing andalusite, orthoclase, or plagioclase to varying degrees and is accompanied by an increase in the amount of groundmass quartz (Figure 12). More thoroughly altered samples consist of embayed quartz phenocrysts and euhedral pyrite crystals in a recrystallized, fine-grained matrix of quartz and sericite; however, even the most strongly altered rocks retain ghost textures from the original rock. The resultant mineral assemblage is easily distinguished from earlier alteration products by the fine-grained nature of the quartz and sericite, as well as their obvious replacement of earlier formed minerals. Identification of the sericite as 2M muscovite (see Appendix I) indicates that it formed at temperatures in excess of 200°C (Yoder and Eugster, 1955). Since petrographic evidence indicates that the sericite is younger than the coarse muscovite, it is assumed to be a product of lower temperature hydrothermal alteration.

Weathering and supergene alteration have affected all of the exposed portions of the Ryan Canyon stock to some degree. The most obvious effect is oxidation of pyrite, which leads to crystallization of jarosite and hematite as pseudomorphs after pyrite and as coatings on fractures. In addition, jarosite replaces muscovite and orthoclase adjacent to pyrite grains. The strong leaching action of acidic meteoric solutions has produced kaolinite and allophane in the near surface rocks; the latter selectively replaces andalusite and muscovite. No other clay minerals were identified, although numerous
FIGURE 12. Photomicrographs showing late stage sericitization in the Ryan Canyon quartz monzonite porphyry. Sericite partly replaces poikiloblastic andalusite. The groundmass consists of sericite and fine-grained, recrystallized quartz. Dark patches are supergene jarosite. A, plane polarized light; B, crossed nicols.
samples were examined by X-ray diffraction. Gypsum is the only other abundant supergene mineral in the weathering zone, where it forms coatings on fracture surfaces and large crystals in crushed zones. In general, the prevailing arid climatic conditions and rapid erosion rate have confined the weathering and supergene alteration to within a few tens of feet from the surface.

Alteration Zonation

The distribution and configuration of quartz-muscovite and andalusite hornfels alteration facies, which are confined to the Ryan Canyon quartz monzonite porphyry rocks, are shown on Plate 1. In detail, the alteration pattern is extremely irregular, but in gross aspect, it shows a definite asymmetric zonation. From northwest to southeast within the Ryan Canyon stock, the relatively fresh quartz monzonite porphyry passes to an altered rock of the quartz-muscovite facies, and then to rocks of the andalusite hornfels facies. A similar trend was noted in the satelliteic bodies where the alteration, in general, changes from weak quartz-muscovite to advanced andalusite hornfels alteration toward the southwest end of the main intrusive body. It is emphasized that these changes are gradational, and that facies boundaries mapped in the field were delimited by recognition of coarse muscovite or andalusite.

The transition from relatively fresh rocks to altered rocks of the hornfels facies represents an increase in alteration intensity toward the southeast. The andalusite hornfels facies is the highest
temperature and most intense alteration zone, as evidenced by the complete destruction of the original rock mineralogy and textures, as well as the crystallization of fibrolite. Although there is nearly a 1,000 feet elevation difference between the extreme southeast and northwest exposures of the intrusion, geologic evidence does not support the hypothesis that the alteration change reflects vertical zoning within the stock.

The alteration zoning observed in the field is reflected by variations of the pyrite to magnetite ratio. As noted previously, rocks of the andalusite hornfels facies contain only pyrite, whereas magnetite predominates in the relatively fresh quartz monzonite porphyry. Where both minerals occur together, magnetite commonly rims the pyrite crystals. This change in relative abundance of the two minerals indicates that the sulfur activity was not uniform throughout the intrusion. The demonstrative change in the pyrite to magnetite ratio suggests a strong correlation between sulfur activity and alteration within the intrusion, and in fact, the alteration zoning appears to be dependent on the availability of sulfur.

PETROCHEMISTRY

Chemical and normative data for samples of the Ryan Canyon quartz monzonite porphyry are presented in Table 3. These data show a systematic change in chemical composition from the quartz-muscovite to andalusite hornfels facies. The most striking chemical differences appear in the alkali and calcium oxide percentages. Both calcium
### TABLE 2. Chemical data for unaltered rocks in the Ryan Canyon area

<table>
<thead>
<tr>
<th>Sample</th>
<th>21-1</th>
<th>32-2</th>
<th>17-2</th>
<th>16-1</th>
<th>3-3</th>
<th>33-4</th>
<th>4-3</th>
<th>23-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minerals</td>
<td>Chemical analyses (weight percent)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SiO₂</td>
<td>Al₂O₃</td>
<td>Fe₂O₃</td>
<td>MgO</td>
<td>CaO</td>
<td>Na₂O</td>
<td>K₂O</td>
<td>H₂O+</td>
</tr>
<tr>
<td>Granodiorite; NW 21 mile north of Section 21</td>
<td>53.7</td>
<td>14.5</td>
<td>8.1</td>
<td>3.9</td>
<td>3.0</td>
<td>3.0</td>
<td>4.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Biotite quartz monzonite; NE 7/8 Section 17</td>
<td>71.1</td>
<td>14.3</td>
<td>2.9</td>
<td>0.9</td>
<td>0.7</td>
<td>3.7</td>
<td>4.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Quartz monzonite porphyry; SE 7/8 Section 17</td>
<td>72.1</td>
<td>13.0</td>
<td>2.4</td>
<td>0.6</td>
<td>0.6</td>
<td>4.8</td>
<td>4.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Biotite quartz monzonite; NE 7/8 Section 16</td>
<td>76.2</td>
<td>13.3</td>
<td>1.7</td>
<td>0.4</td>
<td>0.7</td>
<td>3.7</td>
<td>4.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Leucogranite; NE 7/8 Section 3</td>
<td>77.9</td>
<td>11.6</td>
<td>0.5</td>
<td>0.1</td>
<td>0.2</td>
<td>3.8</td>
<td>4.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Rhyolite (equivalent to the Ryan Canyon intrusion); NE 7/8 Section 4</td>
<td>77.7</td>
<td>11.3</td>
<td>0.4</td>
<td>0.0</td>
<td>0.1</td>
<td>3.7</td>
<td>4.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Hornblende dacite; NE 7/8 Section 4</td>
<td>76.2</td>
<td>13.3</td>
<td>1.7</td>
<td>0.2</td>
<td>0.6</td>
<td>4.6</td>
<td>5.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Andesite flow from the Gold Range Formation; SW 7/8 Section 23</td>
<td>62.1</td>
<td>15.3</td>
<td>4.5</td>
<td>1.6</td>
<td>5.0</td>
<td>3.9</td>
<td>2.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

CIW norms

- **Q**: 11.7 26.6 24.8 33.2 34.9 35.1 17.0 14.9
- **or**: 27.5 29.0 26.0 26.5 28.5 23.5 16.0 3.0
- **ab**: 28.5 32.0 43.5 33.5 35.0 39.5 37.0 24.5
- **an**: 13.3 3.5 1.5 3.0 0.5 18.5 27.0
- **wo**: 0.8 0.6 0.6 0.7 0.4 0.2 0.1 0.0
- **en**: 11.2 2.6 1.6 1.0 0.2 0.2 4.6 17.2
- **mt**: 5.3 2.1 1.5 1.1 0.5 2.8 5.7
- **il**: 1.6 0.2 0.4 0.4 0.2 0.2 1.0 1.4
- **ac**: 0.8
- **py**: 0.1 0.1
- **C**: 1.9 1.3

21-1 Granodiorite; NW 21 mile north of Section 21
32-2 Biotite quartz monzonite; 7/8 mile north of Section 5
17-2 Quartz monzonite porphyry; SE 7/8 Section 17
16-1 Biotite quartz monzonite; NE 7/8 Section 16
3-3 Leucogranite; NE 7/8 Section 3
33-4 Rhyolite (equivalent to the Ryan Canyon intrusion); 7/8 mile north of Section 4
4-3 Hornblende dacite; NE 7/8 Section 4
23-1 Andesite flow from the Gold Range Formation; SW 7/8 Section 23
### TABLE 3. Chemical data for the Ryan Canyon quartz monzonite porphyry

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical analyses (weight percent)</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SiO₂</td>
<td>69.2</td>
<td>69.6</td>
<td>68.3</td>
<td>74.1</td>
<td>75.8</td>
<td>79.4</td>
<td>75.9</td>
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<tr>
<td>Al₂O₃</td>
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<td>13.8</td>
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<td>14.0</td>
<td>14.2</td>
<td>13.4</td>
<td>14.1</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.7</td>
<td>0.7</td>
<td>0.3</td>
<td>0.7</td>
<td>0.0</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>MgO</td>
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<td>1.3</td>
<td>0.2</td>
<td>0.7</td>
<td>0.3</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>CaO</td>
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<td>1.4</td>
<td>1.4</td>
<td>0.6</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Na₂O</td>
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<td>3.7</td>
<td>3.0</td>
<td>2.0</td>
<td>2.1</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>K₂O</td>
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<td>3.7</td>
<td>3.2</td>
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<td>4.0</td>
</tr>
<tr>
<td>H₂O</td>
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<td>1.2</td>
<td>0.8</td>
<td>1.4</td>
<td>1.4</td>
<td>1.9</td>
<td>0.8</td>
</tr>
<tr>
<td>TiO₂</td>
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<td>0.6</td>
<td>0.3</td>
<td>0.0</td>
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<td>0.8</td>
</tr>
<tr>
<td>MnO</td>
<td>0.1</td>
<td>0.1</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.9</td>
<td>4.3</td>
<td>6.6</td>
<td>0.3</td>
<td>1.9</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100.5</td>
<td>99.7</td>
<td>98.9</td>
<td>98.2</td>
<td>101.1</td>
<td>100.5</td>
<td>100.7</td>
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</tbody>
</table>

**Density (grams per cubic centimeter)**

<table>
<thead>
<tr>
<th></th>
<th>2.633</th>
<th>2.691</th>
<th>2.659</th>
<th>2.647</th>
<th>2.686</th>
<th>2.702</th>
<th>2.655</th>
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</table>

**CIPW norms**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Q</th>
<th>a</th>
<th>or</th>
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<th>an</th>
<th>wo</th>
<th>en</th>
<th>mt</th>
<th>ru</th>
<th>py</th>
<th>C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>23.6</td>
<td>31.1</td>
<td>30.7</td>
<td>39.9</td>
<td>40.0</td>
<td>60.3</td>
<td>55.2</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Notes:**

1. The presence of iron in excess of Fe₂O₃ is due to oxidation of pyrite.

---

15-38 Quartz-muscovite facies; NW Section 15
5-6 Quartz-muscovite facies; NW Section 5
9-13 Quartz-muscovite facies; NW Section 9
15-37 Transitional between quartz-muscovite and andalusite hornfels facies; NW Section 15
9-47 Transitional between quartz-muscovite and andalusite hornfels facies; NW Section 9
9-37 Andalusite hornfels facies; NW Section 9
14-2 Andalusite hornfels facies; NW Section 14
and sodium show a marked decrease in absolute abundance, while potassium shows a relative increase as alteration progresses from the quartz-muscovite to the andalusite hornfels facies. This trend is illustrated in Figure 13, which is a CaO-Na₂O-K₂O variation diagram. Further comparison of the chemistry for the major alteration facies reveals a definite change in the ferric iron content as is inferred from the presence of iron in excess of that required to form ferrous sulfide. These changes are reflected in the calculated norms, particularly in the normative corundum content.

Chemical gains and losses for the altered quartz monzonite porphyry have been calculated based on the assumption that the rhyolite, Sample 33-4, represents the original magma composition before hybridization (see "Origin of the Ryan Canyon Stock"). These data are summarized in Table 4. Although the chemical changes can be surmised directly from the weight percent analyses, they are more readily seen as atomic proportions per unit volume. This conversion presumes that alteration proceeded without appreciable changes in rock volume; an assumption that appears justified for samples of the Ryan Canyon intrusion because the alteration is synmagmatic in origin.

Inspection of the gain-loss data indicates that the original rock composition, presumed to be rhyolite, was modified by addition of the elements calcium, aluminum, iron, and sulfur. During subsequent alteration of this rock to an andalusite hornfels, both calcium and sodium were strongly depleted, while potassium, sulfur, and iron appear to have remained relatively constant. Changes in the silica content can be attributed to relative changes caused by the increase or
FIGURE 13. CaO-Na₂O-K₂O variation diagram for altered samples of the Ryan Canyon quartz monzonite porphyry. Sample descriptions are given in Table 3.
TABLE 4. Major chemical gains and losses per 1,000 cc of rock for samples of the Ryan Canyon intrusion

<table>
<thead>
<tr>
<th>Sample 2</th>
<th>Al</th>
<th>Si</th>
<th>Ti</th>
<th>Fe$^{+2}$</th>
<th>Mn$^{+2}$</th>
<th>Mg$^{+2}$</th>
<th>Ca$^{+2}$</th>
<th>Na$^+$</th>
<th>K$^+$</th>
<th>H$_2$O</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Gram-atoms</td>
<td></td>
<td></td>
<td>Gram-equivalents</td>
<td></td>
<td></td>
<td></td>
<td>Moles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-38</td>
<td>1.43</td>
<td>-4.09</td>
<td>0.06</td>
<td>1.24</td>
<td>1.42</td>
<td>0.52</td>
<td>2.54</td>
<td>-1.14</td>
<td>-1.21</td>
<td>1.76</td>
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<tr>
<td>5-6</td>
<td>1.49</td>
<td>-2.93</td>
<td>0.10</td>
<td>1.91</td>
<td>2.10</td>
<td>0.66</td>
<td>1.61</td>
<td>1.74</td>
<td>-0.58</td>
<td>1.85</td>
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<tr>
<td>9-13</td>
<td>1.56</td>
<td>-3.66</td>
<td>0.13</td>
<td>2.92</td>
<td>2.84</td>
<td>-0.02</td>
<td>0.13</td>
<td>0.75</td>
<td>-0.41</td>
<td>0.60</td>
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<tr>
<td>15-37</td>
<td>1.56</td>
<td>-0.97</td>
<td>0.01</td>
<td>0.10</td>
<td>-0.07</td>
<td>-0.01</td>
<td>0.24</td>
<td>1.09</td>
<td>-1.52</td>
<td>-0.06</td>
</tr>
<tr>
<td>9-47</td>
<td>1.53</td>
<td>0.81</td>
<td>-0.07</td>
<td>0.31</td>
<td>0.56</td>
<td>-0.02</td>
<td>0.27</td>
<td>0.10</td>
<td>-1.81</td>
<td>0.59</td>
</tr>
<tr>
<td>9-37</td>
<td>1.29</td>
<td>1.29</td>
<td>0.07</td>
<td>0.09</td>
<td>0.25</td>
<td>-0.03</td>
<td>0.54</td>
<td>-0.28</td>
<td>-3.42</td>
<td>-0.10</td>
</tr>
<tr>
<td>14-2</td>
<td>1.44</td>
<td>-0.96</td>
<td>0.20</td>
<td>1.74</td>
<td>1.83</td>
<td>0.00</td>
<td>-0.13</td>
<td>-0.19</td>
<td>-3.56</td>
<td>0.03</td>
</tr>
</tbody>
</table>

1Chemical gains and losses were calculated assuming that the unaltered rock was a rhyolite; represented by Sample 33-5.
2Sample descriptions are given in Tables 1 and 2.
decrease of other elements, as well as redistribution of silica during the alteration process. Minor variations observed in the rock chemistry may be due either to analytical error, inhomogeneities within the Ryan Canyon intrusion, or both.

DISCUSSION AND CONCLUSIONS

Origin of the Ryan Canyon Stock

Plutonic rocks exposed in the Ryan Canyon area are interpreted as a magma series ranging in composition from granodiorite to rhyolite. This supposition is supported by comparison of the chemical data, which show a well defined and systematic variation between rock types. Table 2 presents chemical analyses of the unaltered rocks from the mapped area, and Figures 14 and 15 summarize the major-element data in variation diagrams. The common major-element oxides plotted against differentiation index, defined as normative quartz plus orthoclase plus albite (Thornton and Tuttle, 1960), indicate that successively younger plutonic rocks are progressively more felsic in composition (Figure 14). A similar trend is shown on the ACF variation diagram (Figure 15). This compositional variation can most reasonably be attributed to fractional crystallization of a common source magma and periodic intrusion of the residual melt (Presnall and Bateman, 1973).

The youngest igneous rock in this series is a rhyolite that is nearly identical in composition to the leucogranite, but is equivalent
FIGURE 14. Weight percentage of common oxides plotted against differentiation index for unaltered plutonic rocks exposed in the Ryan Canyon area. Differentiation index is defined as normative quartz plus orthoclase plus albite.
Figure 14

Differentiation Index $\Sigma(Q+Ab+Or)$
FIGURE 15. ACP variation diagram for unaltered plutonic rocks exposed in the Ryan Canyon area. Altered rocks from the Ryan Canyon quartz monzonite porphyry are superimposed. Sample descriptions are given in Tables 2 and 3.
in age to the Ryan Canyon quartz monzonite porphyry. Textural and mineralogical similarities, particularly the accessory pyrite, suggest that the rhyolite and quartz monzonite porphyry are genetically related, and possibly, are variants of the same intrusion. Therefore, any explanation for the origin of the Ryan Canyon stock must take into consideration the physical, chemical, and mineralogical relationships between these two rock types, as well as the spatial and coeval association of the quartz monzonite porphyry with younger plutonic rocks in the area.

Given the above restrictions, the most feasible method for generating a quartz monzonite from a highly differentiated felsic magma is by hybridization. The geologic model favored by the author involves fractional crystallization of a parent magma and periodic intrusion of the residual melt producing the granodiorite to rhyolite magma series observed in the Ryan Canyon area. Near the end of the plutonic cycle, physical mixing of the lighter, highly differentiated rhyolitic fraction with the more mafic cumulus portion of the magma would produce a hybrid magma of approximate quartz monzonite composition. This process requires addition of aluminum and calcium in the form of plagioclase to a silicate melt of rhyolitic composition. Since iron and sulfur normally are enriched in the cumulus fraction of a magma, physical mixing would explain the presence of these two elements in the hybrid magma. Subsequent intrusion of the quartz monzonite magma to higher levels would result in crystallization of an andalusite-orthoclase-quartz-pyrite mineral assemblage if the sulfur activity of the system was high. Such a mechanism for deriving
the Ryan Canyon intrusion is geologically reasonable and it would explain many peculiarities of this rock, particularly the high sulfur content.

**Alteration Processes**

Petrographic and geologic evidence demonstrates that the hornfelsic texture observed in the Ryan Canyon intrusion is a primary igneous feature and is not derived from a later metamorphic or hydrothermal event. This fact necessitates a synmagmatic origin for the andalusite, quartz, and orthoclase mineral assemblage; such an origin is supported by the inferred high temperature of crystallization required to stabilize both andalusite and fibrolite. Since these rocks are depleted in both sodium and calcium without evidence of late hydrothermal alteration, the loss must be related to alteration processes active prior to or during final consolidation of the magma. Furthermore, the absence of hydrous phases in the assemblage suggests that the andalusite hornfels rocks crystallized in a water undersaturated system.

The processes required to generate andalusite in a magmatic environment, and at the same time deplete the system of sodium and calcium, can be explained by the presence of sulfur in the system. From experimental work (Appendix II), it is known that large sulfur activities render plagioclase unstable at high temperatures in the presence of aqueous chloride solutions; plagioclase breaks down to form anhydrite and a different aluminous phase. Given sufficient
time, and under the proper experimental conditions, it is reasonable to expect that plagioclase will break down to form anhydrite or thenardite and andalusite provided that excess sulfur is present. The pertinent reactions are:

\[
\begin{align*}
4\text{NaAlSi}_3\text{O}_8 + \text{S}_2 + 3\text{O}_2 &\rightarrow 2\text{Na}_2\text{SO}_4 + 2\text{Al}_2\text{Si}_3\text{O}_5 + 10\text{SO}_2 \\
2\text{CaAl}_2\text{Si}_2\text{O}_5 + \text{S}_2 + 3\text{O}_2 &\rightarrow 2\text{CaSO}_4 + 2\text{Al}_2\text{Si}_3\text{O}_5 + 2\text{SO}_2
\end{align*}
\]

When both alkali and calcic feldspars occur together, relative sulfur affinities of the cations, Ca > Na > K, dictate that plagioclase will be the least stable feldspar phase. Extrapolation of these data to a magmatic environment suggests that in a sulfur saturated and water undersaturated magma, such as the Ryan Canyon stock, equilibrium reactions of sodium and calcium between the silicate and sulfate phases will result in the destruction of plagioclase. Whether or not orthoclase will remain stable depends on the prevailing sulfur and oxygen fugacities (Figure 16). Under these conditions, alumina released by the breakdown of plagioclase will crystallize as an aluminum silicate phase, either andalusite or sillimanite.

Furthermore, biotite and magnetite are unstable in a high sulfur environment such that pyrite will crystallize as the principal iron-bearing mineral. This fact can be readily demonstrated in the laboratory (Hammarback and Lindqvist, 1972). In the presence of sulfur, biotite and magnetite are destroyed, at least at high temperatures.

1. Although andalusite did not form in the reconnaissance experiments conducted by the author, Shade (1974) and Henley et al. (1971) have demonstrated that andalusite can form at high temperatures during the destruction of feldspar provided that the cation/H⁺ activity ratio is low.
FIGURE 16. Calculated stability relations for the end member feldspar minerals at 1,000°C and 1 bar in the presence of sulfur. The stability fields for stable iron phases are superimposed. Data are plotted as a function of log $f_{S_2}$ and log $f_{O_2}$. 
The destruction of clinopyroxene increases the water fugacity in the system, and this may promote anorthite dissolution, which in turn affects the paragenetic sequence and crystallization processes. The presence of water in the system can also influence the reaction paths and the stability of minerals. Additional water can lead to the formation of secondary minerals, such as chlorite, which can alter the paragenetic sequence and crystal assemblages.

**Figure 16**

- **Microcline + S = K$_2$SO$_4$ + Al$_2$SiO$_5$ + SiO$_2$**
- **Albite + S = Na$_2$SO$_4$ + Al$_2$SiO$_5$ + SiO$_2$**
- **Anorthite + S = CaSO$_4$ + Al$_2$SiO$_5$ + SiO$_2$**

The diagram illustrates the reaction paths and the stability fields of different minerals under varying water fugacity conditions. The coordinates on the axes represent the log of the water fugacity ($f_w$) and the log of the sulfur fugacity ($f_S$). The reactions and stability fields are indicated by the labeled points and lines on the graph.
through the net reactions:

\[
\begin{align*}
\text{Fe}_3\text{O}_4 + \text{KFe}_3\text{Al}_3\text{O}_{10} (\text{OH})_2 \cdot 6\text{S}_2 & \rightarrow \text{KAlSi}_3\text{O}_8 + 6\text{FeS}_2 + \text{H}_2\text{O} + \text{I}_2 \\
\text{Fe}_3\text{O}_4 + \text{KFe}_3\text{Al}_3\text{O}_{10} (\text{OH})_2 \cdot 12\text{H}_2\text{O} & \rightarrow \text{KAlSi}_3\text{O}_8 + 6\text{FeS}_2 + 12\text{H}_2\text{O} + \text{H}_2
\end{align*}
\]

The destruction of biotite increases the water fugacity in the system, and halogens substituting for \(\text{OH}^-\) in the biotite structure are released to the fluid phase.

Petrographic and laboratory investigations support the hypothesis that the aminalsite hornfels facies of the Ryan Canyon quartz monzonite porphyry developed by autometamorphism during late stage crystallization of the magma. The probable sequence of events involved contemporaneous intrusion and crystallization. A water undersaturated, sulfur-bearing magma of approximate quartz monzonite composition could be expected to undergo crystallization during its ascent toward the surface. The combined effects of crystallization and decreasing pressure would tend to increase the sulfur fugacity to the point that sulfur would react with biotite in the melt to form pyrite. Additional water and halogens released to the system by the destruction of biotite, in conjunction with the high sulfur fugacity, would be sufficient to initiate autometamorphism within the partly consolidated magma. The subsequent reactions would result in destruction of plagioclase and partitioning of calcium and sodium to the fluid phase. Since the sulfurization reactions are exothermic, it is expected that sufficient heat would be released to locally increase the magma temperature.

Intrusion of the magma to a sufficiently high level within the earth's crust would produce pressure quenching if the intrusion passed from a lithostatic into a hydrostatic pressure environment. The
abrupt pressure decrease would allow a portion of the volatile phases to escape from the system, causing crystallization of the magma. Final consolidation of the melt would yield a hornfels textured rock consisting of quartz, orthoclase, andalusite, and pyrite. If a chemical gradient existed within the magma, possibly caused by the slow diffusion rate of sulfur, the resultant rock mineralogy would be expected to change in the direction of decreasing sulfur activity to a normal quartz monzonite porphyry. The fact that barite, but not anhydrite or thenardite, was observed in the andalusite hornfels rocks can be attributed to the relatively high solubilities of the latter two minerals. Normally, they would be removed during late stage crystallization by evolution of the fluid phase from the system.

As the stock cooled below the solidus temperature, it would enter the stability field of muscovite. At this time, the intrusion would suffer deuteric alteration if an aqueous chloride solution was present in the system. In the event that the solution $\mathrm{K^+/H^+}$ activity ratio was small, orthoclase would become unstable and react to form muscovite (Figure 17). The pertinent reaction is:

$$3\text{KAlSi}_3\text{O}_8 + \text{H}^+ \rightarrow \text{KAl}_3\text{Si}_3\text{O}_10(\text{OH})_2 + 6\text{SiO}_2 + 2\text{K}^+$$

If the $\mathrm{Ca^{2+}/H^+}$ and $\mathrm{Na^{+}/H^+}$ activity ratios were small, surviving plagioclase would be replaced, as well. Calcium and sodium released during alteration of the feldspars would be available to form secondary Ca- and Na-silicates in the wall rocks or the chilled margins of the host intrusion. This mechanism can explain the quartz-albite veins in the chilled marginal rocks and the quartz-muscovite alteration facies of the Ryan Canyon stock, as well as much of the quartz-epidote veining.
FIGURE 17. Reaction curves for the system K$_2$O-Al$_2$O$_3$-SiO$_2$-H$_2$O in an aqueous chloride environment. Analogous curves for the Na- and Ca-bearing systems are superimposed. Data compiled from Shade (1974), Hemley et al. (1971), and Hemley et al. (1981).
FIGURE 17

The diagram shows the stability fields of various minerals such as muscovite, orthoclase, and pyrophyllite. The diagram includes lines for different systems:
- K system
- Na system
- Ca system

Quartz is present, and the total pressure is 1000 bars. The diagram also includes the relationship between m^2 KCl, m^2 NaCl, m CaCl_2, and m^2 HCl.
in the country rocks. The fact that the quartz-muscovite alteration is not uniformly distributed throughout the stock must result from an inhomogeneous distribution of the fluid phase within the system.

Since the quartz-muscovite alteration assemblage is younger than the analusite hornfels alteration assemblage and is related to distribution of the fluid phase within the stock, it might be expected that some overlap of the alteration facies will occur. In the case of the transition zone between the quartz-muscovite and analusite hornfels facies described earlier, muscovite was observed replacing the earlier formed analusite and orthoclase. This reaction is readily explained by Figure 17. Below 640°C, analusite and orthoclase are incompatible phases in the presence of an aqueous chloride solution; consequently, analusite must react to form muscovite (Reaction 6). Potassium is supplied to the reaction by destruction of orthoclase (Reaction 5).

\[
3\text{Al}_2\text{Si}_3\text{O}_9 + 3\text{SiO}_2 + 3\text{H}_2\text{O} + 2\text{K}^+ \rightarrow 2\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + 2\text{H}^+ \quad (6)
\]

The degree to which muscovite replaces analusite plus orthoclase will depend on the availability of the fluid phase and the presence of both reactants.

Late sericitization observed in the intrusion is believed to be a classic example of hydrogen metasomatism as defined by Hemley and Jones (1964). This type of hydrothermal alteration involves exchange of hydrogen ions for potassium, sodium, and calcium in silicate minerals. In the proposed model for the Ryan Canyon stock, the necessary water is derived from the country rocks by convection. Large solution volumes are not required; however, the cation/\(\text{H}^+\) activity ratio must remain below the permissible limits for feldspar.
stability (lower temperature region of Figure 17). The resultant alteration assemblage consists principally of quartz, sericite, and montmorillonite.

Significance of Sulfur

In the proposed alteration model, autometamorphism occurred during late stage crystallization of the magma under conditions of high sulfur fugacity. The resultant chemical reactions involved consumption of first biotite and then plagioclase, accompanied by the formation of pyrite as well as sodium and calcium sulfates. Since plagioclase and biotite were unstable in this environment, the system contained excess alumina that combined with silica to form either andalusite or sillimanite. At the prevailing high temperatures, recrystallization of the stock to the new andalusite-bearing mineral assemblage destroyed the original igneous textures and produced the characteristic hornfelsic texture observed in portions of the Ryan Canyon stock. A high sulfur activity within the system is required to initiate the chemical reactions that lead to excess alumina and ultimately crystallization of andalusite in the intrusion. The significant role of sulfur in the formation of andalusite under magmatic conditions, as in the Ryan Canyon stock, is supported by the petrographic and experimental data presented in this paper.
REFERENCES

Barosh, Patrick James, 1960, Beaver Lake Mountains, Beaver County, Utah — their geology and ore deposits: Utah Geol. Mineralog. Survey Bull. 65, 89 p.


APPENDIX I

X-ray Powder Data for Muscovites

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Refined cell constants:
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\[ b = 9.87 \]
\[ c = 5.06 \]
\[ \beta = 93.9^\circ \]
Coarse Muscovite (Sample 15-39)

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Refined cell constants:

- $a = 5.211$
- $b = 9.008$
- $c = 20.018$
- $\beta = 95.81^\circ$

1. Interference by quartz was observed.
APPENDIX II

Results from High Temperature - High Pressure Experiments
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1. WMP = wüstit-magnetite-pyrrhotite, MPR = magnetite-pyrrhotite-pyrite, MHP = magnetite-hematite-pyrite, and MPP = magnetite-pyrrhotite-iron.

2. Brackets indicate separated charges. K-spar = adularia, ann = annite, qtz = quartz, and = andalusite, plag = plagioclase, mag = magnetite, py = pyrite, S = sulfur, and Fe = iron.
0-65  
Rye Canyon quartz monzonite porphyry. Altered to quartz-methacrylate-amphibolite breccia with muscovite. Rock contains epidote, clay, pyrite altered to 
gorceite, and minor chloritoid biotite.

65-140  
Gold Range Formation (?). Contains biotite, green, and minor magnetite. 
Biotite content clines are noted between 130° and 170°.

180-666  
Rye Canyon quartz monzonite porphyry. Weakly chloritized with disseminated 
magnetite and pyrite, secondary biotite, and rare chalcopyrite. Locally 
fractured with clay and late gypsum wedges. Pyrite content %, locally to 2%. 
Occasional healed quartz relics with secondary biotite, magnetite, 
and chalcopyrite.

Below 630' textural change to porphyrite quartz latite accompanied by 
an increase in muscovite which replaces biotite.

* Petrographic sample

No data

Contact

Fault