

APLITES AND PEGMATITES IN CERTAIN PRODUCTIVE
AND BARREN NORTH AMERICAN LARAMIDE
AND MID-TERTIARY INTRUSIONS

by

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SIGNED: Osman Abdel Wahab

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ABSTRACT

Investigations of the structure, texture, and mineral and chemical composition of 62 aplite and pegmatite samples from eight Laramide and one mid-Tertiary intrusions are reported. Four intrusions known to be genetically related to porphyry copper deposits include the Boulder batholith at Butte, Montana, the Patagonia and Sierrita intrusions in Arizona, and the Santa Rita stock, New Mexico and are classified as productive. The Amole, Swisshelm, Texas Canyon, and Whetstone stocks, Arizona, are not known to be genetically related to porphyry copper deposits and are classified as barren. The Troy stock, Arizona, which is presently being investigated by several companies, was included to evaluate its mineral potential and is consequently not included in either of the preceding classes.

Results of these investigations indicate a strong difference in abundance of dikes in productive and barren intrusions. The former contain thinner and fewer dikes per line mile mapped. Individual aplite dikes are texturally, mineralogically, and chemically homogeneous, and this homogeneity holds for large numbers of dikes from a single intrusion. An inverse relationship exists between modal K-feldspar and plagioclase and also between normative orthoclase and albite. Dikes from productive intrusions always have high K-feldspar-low plagioclase contents, a trend agreeing with the high potassium content of K-feldspar in dikes from productive intrusions. Fe, Ca, K, and Cu are high in the dikes from productive intrusions, but only Fe and K are high in the

K-feldspar. A higher P_{H_2O} is indicated for dikes from productive intrusions, except those from Texas Canyon, suggesting that productive intrusions crystallized at greater depth.

Continuity of these dikes from the host intrusion into the surrounding country rocks and textural, mineralogical, and chemical homogeneity of aplite dikes from a single intrusion strongly suggest a magmatic origin for the studied dikes. Scarce thin dikes are believed to be due to the passive intrusive nature of productive stocks, whereas abundant thick dikes developed in forcefully intruded barren stocks. A fracture filled by water-saturated residual magma generated a pegmatite dike upon slow crystallization. Where more fractures form, creating a sudden pressure drop, volatiles escape from the potential pegmatite dike, leaving behind a viscous melt which upon crystallization yields aplite. Formation of many nucleation centers and the slow growth of crystals result in homogeneous, fine-grained, xenomorphic granular aplites. Pegmatites form within the aplite if the entire water-rich melt is not pressure quenched to aplite.

It is proposed that aplites and pegmatites in productive intrusions develop from a residual melt, which coexists with a chloride-rich aqueous phase before injection. Potassium, sodium, calcium, iron, and base metals prefer this chloride-rich aqueous phase. At temperatures below 880°C , potassium and calcium were found to partition preferentially into the melt and sodium into the aqueous phase. A silicate melt coexisting with a base metal-enriched aqueous phase should be enriched in the base metals.

Aplite-pegmatite dike population may well be a useful exploration tool in well-exposed plutons. The aplite-alkali index and the ratio of K-feldspar to plagioclase in aplites and pegmatites appear to have the greatest potential as porphyry copper prospecting tools, particularly in poorly exposed or remote plutons.

CHAPTER 1

INTRODUCTION

The derivation of magmatic aplites and pegmatites from water-saturated residual magmas proposed by early workers (Derry, 1931; Andersen, 1931; and Emmons, 1940) has been confirmed by contemporary workers (Jahns, 1955; Jahns and Tuttle, 1963; Burnham, 1967; Krauskopf, 1967; Fournier, 1968; and Jahns and Burnham, 1969). Similarly, it was also believed by these and others that a hydrothermal solution can be derived by "second boiling" in a hydrous magma which attains supersaturation with respect to water and other volatiles in response to reduction in confining pressure, crystallization of anhydrous minerals, or some combination of these factors. It has also been advocated and generally accepted that the metallic components of ore deposits can be derived from a magma and transported to their present location by hydrothermal solutions (Holland, 1972). A close genetic relationship between hydrothermal solutions on one hand and aplite and pegmatite on the other has been suggested by many workers (Bowen, 1933; Ross, 1933; Lutton, 1959; and Krauskopf, 1967). The common association of certain metallic ore deposits with specific igneous rocks (Buddington, 1933, and Wilson, 1953) argues for the derivation of these metals from the same magma that produced the spatially and temporally related igneous rocks. This concept is also supported by the common tendency for igneous rocks to be enriched in the same metals that occur

in spatially and temporally associated ore deposits (Slawson and Nackowski, 1959; Parry and Nackowski, 1963; Putnam and Burnham, 1963; and Wahab, 1968).

If the genetic relationship of aplites and pegmatites to hydrothermal solutions be accepted, the study of the physical and chemical characteristics of these rocks in productive and barren intrusions should be both explorationally and scientifically rewarding in terms of locating new natural resources and in better understanding the processes and environments linking aplites and pegmatites to the hydrothermal solutions.

Within the context of this paper, aplite is defined as intrusive, xenomorphic, sucrosic, granular rock composed essentially of quartz, potassium feldspar, and alkalic plagioclase with grain size ranging from 0.2 to about 1.0 mm. Pegmatites are here defined as a generally unzoned assemblage of quartz, potassium feldspar, and sodic plagioclase, a mineral composition similar to aplite but decidedly coarser than related aplites, with grain size measuring about 1.5 cm. Complex pegmatite which was observed in one area studied has the same mineral composition as simple pegmatite but is texturally and mineralogically zoned. Aplites and pegmatites always occur as dikes, and the word "dikes" is used in this report virtually interchangeably with the phrase "aprites and pegmatites."

A productive or mineralized intrusion is defined as one which has been found to involve an occurrence which generally fits the description of a porphyry copper deposit (Lowell and Guilbert, 1970) containing commercial amounts of copper and molybdenum sulfides disseminated in the stock and the surrounding host rocks. A nonproductive,

unmineralized, or barren intrusion, in contrast, is one that contains neither commercial sulfides of these metals within it and the surrounding host country rocks nor significant evidence of silicate alteration phenomena.

The possible close genetic relationship between aplites and pegmatites and the ore-carrying solutions is not the only factor involved in selecting these rocks for this research. Aplites, by virtue of their relatively lighter color and resistance to weathering, are both readily distinguishable from their commonly darker colored, generally more badly weathered host rocks (Fig. 1) and relatively fresh samples of end-stage magmatic reaction products. Their resistance to weathering facilitates sample collection.

The objective of this research was to study the geologic occurrence of aplites and pegmatites in certain productive and barren Laramide and mid-Tertiary intrusions (Fig. 2), to evaluate the exploration significance of these dikes, and to investigate the genesis and possible genetic link between igneous intrusions and related hydrothermal ore deposits. This work considers differences in structure, texture, mineralogy, and chemical composition of aplites and pegmatites and tests the proposal that any outstanding variations in these features might provide insight into the environment of formation of these rocks and may ultimately be explorationally useful in the search for porphyry copper deposits.

To accomplish this objective, 62 samples were collected from 8 Laramide stocks and 1 mid-Tertiary intrusion. Attitudes and other structural features of dikes were noted, and the nature of their contacts



Figure 1. Fresh aplite dike in weathered granodiorite, Patagonia stock, Arizona



Figure 2. Location map of areas investigated
Intrusions are not to scale.

with the host rock were studied. Eighty stained thin sections were point counted to 1,000 counts each and studied to determine textural features and mineral compositions. Seven hundred two major and 234 trace elements in bulk rock samples and K-feldspar separates were also analyzed.

Major findings include the presence of scarce thin aplite and pegmatite dikes in the passively intruded productive stocks in contrast to the presence of abundant thicker dikes in barren ones. Aplite dikes are texturally, mineralogically, and chemically homogeneous across the width of a dike and among dikes from a single intrusion. K-feldspar in aplite dikes from productive intrusions dominates plagioclase with a ratio of over 2:1, whereas this ratio is about 1:1 in dikes from barren ones. This fact is supported by the chemically high K:Na in dikes from productive intrusions. The K content in K-feldspar of dikes from productive stocks is higher than that in K-feldspar of dikes from barren ones.

A differentiating magma follows a course in which a hydrothermal solution ultimately forms, or it may follow a second course in which a hydrothermal solution fails to form. The concern of this study primarily is the first course where a hydrothermal solution forms. Major parameters controlling the development of a hydrothermal solution include initial water content of the melt, temperature, pressure, and composition of the melt, and type of minerals crystallizing from the melt.

Burnham and Jahns (1962) found that the solubility of water in a granitic melt increases as the pressure is raised but that it would not exceed 15 percent by weight at temperatures and pressures to be expected in a cooling magma. If the initial water content of a magma is sufficiently high, crystallization of anhydrous silicate minerals and

decrease in pressure may cause this melt to saturate with water. Further drop in pressure causes the magma to supersaturate with water and ultimately boil off, giving a hydrothermal solution.

However, a hydrothermal solution might not evolve even if the initial water content is high. Pressure drop may not be high enough to saturate and supersaturate a given melt. Crystallization of sufficiently high amount of hydrous minerals (Burnham, 1967) may use most of the water, thus preventing saturation of the melt.

When a hydrothermal solution coexisting with a silicate melt forms, almost all of the chloride in the silicate partitions into this aqueous phase (Burnham, 1967; Kilinc and Burnham, 1972; Holland, 1972). If the initial content of Cl^- in the melt is sufficiently high, the hydrothermal solution becomes chloride rich. Alkalies, base metals, ferric iron, and other trace elements that were rejected by crystallizing silicate minerals partition into this chloride-rich hydrothermal solution (Borina, 1963; Helgeson, 1964; Roedder, 1967; Burnham, 1967; Gammon, Borcsik, and Holland, 1969; and Holland, 1972). Silicon and aluminum that remain after crystallization of most of the melt also go into this hydrothermal solution, giving free quartz and aluminum-bearing vein minerals, such as feldspars and sericite.

CHAPTER 2

SAMPLING AND SAMPLE TREATMENT

Sampling

A major sampling objective was to obtain samples sufficiently fresh to be adequately representative of the texture, mineralogy, and chemistry of the aplites and pegmatites in the stocks under consideration. Fresh, unweathered samples of from 5 to 10 pounds trimmed of any weathered rinds were cut from each dike. To assure optimum representation at each site, a continuous sample was collected across the width of each sampled dike. Duplicate chip samples were simultaneously collected from selected dikes for comparison with continuous samples from the same dikes. The two sampling methods are indicated in Table 1 to have given similar chemical results.

At least 5 to 10 samples were selected per stock. A total of 63 samples were collected from 9 Laramide and 1 mid-Tertiary intrusions in Southern Arizona, New Mexico, and Montana (Fig. 2). Four of these intrusions are known to be genetically related to porphyry copper deposits. These include the Boulder batholith, in which the Butte, Montana, copper-molybdenum deposit occurs; the Sierrita intrusion, Arizona, which is spatially and temporally related to the Esperanza and Sierrita porphyry copper deposits; the Patagonia stock, Arizona, which hosts the Red Mountain ore deposit and at least several other small porphyry

Table 1. Comparative chemical analyses of channel versus chip sampling of aplites

Sample No.	Type	Percent by Weight						ppm		
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	Cu	Zn	
Amole	3	channel	78.50	11.99	0.81	0.25	3.25	5.52	17	41
	3	chip	78.50	11.99	0.84	0.25	3.25	5.38	17	38
	6	channel	77.50	12.34	1.40	0.72	2.60	5.90	13	36
	6	chip	78.50	11.82	1.26	0.70	2.77	5.80	13	39
Sierrita	40	channel	77.40	12.25	0.99	0.66	2.70	6.05	18	34
	40	chip	77.49	11.99	0.90	0.80	3.40	5.02	23	34
Santa Rita	51	channel	77.30	12.25	1.18	0.60	2.16	6.80	66	88
	51	chip	77.62	12.10	1.03	0.78	2.30	6.40	66	61
Troy	67	channel	76.26	13.38	0.32	0.65	3.30	6.05	11	33
	67	chip	77.40	12.69	0.28	0.67	3.15	5.75	12	33

copper-like occurrences; and the Santa Rita stock, New Mexico, the source of the Chino porphyry copper deposit.

The four other intrusions studied are not presently known to be genetically associated with any porphyry copper deposit. These include the Amole stock in the Tucson Mountains, the Swisshelm stock east of Elfrida, the Texas Canyon granite in the Little Dragoon Mountains, and the Whetstone stock of the Whetstone Mountains, all in southern Arizona. The Troy granodiorite in the Dripping Spring Mountains of central Arizona, which is presently attracting active exploration, was also studied.

Sample Treatment

One or more thin sections were cut from each sample for petrographic study. Each section was stained to facilitate identification of potassium feldspar and plagioclase (Baily and Stevens, 1960).

Five to 10 pounds of sample were passed through two successive jaw crushers and then through a roller crusher, reducing the sample to 1/8 inch. All crushers were scrupulously pre-cleaned, and discarded aplite samples from the stock for which samples were being prepared were run before the samples used for analyses were crushed. Each sample was halved, with one half stored in reserve and the other half split into a quantity sufficiently small to be further processed by a Pica ball mill. This size fraction was pulverized to 200 mesh in a porcelain Pica ball mill and stored without further treatment for bulk rock chemical analysis. Aluminum contamination from the porcelain Pica mill is negligible; two splits of a sample, one pulverized in a tungsten carbide Pica ball mill and the other in a porcelain Pica ball mill, were within 0.2% Al_2O_3 . The remaining sample fraction was pulverized to -150 mesh

in a Braun steel disc pulverizer, washed well in distilled water to remove fine material, and then dried. This dried material was then sieved and the - 150 + 170 mesh fraction retained from K-feldspar separation. This size fraction proved to be optimal for maximum K-feldspar recovery. Iron from the disc pulverizer, magnetite, and any mafic minerals were removed by a hand magnet and subsequently by a Carpco magnetic separator.

Heavy Liquid Separation

K-feldspar, quartz, and plagioclase were the principal minerals remaining in the samples after magnetic separation. K-feldspar was separated from these by heavy liquid separation. The specific gravity for K-feldspar separation (2.58) was obtained by mixing acetone and acetylene tetrabromide. The K-feldspar separate was thoroughly cleaned with acetone followed by distilled water, then dried. A portion of each sample was stained with sodium cobaltinitrite to determine its purity. Those that contained 95 percent or more K-feldspar were stored for subsequent chemical analysis. Most samples contained 97 percent K-feldspar.

Chemical Analysis

Seven hundred two major and 234 trace element analyses were run on prepared bulk rock and K-feldspar samples. Prepared samples were digested using the lithium metaborate fusion technique (Medlin, Suhr, and Bodkin, 1969) and analyzed on a Perkin-Elmer 403 atomic absorption spectrophotometer. Detailed description of the method, its accuracy and precision is given in Appendix A. However, the standard deviation is less than 1% for Si, less than 1.5% for Al, K, and Na,

and about 4.5% and 3% for Fe and Ca, respectively. Copper and zinc, because of their low concentration in these aplites and pegmatites, show 7% and 11% standard deviation, respectively.

CHAPTER 3

CRYSTAL CHEMISTRY

Because of their geochemical characteristics, some elements are incorporated into the structures of early-formed minerals in a differentiating magma, while other elements are not taken into lattices of developing minerals and are thus concentrated in late magmatic residual liquids. Their passage into various end-stage liquid or gaseous phases is similarly controlled. The behavior and occurrence of major and trace elements in a differentiating magma in general and in the porphyry copper environment in particular cannot be well understood and interpreted without a good grasp of crystal chemical knowledge.

To the extent that rules controlling the behavior of trace and major elements in a crystallizing silicate melt are known, we may develop a predictive model indicating which elements are concentrated at different stages of magmatic differentiation. Goldschmidt (1937) and Ahrens (1953) were among the first to consider crystal chemistry of major and trace elements and their behavior during differentiation of a crystallizing magma. Their work has been refined by the work of Ringwood (1955), Curtis (1964), Nockolds (1966), and Damon (1968).

Ionic Charge and Radius

Goldschmidt (1937) proposed a set of rules which govern the behavior of ions in a silicate melt during magmatic crystallization. When two ions of equal charge are competing for the same lattice site in

a solid crystallizing from a melt, the ion with the smaller radius is preferentially incorporated. Similarly, when two ions of similar radius are competing for sites, the one with the higher charge is preferentially incorporated. However, Goldschmidt's model assumes a totally ionic bond. Since covalent bonding is also important in crystal formation, Goldschmidt's rules are only partly successful.

Electronegativity

Ahrens (1953) and Ringwood (1955) realized deficiencies in Goldschmidt's rules with respect to a covalent component in silicate bonding, the effect of which is an overall decrease of the total bond energy. Electronegativity, which is defined by Pauling (1940) as the power of an atom in a molecule to attract electrons to itself, accounts very well for this bond weakening. Applying electronegativity to explain the behavior of elements during magmatic crystallization, Ringwood (1955) derived the rule that whenever diadochy in a crystal is possible between two elements possessing appreciably different electronegativities, the one with the lower electronegativity will be preferentially incorporated because it forms a stronger and a more ionic bond than the other. This rule, however, only applies to diadochic substitution involving elements which differ in electronegativity by more than 0.1.

Ionic Potential

Ringwood (1955) introduced the concept of complex ion formation to predict the behavior of elements during magmatic crystallization. The formation of a complex ion is a function of its ionic potential (I.P.), which Ringwood (1955) defined as the cation charge divided by its ionic

radius. Cations with charges of four or more and trivalent cations with small ionic radii form complexes with oxygen and hydroxyl ion in the magma. Ringwood found that the stability of a complex decreases as ionic potential decreases. He thus divided the elements into three categories: cations with I.P. = 0.60-2.60 behave as free ions in the melt and occupy sites in the lattice of minerals and are "network modifiers"; cations with I.P. = 4.83-25.00 occur as complexes which join together to form the structural network of the silicates and are referred to as "network formers"; and cations with intermediate I.P.'s from 2.7 to 3.12 behave as network formers when the (Si+Al)/O ratio is low and as network modifiers when the ratio is high.

Ringwood contended that the property of the complex as a whole rather than the property of the individual cation governs its behavior during magmatic crystallization. Accordingly, he formulated the following rules:

1. Complexes which are not of the MO_4 tetrahedral type cannot substitute for $(\text{SiO}_4)^{-4}$ and hence tend to concentrate in the residual fraction of the crystallizing magma, eventually reaching a concentration which is sufficient to precipitate them as primary minerals. Examples include CO_3^{-2} and BO_3^{-3} .
2. The larger the charge on the cation, the smaller will be the tendency for MO_4 complexes to replace SiO_4^{-4} tetrahedra. Examples include WO_4^{-2} , SO_4^{-2} , AsO_4^{-3} , and PO_4^{-3} .
3. The larger the size of the central cation, the smaller will be the tendency for MO_4 groups to replace SiO_4^{-4} tetrahedra. Examples of this are Ge_4^{-4} , TiO_4^{-4} , and SnO_4^{-4} . Ionic radii

of Si^{+4} , Ge^{+4} , and Sn^{+4} are 0.42, 0.53, 0.68, and 0.71 angstroms, respectively.

Total Bond Energy

The most recent approach to total bond energy is taken by Nockolds (1966), who devised a single function which he call total bond energy. He defined this as the summation of ionic bond energy (V_I), covalent bond energy (V_C), and crystal field energy (V_S) in the case of transitional elements (Curtis, 1964). Damon (1968) subsequently modified this definition of total bond energy. Elements with high total bond energies are preferentially accepted into silicate lattices, while those with low total bond energies concentrate in the residual liquid of a crystallizing magma.

Behavior of Certain Elements during Magmatic Crystallization

As mentioned earlier in the introduction, one of the purposes of this research is to examine the distribution of major and minor elements in whole-rock samples of aplite and pegmatite and in K-feldspar separated from them, with the understanding that controls on the absolute amounts or interrelationships of some of these elements might reveal differences between aplites and pegmatites in base metal-producing stocks versus nonproducing stocks.

Table 2 summarizes the important physical properties of the elements in question. Values for radius, charge, electronegativity, and ionic potential are from Ringwood (1955). Values for total bond energy are from Damon (1968), except for Cu^{++} and Fe^{+++} which are calculated

Table 2. Some physical properties of selected elements

Element	Charge	Ionic Radius	Electro-negativity	Ionic Potential	Total Bond Energy
Si	+4	0.41	1.8	9.8	388
Al	+3	0.51	1.5	5.88	336
Fe	+3	0.64	1.8	4.68	244
Fe	+2	0.74	1.65	2.70	185
Ca	+2	0.99	1.0	2.02	236
Na	+1	0.97	0.9	1.03	117
K	+1	1.33	0.8	0.75	105
Cu	+2	0.72	2.0	2.78	200
Zn	+2	0.74	1.7	2.70	180
O	-2	1.40	3.5	--	--

according to the formula given by Damon:

$$V_T = 330 \frac{Z_C F}{R} + V_S$$

where Z_C is cation valence

$F = e^{-0.25\Delta^2}$, where Δ is the O-X electronegativity difference

R is the O-X bond length

V_S is the crystal field stabilization energy.

The behavior of elements under consideration will be reviewed in light of the geochemical rules developed earlier. This knowledge provides us with an understanding of the mineralogical and chemical composition of aplites and pegmatites under consideration and will be used in discussion of results in a later chapter.

Silicon. Because of its high charge (4^+) and small ionic radius (0.4 Å), silicon has a high ionic potential (9.8). Accordingly, it occurs as the complex ion $(\text{SiO}_4)^{-4}$ in a silicate melt (Ringwood, 1955). Its high total bond energy (388) also governs silicon's behavior during magmatic crystallization. Aluminum and germanium are among the few elements that have properties sufficiently close to silicon to substitute for it. Application of geochemical rules to silicon indicates that silicon is most preferred in silicate minerals because it forms tetrahedra basic to the framework of these minerals.

Whether free quartz forms in the late stages of magmatic crystallization or not depends on the differentiation history and the composition of the original magma (Krauskopf, 1967). If the magma contains excess silica over the amount necessary to satisfy the cations of olivine,

pyroxene, amphibole, and feldspars, the excess must become increasingly concentrated in the liquid as differentiation proceeds. Thus, free quartz is often formed as an end product of crystallization. If, on the other hand, silica is just sufficient to satisfy these cations, the end product would be largely feldspar without quartz. Similarly, if silica-deficient minerals, like olivine, are formed and armored from further reaction by a reaction rim or removed by gravity settling, the melt is gradually enriched in silica as differentiation proceeds and free quartz is among the end products of crystallization. In view of the universal presence of quartz and other silicates in hydrothermal deposits, silicon certainly partitions into a developing hydrothermal phase. Fenner (1933) contends that this partitioning takes place as SiCl_4 or SiF_4 in a vapor phase.

Aluminum. As for silicon, the behavior of aluminum is governed principally by its high ionic potential (5.88) and total bond energy (366). Because of these parameters, aluminum occurs in a magma as ion complexes and behaves as a "network former" (Ringwood, 1955). The physical properties of aluminum are sufficiently close to those of silicon that it frequently substitutes for it in the tetrahedral layer, with concomitant substitution of sodium, potassium, or calcium to maintain electrical neutrality. Aluminum may also be in sixfold coordination and form octahedra that connect two tetrahedral layers.

When there is enough aluminum in a magma to satisfy cations in feldspars and micas, it is progressively removed from the melt. Consequently, highly differentiated igneous rocks contain less aluminum

than those that are less differentiated. Magmatic alumina in excess of the amount necessary to take care of cations of feldspars and micas results in increasing concentration of this excess in the residual liquid. Corundum, feldspathoids, and feldspars may form the end product of crystallization in this instance. The presence of alumino-silicates in hydrothermal ore deposits indicates that aluminum partitions into a developing hydrothermal phase. As for silicon, Fenner (1933) suggests that partitioning occurs as AlCl_3 in a vapor phase.

Iron. Iron occurs as Fe^{++} and Fe^{+++} in a magma, although relatively low oxygen fugacities dictate that the former is the more abundant. Because of their ionic potentials, both ferrous and ferric ions occur as simple ions in a silicate melt, although in a volatile-rich magma they may occur and behave as complex ions (Ringwood, 1955). Because of its smaller electronegativity (1.65), high concentration, and the availability of proper structural sites in growing mafic minerals, ferrous iron is preferred to the ferric iron in the lattices of pyrogenic silicate minerals. This fact is verified in that early-forming ferromagnesian minerals, such as olivine and pyroxene, contain relatively more ferrous iron. When a high enough concentration of ferric iron is reached, it is incorporated in minerals, such as spinels and hematite.

Accordingly, ferrous iron concentrates in early-forming minerals from a mafic magma. Ferric iron, in contrast, stays in solution until a sufficiently high concentration is reached, and it crystallizes in ferric iron-bearing minerals. This predicted behavior is confirmed by formation of hematite in rocks formed during later stages of differentiation. Some late-forming feldspars have a pinkish color which is probably due to

exsolved or occluded hematite (Andersen, 1915; Wones, 1962; and Boone, 1969).

Calcium. Calcium occurs as a simple ion in a magma because of its low ionic potential (2.78). Its behavior during magmatic crystallization is explained by its charge (2^+), ionic radius (0.99 Å), and electronegativity (1.0). Calcium is more successful in competing for structural sites than either sodium or potassium because it has a relatively higher charge and total bond energy (236). Although it has a larger ionic radius than sodium and a higher electronegativity than either sodium or potassium, these properties are offset by its higher charge and total bond energy.

Accordingly, calcium should concentrate in early-forming silicate phases and be progressively impoverished in the melt. This trend is observed in igneous rocks. Early-formed plagioclase is high in calcium content, and the melt is impoverished in this element such that late-forming plagioclase is progressively poorer in calcium. Aplites form from a residual magma that must be very low in calcium. When a chloride-rich aqueous phase develops, calcium partitions in it (Burnham, 1967; and Gammon and others, 1969).

Sodium. Because of its small ionic potential (1.03), sodium occurs as a simple ion in a silicate melt. Its behavior in the course of magmatic crystallization is accounted for by its charge (1^+), ionic radius (0.97 Å), electronegativity (0.90), and total bond energy (117). Sodium is admitted in plagioclase in preference to potassium because it has a smaller ionic radius (0.97 Å) and a higher total bond energy (117). Its behavior relative to calcium has been discussed. However, the

similarity of sodium and potassium permit diadochy in alkali feldspar. By virtue of its physical properties, sodium concentrates in late magmatic liquids and in late-forming plagioclase. This behavior is confirmed in nature by consistently high values of calcium in feldspar from gabbro as contrasted to high values of sodium in plagioclase from granite. In the event a hydrothermal solution forms, sodium partitions into it in preference to the coexisting silicate melt (Orville, 196; Jahns and Tuttle, 1963; Burnham, 1967; and Gammon and others, 1969).

Potassium. Potassium occurs and behaves as a simple ion in a crystallizing magma because of its low ionic potential (0.75). Potassium's behavior during magmatic crystallization is explained by its single positive charge, ionic radius (1.33A), and its total bond energy (105). Potassium is rejected with respect to either sodium or calcium in crystallizing plagioclase, because it has a larger ionic radius and a smaller total bond energy. However, the electronegativity advantage of potassium (0.8) over sodium (0.9) and calcium (1.0) is offset by the smaller ionic radius and higher total bond energy of the latter elements. The physical properties of potassium and sodium are sufficiently close that they readily substitute for each other in alkali feldspar. Potassium intake in early-forming alumino-silicate minerals should be moderate, while the bulk of the element should concentrate in late-forming alumino-silicates, particularly in the residual magma. This predicted behavior is corroborated in magmatically derived rocks. Quartz diorite, quartz monzonite, and granite, for example, are arranged in both an increasing order of differentiation index and potassium content. Like sodium, potassium partitions in a hydrothermal solution in preference to a

coexisting silicate melt (Orville, 1963; Jahns and Tuttle, 1963; Burnham, 1967; and Gammon and others, 1969). As the temperature drops below 880°C, k^+ partitions back into the melt (Orville, 1963; Ellis and Mahon, 1967; and Gammon and others, 1969).

Copper. Because of its low ionic potential (2.78), copper's behavior as a simple ion in a silicate melt is explained by its electronegativity (2.0), ionic charge (2+), and ionic potential (200). Although copper has a much smaller ionic radius than calcium, potassium, or sodium, the last three elements are preferentially admitted into aluminosilicate minerals with respect to copper principally because of their relatively low electronegativities and relatively high concentrations in silicate melts. Similarly, iron is preferred relative to copper by crystallizing ferromagnesian minerals because of its lower electronegativity and greater abundance. However, copper may substitute for iron because of almost identical ionic radii and total bond energies.

Copper therefore does not importantly enter early-forming ferromagnesian minerals in lithophile melts. By virtue of its chalcophile nature, copper is partitioned into a sulfide liquid. In the absence of an early-forming sulfide liquid, the more strongly or more plentiful chalcophile elements complex sulfur, allowing copper to concentrate in the residual liquid. Eventually, when a hydrothermal solution forms, copper may be sufficiently enriched to form copper sulfide minerals in the presence of sufficient sulfur. When anomalously high concentrations of copper are reached in the residual magma, ferromagnesian minerals are enriched in copper through copper substitution for iron. This predicted behavior is confirmed by the observed enrichment of copper in biotite or hornblende from intrusions genetically associated with ore deposits.

(Parry and Nackowski, 1963; Putman and Burnham, 1963; Wahab, 1968). When a hydrothermal solution forms, copper is observed to partition into it probably as chloride complex ion in preference to the coexisting silicate melt.

Zinc. The crystal chemistry of zinc is similar to that of copper (Table 1). Consequently, the features controlling the behavior of copper also control that of zinc. Anomalously high values of zinc in biotite or hornblende are indicative of its high concentration in the melt from which these minerals crystallized.

The information developed in this chapter will be used in the discussion of results obtained in this report.

CHAPTER 4

GENESIS OF APLITES AND PEGMATITES

The purpose of this chapter is to summarize theories of aplite-pegmatite formation described in the literature and to cite geologic constraints for the application of the different models. This information will be used in subsequent chapters to examine genetic features of aplite and pegmatite bodies in the areas studied.

Work done on aplites and pegmatites has resulted in many theories to account for their origin and mode of emplacement. A recent summary of these theories is found in Cameron and others (1949) and Jahns (1955). Among many theories presented, the metamorphic and igneous models are the most widely accepted.

Metamorphic Theory

A metamorphic origin for aplite and pegmatite bodies, especially those found in foliated rocks, has been proposed by King (1948), Ramberg (1952, 1956), Reitan (1965), and Matter (1969). These workers assigned this origin principally on the basis of structural and compositional criteria. Among pegmatites and aplites of metamorphic origin are those which derive their necessary components from proximally surrounding rocks by metamorphic differentiation, to form concretion, secretion, or replacement aplites and pegmatites. This concept has been described by Ramberg (1952), Turner and Verhoogen (1960), and Barth (1962). According to this theory, chemical components move by diffusion as ions,

atoms, or molecules mainly along intergranular films and mosaic fissures (Ramberg, 1952) to reach sites where their free energies or chemical activities are lowest. This migration takes place in response to pressure, temperature, and chemical potential gradients developed primarily as a result of fissuring in a body of rock.

The metamorphic hypothesis requires that the most mobile elemental constituents of the host rocks, that is, Na, K, Si, and Al, migrate toward low-pressure sites in response primarily to pressure differential and chemical gradients to form quartzo-feldspathic aplite and pegmatite bodies. A similar model has been proposed by Boyle (1961) to explain the origin of Yellowknife gold vein deposits in Canada.

Criteria for Identification of Metamorphically Derived Aplites and Pegmatites

Criteria pertinent to aplites and pegmatites of metamorphic derivation and their application to the aplites and pegmatites under study provides a basis better to judge the origin of the latter. It should be realized that none of the criteria enumerated below can be considered alone as a uniquely compelling criterion, although each may be useful when applied along with others to specific occurrences. The following is a summary of criteria indicative of the metamorphic origin of aplites and pegmatites:

1. A nondilational mode of emplacement (King, 1948).
2. Presence of structural elements inherited from host rocks or the inclusion of host rocks that have not been moved from their original position.

3. Porphyroblasis or concretionary growth at the expense of host rock (Barth, 1962).
4. The fringing of pegmatites or aplites by mafic minerals evidently rejected and expelled from the host rock (Ramberg, 1952) or residual minerals of the host rock.
5. Absence of pegmatite-filled feeder channels (Barth, 1962).
6. Presence of tectonically folded masses of pegmatites in foliated rocks, interpreted by Ramberg (1952) as products of metamorphism and contemporaneous plastic deformation.
7. Absence of igneous rocks with which the pegmatites can be logically correlated.
8. Restriction of pegmatite masses to metamorphic terranes in which there is evidence of differential fusion or recrystallization.
9. Specific dependence of pegmatite composition upon host-rock composition (Ramberg, 1956).
10. Systematic distribution of pegmatites of contrasting composition with host rocks of contrasting composition.

The presentation and discussion of an igneous model as presented below permits the development of criteria for identification of aplites and pegmatites thus derived.

Igneous Theory

Both magmatic and hydrothermal models for derivation of aplites and pegmatites will be considered in this section. Criteria developed here will be applied to the aplites and pegmatites under consideration.

"Magmatic" here means a natural silicate melt which may be saturated or undersaturated with respect to volatiles, especially water. "Hydrothermal" refers to an aqueous siliceous fluid separating from a crystallizing cooling magma.

Magmatic Theory

Aplite and pegmatite-forming magmas were viewed by early workers (Merritt, 1923) as viscous liquids or gels. However, due to convincing field and laboratory evidence, this theory soon yielded to the "fluid magma theory." "Fluid magma" has also been referred to as residual magma, rest magma, residual solutions, hydrous magma, or pegmatitic magma. The importance of fluid magma in the development of aplite and pegmatite bodies was stressed by Vogt (1923), Andersen (1931), Emmons (1940), Cameron and others (1949), Jahns and Tuttle (1963), Fournier (1968), and Jahns and Burnham (1969).

Fluid magma is a silicate melt, saturated or approaching saturation with volatiles, which separates from silicate-rich magma because of crystallization of anhydrous minerals and decreasing miscibility over a falling temperature and pressure gradient. Emmons (1940) invokes differential pressure and Fournier (1968) adds permeability of host rock to differential pressure as major factors in the formation of aplites and pegmatites from fluid magma. When a fracture develops in a crystallizing igneous body, fluid magma under the influence of a pressure differential migrates into it. Such a melt, if undisturbed with regard to its high volatile content, crystallizes as a pegmatite body. With development of more fractures due to cooling or other causes, a pressure differential is re-created and the volatiles in a potential pegmatite dike

escape, thus impoverishing the residual melt in volatiles. Crystallization of this relatively "dry" melt was said to form an aplite dike (Emmons, 1940). Through extensive field and laboratory work, Jahns and Tuttle (1963) confirmed that substantial and rapid loss of dissolved volatiles from a fluid magma raises its liquidus temperature and leads rapidly to the formation of aplite bodies. Aplites thus formed are therefore a "pressure quench" rock. As for the origin of mixed aplite-pegmatite dikes, Emmons (1940) proposes that a fracture filled with fluid magma may partially crystallize to a pegmatoid mass, while the remainder may lose its volatiles and form an aplite dike. If, however, an appreciable fraction of water is retained within the crystallizing body, not all of the melt is necessarily quenched and this rest liquid with its high water content can yield masses of pegmatite within a body of otherwise aplitic rock (Jahns and Burnham, 1969).

Literature on aplites and pegmatites indicates that they form at depths ranging from 1,500 feet to 7 km. Rose and Baltosser (1966) reported that the Santa Rita stock, New Mexico, which contained aplites and pegmatites intruded within 1,500 feet of the surface. Putman and Alfors (1965) indicated that aplite dikes at the Rocky Hill stock, California, formed at depths of 5.5 to 7 km. Temperature of formation of aplites and pegmatites is also variable. Jahns (1955) summarized that they form in the range of 700°C to 400°C, whereas Jahns and Burnham (1969) cited temperatures of formation as high as 800°C.

Criteria for Identification of Magmatically Derived Aplites and Pegmatites. The characteristics of essentially magmatically derived aplites and pegmatites will be developed by studying appropriate criteria which have been proposed as diagnostic of magmatic origin of these rocks, as follows:

1. Occurrence within or around exposed plutons with which they are thought to be genetically related.
2. Compositional similarity of host rocks and their enclosed aplites and pegmatites (Miller, 1919; Jahns, 1955).
3. Continuity of aplite and pegmatite dikes from intrusive host rocks into surrounding older rocks.
4. Zoning in complex pegmatites (Cameron and others, 1949; Jahns, 1955). Zones presumably develop from the wall inward by fractional crystallization and incomplete reaction in a restricted system.
5. Spatial relationship and similarities in composition between aplites and pegmatites and associated plutonic bodies (Cameron and others, 1949; Montgomery, 1950).
6. Lack of influence of composition of the host rocks upon the composition of the enclosed aplite and pegmatite bodies (Derry, 1931; Jahns and Wright, 1951; this report).
7. Relative enrichment of adjacent wall rocks in constituents common to the enclosed pegmatites compared to the average country rock at some distance from the body (Chadwick, 1958).

8. Emplacement of aplite and pegmatite bodies by forceful or permissive injection.
9. Lack of evidence of rock replacement mechanisms.
10. Matching of opposing walls of irregular dikes.
11. Mineralogical, chemical, and textural homogeneity across width of aplite dikes and among dikes in a single intrusion (Derry, 1931; this report).
12. Presence of graphic and granophyric textures (Barker, 1970; this report).

Hydrothermal Theory

A knowledge of the hydrothermal theory and features characteristic of aplites and pegmatites derived hydrothermally must be carefully applied to the aplites and pegmatites under consideration. This theory grew out of attempts to explain the presence of replacement minerals and textures in some aplites and pegmatites. It involves the formation of aplites and pegmatites by precipitation of new minerals introduced by hydrothermal fluids of magmatic origin, usually through the replacement of preexisting rocks. Replacement is guided by fractures, minerals or textural zones, contacts between pegmatites and host rocks, or by any other structural, textural, or lithologic elements within aplite and pegmatite masses (Cameron and others, 1949).

Criteria for Identification of Hydrothermally Derived Aplites and Pegmatites. Replacement has been used as a criterion for both metamorphic and hydrothermal aplites and pegmatites. Similarly, another criterion

common to magmatic and hydrothermal aplites and pegmatites is their common genetic relationship to associated plutons. Cameron and others (1949) restrict hydrothermal replacement pegmatites to those (1) whose minerals have been formed, at least in large part, at the expense of pre-existing pegmatites and (2) whose constituents have been completely recrystallized before replacement. Bastin and others (1931) and Park and MacDiarmid (1970) cite criteria more applicable to ore minerals, although most are applicable to aplites and pegmatites as well. Such criteria include:

1. Nondilational mode of emplacement in which replacement along a fissure causes no offset of an intersecting planar body (Park and MacDiarmid, 1970).
2. Pseudomorphic preservation of the forms of preexisting minerals (Cameron and others, 1949).
3. Presence of structural elements inherited from the host rocks or the inclusion of relicts of host rocks that have not been moved from their original positions (Bastin, 1935).
4. Unmatching or radical difference of opposing walls of bodies, where replacement has worked outward from a central fissure (Bastin and others, 1931).
5. Selective replacement of bodies in some aplites and pegmatites due to the distribution of early minerals or mineral aggregates susceptible to replacement (Cameron and others, 1949).
6. Presence of "complex pegmatites" which carry tin, lithium, tantalum, beryllium, and other rare elements formed through replacement of "common pegmatites" composed of potash

feldspar, quartz, mica, and sometimes black tourmaline (Schaller (1925), Hess (1925), and Derry, 1931).

7. Formation of albite to the exclusion of K-feldspar in "complex pegmatites" (Derry, 1931).
8. Formation of "pocket minerals" and numerous mineral aggregates through exchanges of material among aqueous fluid and earlier formed crystalline phases in pegmatites (Jahns and Burnham, 1969).
9. Occurrence of aplites and pegmatites within or around exposed plutons with which they are genetically related, provided that they show other hydrothermal criteria.
10. Relative enrichment of adjacent wall rocks in constituent minerals, evidently derived from the aplite or pegmatite fluids, compared to the average country rock at some distance from the bodies, though only where other hydrothermal criteria are available.

It should again be emphasized that none of the criteria enumerated above can be considered alone as a criterion for general use, although each may be of value when applied along with others to specific occurrences. Zoned pegmatites will not be further considered in this report.

CHAPTER 5

GEOLOGY

Geologic descriptions of intrusions from the literature and by the author are presented in this chapter. These descriptions emphasize age relationships, regional and district structural settings, and internal structures of plutons and those in the surrounding host rock which permit determinations of mode of emplacement. Mineralogical variation and hydrothermal alteration and mineralization where present are also included. Hydrothermal alteration in the intrusions and associated aplites and pegmatites is studied to determine its intensity and pervasiveness and its bearing on mineralogy and chemical composition of aplites and pegmatites. This study also includes short descriptions of mineralization in each intrusion; location of known ore deposits, aplites, and pegmatites are given.

Detailed descriptions of aplites and pegmatites include their mode of occurrence and their location relative to the intrusions and relative to alteration and mineralization. Abundances and average widths of dikes are reported along one-mile traverses through selected area known by reconnaissance mapping and literature review to carry the maximum concentration of dikes. Trends of traverses represented by the lines A-B on respective figures are directed at angles of 60-90 degrees to the general strikes of dikes so as to intersect the maximum number of dikes. Since all dikes do not maintain the same strike, these traverses

in some instances intersect dikes at angles smaller than 60 degrees. This variation in the angle of intersection of dikes under consideration was not found materially to affect the number of dikes per line mile. A dike must be counted more than once were it offset by a fault or were it to be nonlinear in shape. The writer was vigilant with regard to this situation, and no dike was counted more than once. True width of a dike was always recorded whether a dike was intersected at right angle or any other smaller angle. Dikes intersected by a traverse were counted and their average true width computed. Traverses through the Amole and Patagonia intrusions were partly covered by alluvium and rock debris, respectively. In the case of the Amole intrusion, the distance under alluvium cover may include, according to distribution of other dikes along the traverse, not more than two additional dikes, and the same situation holds true for the Patagonia intrusion. In spite of these shortcomings the difference in the number of dikes per line mile and the difference in average width of dikes in productive and barren intrusions is real. As is shown later, productive intrusions have 8 to 10 dikes per line mile with widths ranging between 3 and 7 inches, whereas barren intrusions have 10 to 45 dikes with widths ranging between 10 and 72 inches.

Mineralogy, megascopic and microscopic texture, homogeneity across widths of dikes, and distribution of aplites and pegmatites were recorded. Deuteric and hydrothermal alterations were closely looked for and carefully studied so as to establish the relation of each to the presence of sulfides and secondary K-feldspar.

Sample collection was not systematic and the distance between them and mines, deposits, or prospects was not kept constant. Although local sampling was random, most of the samples, except for those from Texas Canyon and some of those from the Boulder batholith, Butte district, were located within mines or within a radius of one mile of known mineralization. Samples from Texas Canyon range between 2.5 to 5 miles from known mineralization, and samples from Butte district were collected from within 1.5 to 9 miles of the center of the district.

This study is done to find distributional, structural, textural, or mineralogical variations in productive and barren intrusions. It is therefore the intention in this chapter to treat productive intrusions as one group and the barren ones as another and then study each group in alphabetical order.

Productive Intrusions

Boulder Batholith

The Boulder batholith is a large pluton in southwestern Montana with an exposed area of 1,100 square miles (Fig. 3). It extends from approximately 20 miles southwest to about 50 miles northeast of Butte, Montana, in a northeasterly direction. It intrudes rocks ranging in age from Archean to Cretaceous (Fig. 4). Knopf (1964) determined its absolute age as 70-78 m.y.

According to Knopf (1957), Klepper (1962), and Meyer and others (1968), the Boulder batholith was emplaced as successive surges of magma of differing composition. The batholith occupied a zone of weakness between two major tectonic blocks (Fig. 3). The northern

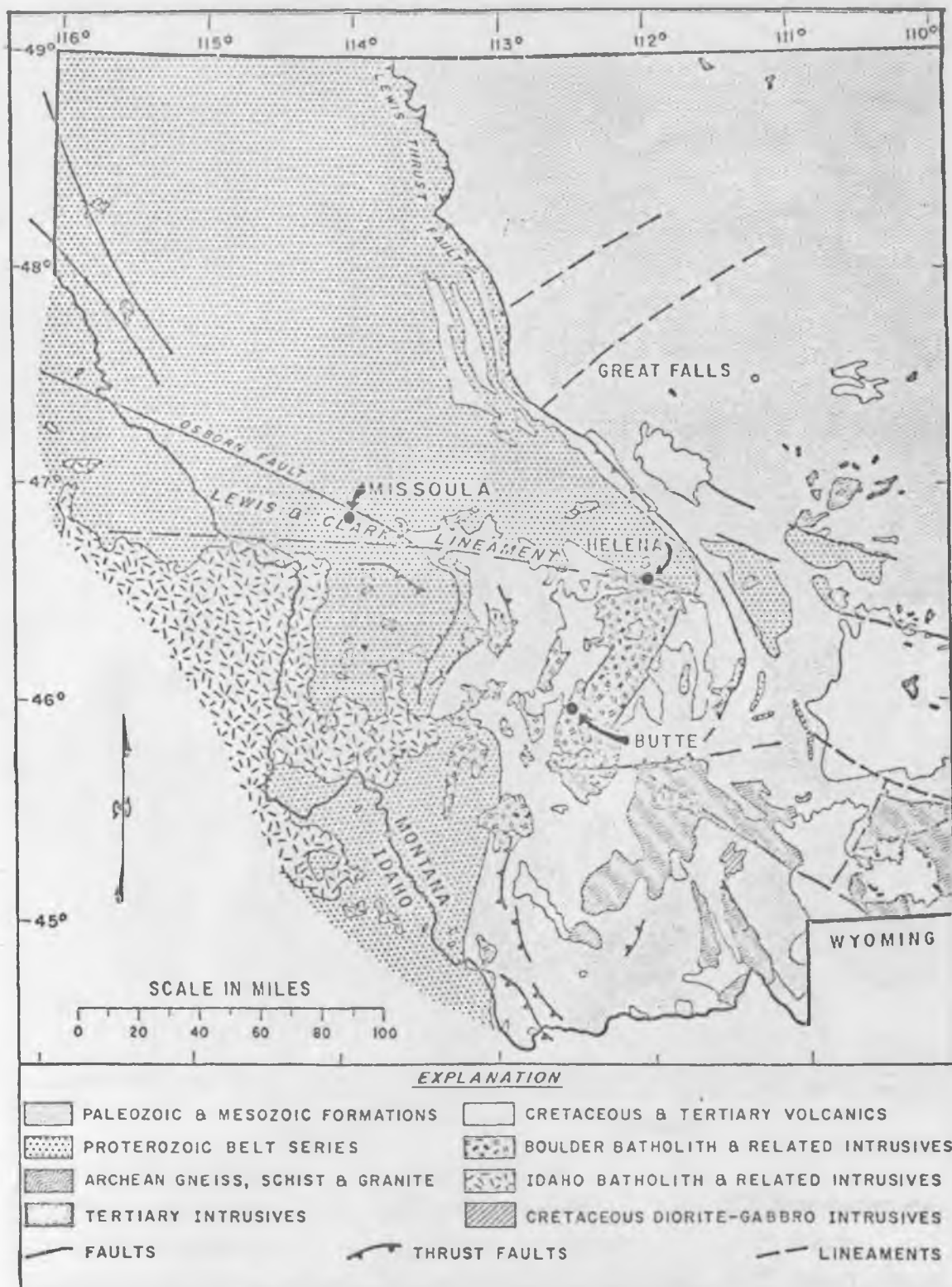


Figure 3. Tectonic elements of western Montana showing the location of the Boulder batholith relative to major tectonic elements.-- From Meyer and others (1968)

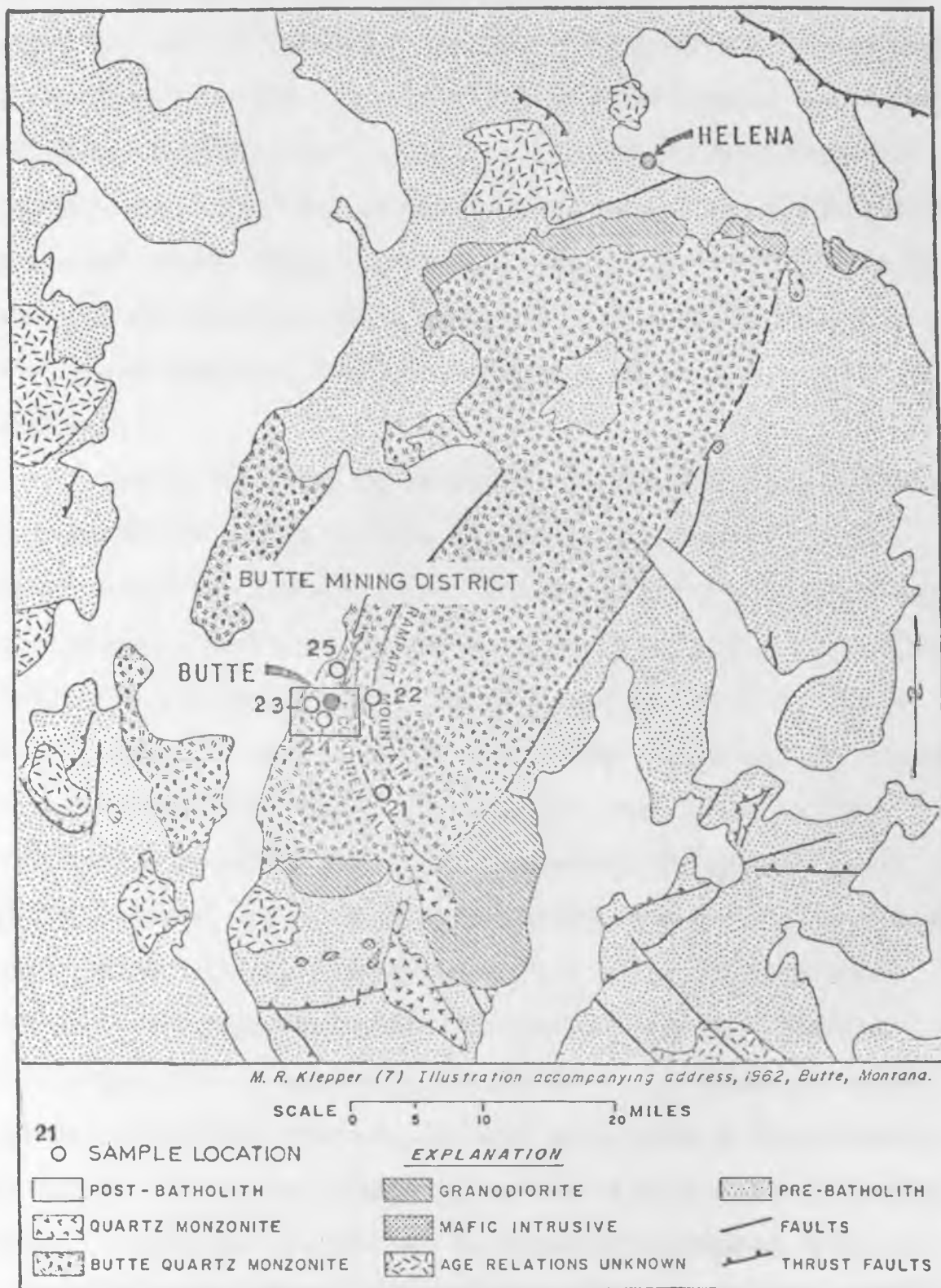


Figure 4. Rock types, contact features, and numbered sample locations of the Boulder batholith, Montana.--After Meyer and others (1968)

block is separated from the southern one by the Lewis and Clark lineament. The southern Precambrian buttress block is located about 20 miles south and east of Butte. The wedge-shaped central zone between these two blocks has been a zone of recurrent subsidence since the Precambrian era and is internally characterized by extensive deformation (Meyer and others, 1968). Klepper (1962) suggested that pre-batholithic faults and fractures trending north-northeast and north-northwest formed or were reactivated during the Laramide orogeny and localized the Boulder batholith.

Meyer and others (1968) reported that the Boulder batholith is a composite intrusion (Fig. 4) formed by early emplacement of mafic bodies followed by intrusion of massive granodiorite. The Butte quartz monzonite then formed the major mass of the batholith and was, in turn, followed by intrusion of younger quartz monzonite in dike-like plutons south of Butte. Magmatic aplites and alaskites are related to the period of emplacement of the Butte quartz monzonite unit. Quartz porphyry dikes and plugs locally containing disseminated chalcopyrite cut the quartz monzonite and its aplite and pegmatite, especially in the eastern portion of the district. Of these several rock units, the Butte quartz monzonite is mineralizationally most important as it hosts the famed Butte copper-zinc-manganese-silver deposits. It is medium to coarse grained and granitic in texture, although local zones showing poikilitic K-feldspar occur. Mineralogically, the rock is composed of 21 percent quartz, 21 percent microperthite, 36-40 percent plagioclase with hornblende and biotite composing 15-20 percent (Meyer and others, 1968).

Alteration in the Butte mining district is described in many articles, especially those by Sales and Meyer (1948) and Meyer and Hemley (1967). A "potassium silicate assemblage," a term adopted by Meyer and others (1968) after Creasey (1959), is characterized by green and brown biotite replacing mafic minerals and plagioclase. Plagioclase and primary orthoclase are replaced by biotite and sericite, and albitic K-feldspar replaces and rims plagioclase. Anhydrite in veinlets, in altered plagioclase sites, and with recrystallized biotite is an important minor mineral in this assemblage, which envelops some early quartz veinlets and is referred to as pre-main stage alteration. Main stage alteration (Sales and Meyer, 1948) can be described as a central sulfide vein successively enveloped by phyllic, argillic, and propylitic alteration assemblages. Advanced argillic alteration rarely occurs near sulfide veins in intermediate levels on the east side of the district, the central zone of Sales and Meyer (1948), and is distinguished by minerals, such as dickite, alunite, pyrophyllite, zunyite, and topaz. This assemblage is enclosed outward by ubiquitous quartz-sericite-pyrite alteration. In the absence of advanced argillic alteration, phyllic alteration occurs adjacent to sulfide veins. Next outward, the argillic alteration envelope consists of a kaolinitic subzone toward the vein and a montmorillonite subzone toward fresh rock.

Aplites and Pegmatites. Samples from aplite and pegmatite dikes were collected from within and outside the Butte mining district, about 1.5 to 9 miles from the center of the district. Evidence, such as crosscutting of these dikes by hydrothermal alteration and mineralization, as reported by Meyer and others (1968), indicates that the sampled dikes

are younger than the Butte quartz monzonite and older than both hydrothermal alteration and mineralization.

Isolated dikes and irregular masses of aplite and pegmatite occur sparsely throughout the quartz monzonite (Meyer and others, 1968), although a concentration of dikes and sheets, predominantly of aplite, is found west of the district and also high on East Ridge on the east side of the district. Sheetlike habit is common, and individual units may reach 40 feet in thickness. Most of the aplites and pegmatites are tabular bodies, filling fractures in the quartz monzonite, but some are pod-shaped or irregular masses. In a few places, aplite dikes show internal zoning to pegmatite and quartz-sulfide cores. Locally, there is minor black tourmaline, pyrite, chalcopyrite, molybdenite, and very rarely pyrrhotite. Meyer and others (1968, p. 1380) state that "the sulfides are usually present with quartz in core zones in the pegmatite, and locally the cores emerge from the granophyric or aplitic sheaths to invade the adjoining quartz monzonite as irregular quartz molybdenite pods or veinlets." This relationship bears special significance in the discussion of genesis of pegmatites and aplites. Aplites and pegmatites from the Boulder batholith are buff to white and display fine-grained aplitic texture, although local coarse-grained patches are observed.

Microscopically, the aplites are sugary xenomorphic granular, although the aplite in sample 24 (Table 3) showed a granophyric texture. Pegmatite, as seen in sample 21, shows well-developed graphic texture. Average grain size is 0.8 mm, but some grains as small as 0.2 mm were observed. Closely spaced fracturing in quartz grains and deformation of plagioclase crystals were observed.

Table 3. Modal mineralogic composition and grain size of aplites from Boulder batholith, Montana

Sample No. ¹	Percent by Volume				Average Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Accessory Minerals	
22	35	47	18	biotite, magnetite, sphene: < 1	0.7
23	35	43	22	biotite, magnetite, sphene: < 1	0.8
24	33	45	21	biotite, magnetite, sphene: < 1	0.5
25	33	46	21	biotite, magnetite, sphene: < 1	0.9

1. Sample locations are shown on Figure 4.

Mineral composition is 33-35 percent quartz, 43-47 percent K-feldspar, and 18-22 percent plagioclase (An₁₆). Biotite, sphene, and magnetite are accessory minerals. Quartz occurs as clear anhedral crystals in contact with K-feldspar and plagioclase. Anhedral to subhedral crystals of perthitic orthoclase and microcline are present, but the former is more abundant. Sample 24 shows more microcline than perthitic orthoclase, and it is the same sample that has been noted before to display granophyric texture. Oligoclase (An₁₆) forms subhedral to anhedral crystals which locally show sericitic alteration. Twinning is either absent or poorly developed. Except for local sericitization of plagioclase, samples collected from the Butte district do not display hydrothermal alteration.

Mineralization. The Butte quartz monzonite unit of the Boulder batholith is the host rock of the fabulous Butte copper-zinc-manganese-silver mining district. It is outside the scope of this study to describe the Butte ore deposit, descriptions of which may be found in many publications, the most recent of which is that by Meyer and others (1968). Broadly speaking, mineralization in large veins at Butte falls into a crudely concentric array with copper in the center, surrounded by an intermediate zone of copper and zinc, and followed outward by zinc, manganese, lead, and silver. Major constituent minerals are pyrite, chalcopyrite, bornite, chalcocite, enargite, covellite, digenite, sphalerite, and rhodochrosite. Only slightly offset from these zones at the geographic center of the district and at about the 2800 level and deeper is a zone in which quartz-molybdenite veinlets are present. Quartz and molybdenite occurrences east of the Continental fault may be the up-thrown extension of the molybdenite zone west of that fault and at depth. Meyer and others (1968, p. 1387) believe that "the molybdenite zone with its content of pre-main stage disseminated and veinlet chalcopyrite appears to be expanding rapidly in extent below the 3800 level. It may eventually become an important source of copper and molybdenum for the district."

Although the Butte mining district is not at first inspection like a typical porphyry copper deposit (Lowell and Guilbert, 1970), it has many porphyry copper features. The pre-main stage mineralization of molybdenite, chalcopyrite, and pyrite in an alteration assemblage of orthoclase, biotite, quartz, and minor sericite and anhydrite (Meyer and others, 1968) is similar chemically and texturally to the innermost zone

of Lowell and Guilbert (1970), who also indicate that this innermost zone forms first and is usually centrally located with respect to other zones and the deepest among them, where sulfides are more disseminated than vein controlled. Similarly, the pre-main stage mineralization of Butte formed earliest, its sulfide mineralization is more disseminated and veinlet controlled than vein controlled, and gains significance with depth.

Mineralization of the main stage at Butte is qualitatively similar to that of a porphyry copper deposit, with chalcopyrite as perhaps the most abundant primary copper mineral. Alteration in a porphyry copper environment is expressed by zonal sequence in which a central and deep zone of potassic alteration is enveloped and followed outward and probably upward by phyllic, argillic, and propylitic alteration assemblages. This zonation holds for Butte with respect to individual sulfide veins, where generally a phyllic alteration assemblage is symmetrically followed outward by argillic and propylitic assemblages.

Hypogene metallic zoning in Butte is similar to that of porphyry copper deposits, such as at Bingham Canyon and Santa Rita, where a molybdeniferous copper zone is followed outward by a copper zone and a copper, zinc, and lead zone.

The texture of quartz porphyry and disseminated chalcopyrite in it is similar to those in porphyry coppers and consequently induced Meyer and others (1968, p. 1381) to remark that "the sugary texture of the groundmass is reminiscent of some of the 'porphyry coppers.'" Interestingly, a few disseminated grains of chalcopyrite were observed in the groundmass of the freshest quartz porphyry available underground."

Like most porphyry copper deposits, Butte is hosted and genetically related to an intermediate plutonic intrusion of Laramide age. Lowell and Guilbert (1970) classified it as a porphyry copper, a classification confirmed by the above considerations.

Patagonia Intrusion

The Patagonia stock is located in the Patagonia Mountains about 15 miles northeast of Nogales, Arizona. It has a northwesterly trend and covers an area of about 30 square miles. It intruded Precambrian, Paleozoic, and Mesozoic igneous and sedimentary rocks (Fig. 5). Damon and others (1964) dated it as 63.9 m.y. by the K-Ar method.

The granodiorite stock is strongly jointed and is cut by several persistent vein structures which probably followed preexisting regional fault planes. Brecciation is spectacularly developed in the Four Metals breccia pipe. Although the stock is slightly variable in composition, granodiorite is the predominant phase (Fig. 6). Near the Four Metals mine, both porphyritic and nonporphyritic phases of this granodiorite are identified (Graybeal, 1972). Porphyritic texture is clearly associated with and developed with respect to the breccia pipe (Fig. 6). The nonporphyritic variety, which constitutes most of the stock, is medium-grained equigranular and is constituted by volume of 18.9-29 percent anhedral quartz, 17-22.3 percent anhedral and commonly perthitic orthoclase, 38.2-58.5 percent subhedral to euhedral, slightly altered, zoned andesine (An₃₉), 1.8-6.9 percent subhedral flakes of biotite always partly altered to chlorite, 2.2-4.9 percent hornblende, 0.5-8.6 percent chlorite, 0.6-1.4 percent magnetite (Graybeal, 1972). Sphene, epidote, and apatite are accessory minerals. Porphyritic granodiorite is similar

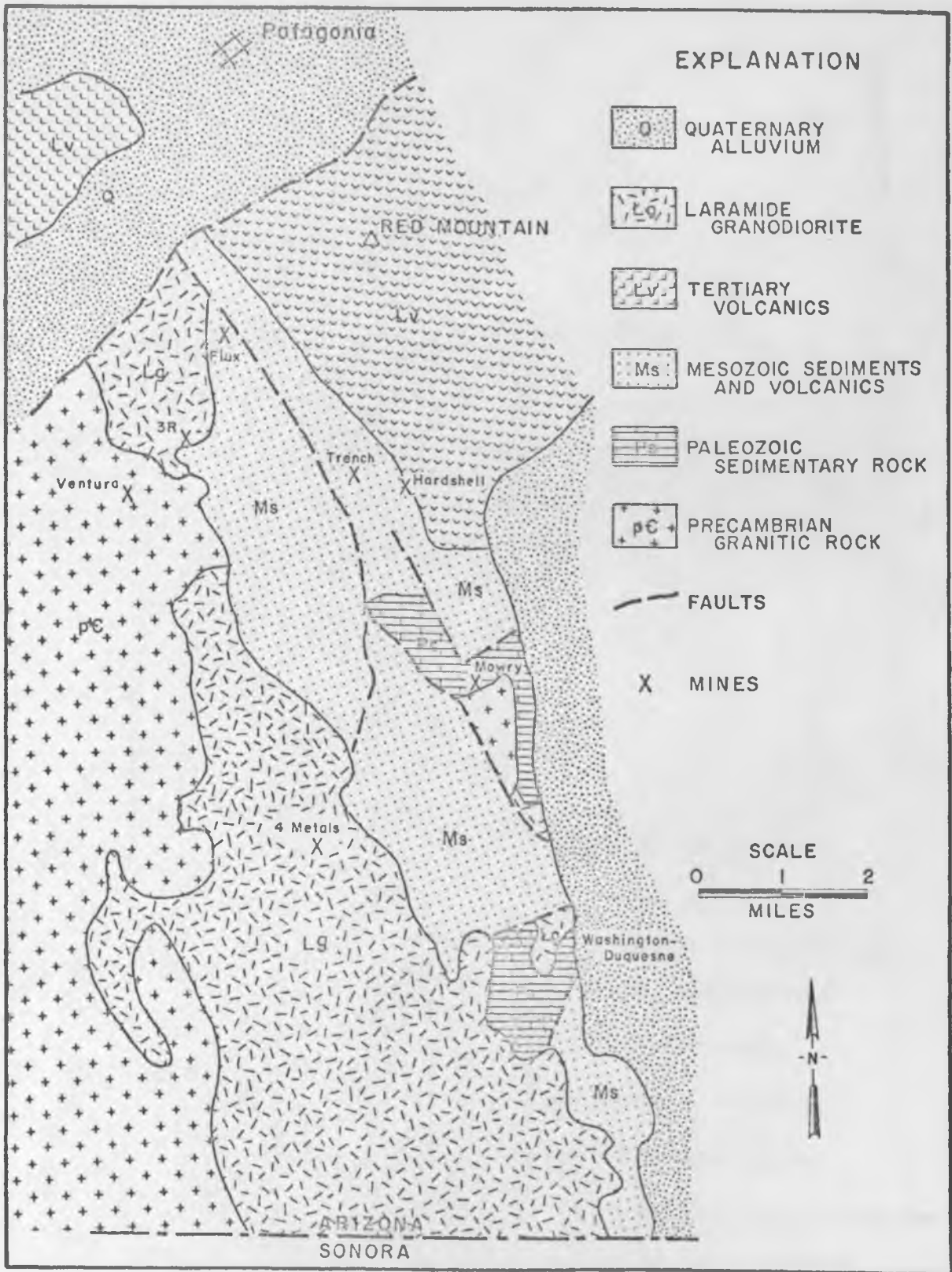


Figure 5. Geologic map of the Patagonia Mountains, Arizona, --
From Graybeal (1972)

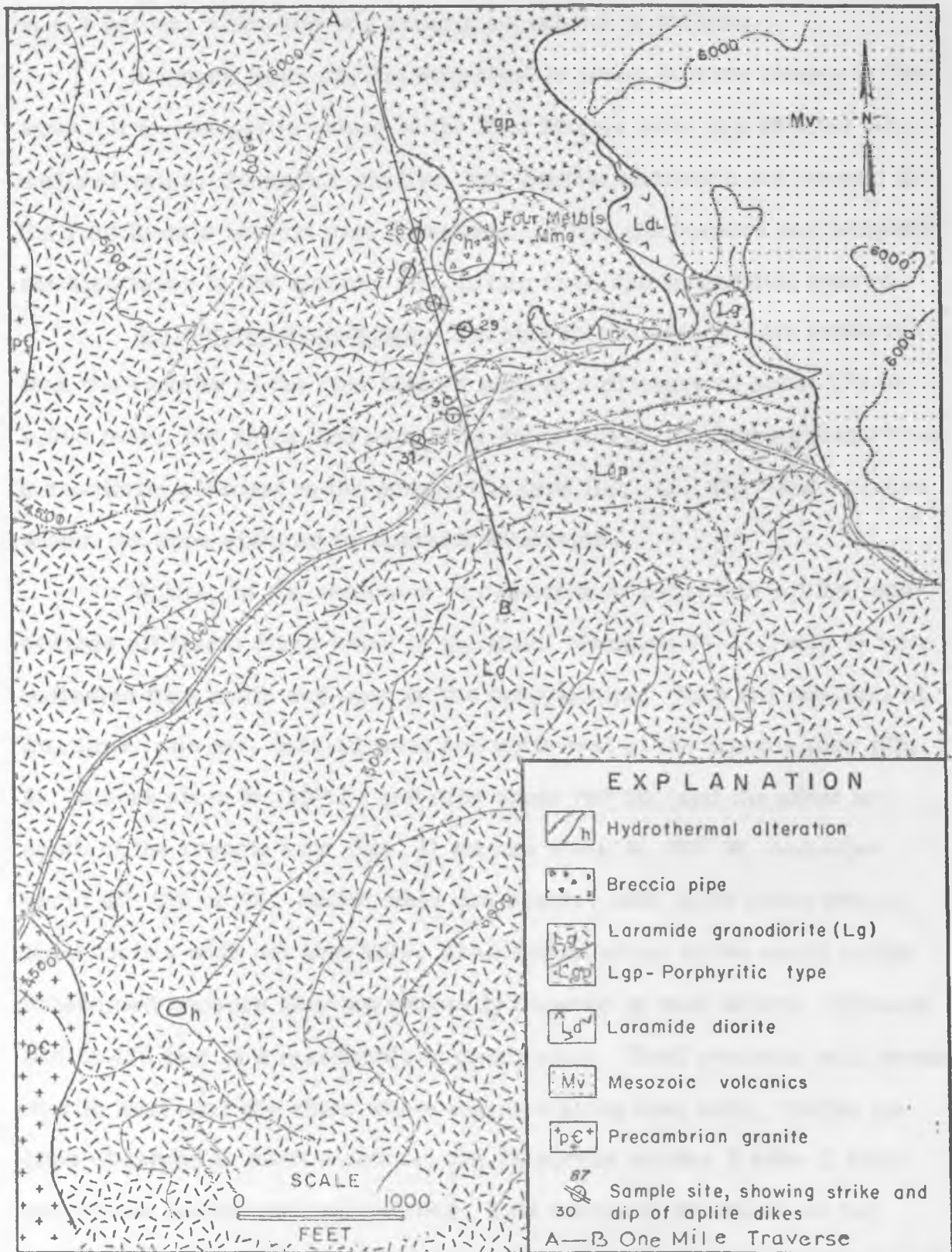


Figure 6. Geologic map of the Four Metals area, Patagonia Mountains, Arizona.--From Graybeal (1972)

in composition to the nonporphyritic variety, except that it contains up to 4.1 percent magnetite and usually no sphene or chlorite.

Although weak phyllic alteration is found in many places in the stock, it is especially strong in the Four Metals mine and at other mineralized veins. Potassic, phyllic, and argillic alteration are present in the Four Metals breccia pipe (Graybeal, 1972). Carbonates and anhydrite are also found in the breccia pipe filling vugs and interstitial spaces.

Aplites and Pegmatites. Samples for this study were collected from the vicinity of the Four Metals mine at a distance of about 370 to 1,300 feet. The aplite and pegmatite dikes mainly lie in the equigranular granodiorite adjacent to the porphyritic type (Fig. 6). They are included within the zone affected by potassic alteration.

Aplite, to the exclusion of pegmatite or pegmatite-aplite, constitutes all felsic dikes found in the field. Samples 26-31 (Table 4) were collected from south and west of the breccia pipe. They fill two sets of fractures; one set, located west and northwest of the breccia pipe (Fig. 6), strikes about N. 20° E. and dips about 70° SE, and the other set south of the breccia pipe (Fig. 6) strikes about N. 80° W. and dips about 85° SW or NE. Aplite dikes are sparse, with eight dikes averaging 4 inches wide per line mile. Their extent along strike could not be determined because they are generally covered by rock debris, although 300 to 400 feet is a reasonable approximation. Their contacts with granodiorite host rock are sharp where exposed along road cuts. Unlike aplites observed in other districts, the Patagonia aplites (Table 4) show many more coarse-grained patches. This tendency increases as the breccia pipe is approached from the south. But for these coarsely

Table 4. Modal mineralogic composition and grain size of aplites from Patagonia stock, Santa Cruz County, Arizona

Sample No. ¹	Percent by Volume				Average Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Accessory Minerals	
26	34	46	19	biotite, hematite: <1	0.30
27	36	43	20	biotite, magnetite, hematite: <1	0.3
28	37	48	14	biotite, magnetite, hematite, sphene: <1	0.3
29	35	48	16	biotite, magnetite: <1	0.4
30	39	40	19	biotite, magnetite: <1	0.4
31	33	44	21	biotite, magnetite, sphene: <1	0.65

1. Sample locations are shown on Figure 6.

crystalline patches, their xenomorphic granular textures are monotonously similar. Hematite after pyrite is observed in some samples, especially sample 28. Color is tan on weathered surface and pinkish where fresh surfaces are exposed.

Microscopically, aplite dikes show both xenomorphic granular sugary and granophyric textures, with the latter predominant (Fig. 7). Graybeal (1972) observed granophyric texture in the transition zone of the porphyry. Grain size ranges between 0.2 and 0.65 mm, averaging 0.4 mm. One thousand point counts for each sample indicated an average mineral composition of 33-39 percent quartz, 40-48 percent K-feldspar,

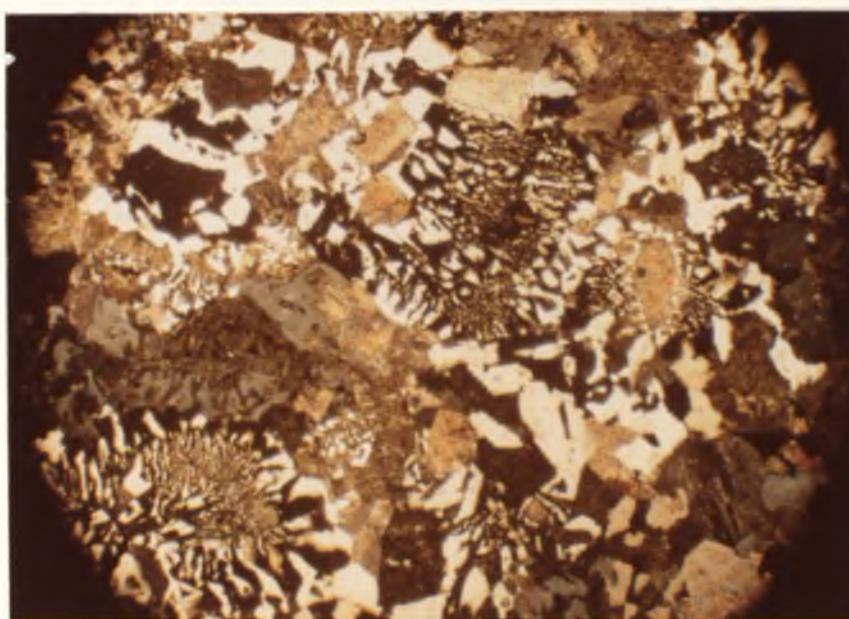


Figure 7. Photomicrograph showing granophyric texture, Patagonia stock, Arizona

Note quartz (colorless and at extinction), K-feldspar (yellow and at extinction), and plagioclase (turbid pink and at extinction). Stained thin section of sample 30; crossed nicols, X25.

and 14-21 percent plagioclase, with biotite, magnetite, and sphene as accessory minerals constituting less than 1 percent (Table 4). Quartz is clear and anhedral with undulose extinction where it is not granophyrically intergrown with K-feldspar. Locally, quartz and K-feldspar form coarse crystals 0.6 mm in diameter. K-feldspar, where not granophyric in texture, forms anhedral to subhedral, slightly turbid, sparsely twinned crystals. Carlsbad twinning is developed to the exclusion of microcline twinning, indicating that almost all K-feldspar here is orthoclase. Perthitic texture is common but not universal. Plagioclase (An₁₆) forms subhedral to anhedral, sparsely twinned crystals. Locally, sericite is thinly distributed in plagioclase crystals, occasionally following zones and rarely peripherally distributed. Plagioclase is locally discontinuously mantled by K-feldspar. Brown biotite of a grain size similar to that of the principal minerals is randomly distributed. Secondary biotite, greenish brown and of minute (0.05 mm) grain size, occurs in fractures and as patches. Hematite is present as individual crystals, rarely surrounding magnetite and occasionally found in lineations, indicating the presence of early micro-fractures. Although no sulfide is observed, the presence of halos filled with hematite is taken to indicate sulfide replacement. Weak potassic alteration is indicated by sericite after plagioclase, secondary biotite, and mantling of plagioclase by orthoclase.

Mineralization. There are several mines and mineral prospects within and around the Patagonia stock, the most important of which is the Four Metals prospect. A major porphyry copper discovery has been made by Kerr-McGee Mining Corporation at Red Mountain, but no geologic information has been released. The Four Metals prospect shows

many porphyry base-metal deposit features. Chalcopyrite, supergene chalcocite, molybdenite, and pyrite mineralization occur in the Four Metals breccia pipe as disseminations and vug fillings. This mineralization is found in a potassic alteration assemblage of orthoclase, biotite, and quartz, with minor apatite. Minerals of this assemblage occur as replacements of breccia fragments and as euhedral crystals in the vugs of the breccia. Anhydrite is partly hydrated to gypsum along the edges of the filled vugs. Graybeal (1972, p. 41) observed that "in the larger fragments the potassic assemblage yields inward to a phyllic assemblage with quartz and sericite dominant, which in turn passes into an argillic assemblage with kaolinite dominant. Outside the mineralized zone, the phyllic assemblage appears to be dominant with chlorite and carbonates locally abundant."

Ore deposits are also found in the sedimentary and igneous rocks around the stock. Lead-zinc-silver replacement deposits along the northeast side occur in limestone along strongly shattered zones at the Mowry mine (Smith, 1956). The mines of the Washington Camp area on the southeast border are massive replacement deposits of pyrite, sphalerite, chalcopyrite, and galena in contact skarn rocks. The 3R mine to the northwest of the Four Metals mine in the Patagonia granodiorite produced 10 million pounds of copper from a steeply dipping lens (Handverger, 1963). There, secondary chalcocite is found to have replaced pyrite in a northwesterly striking fault. Copper mineralization is thought to be derived from the weakly mineralized granitic host. The Ventura prospect (Fig. 5), a breccia pipe northwest of the stock in Precambrian granite, has copper-molybdenum mineralization.

Santa Rita Intrusion

The Santa Rita porphyry copper deposit is about 12 miles northeast of Silver City in southeastern New Mexico (Fig. 2). The Santa Rita stock is elongate northwesterly and comprises an area 2,600 by 6,200 feet at the surface. The Santa Rita area lies in a horst bounded on the north by northeasterly structures like the Barringer fault (Fig. 8), on the east by the northwesterly trending Mimbres fault, and on the west by the similarly trending inferred Silver City fault. The strata within the horst form a broad shallow syncline that is locally modified by domes, arches, and tight superficial folds peripheral to several plutons (Jones, Herson, and Moore, 1967). The Santa Rita granodiorite porphyry stock and its ore body occurs near the intersection of northeast- and northwest-trending zones of structural weakness.

The Santa Rita stock passively intrudes a gently dipping section of the Pennsylvanian Oswaldo and Syrena limestone formations, the Permian Abo Formation, and the Cretaceous Beartooth Quartzite and Colorado formations. The stock has been dated as 63 m.y. by the K-Ar method (Schwartz, 1959). The contact with the wall rocks appears to dip steeply outward from the center of the pluton (Nielson, 1968). The structures of the sedimentary rocks surrounding the intrusion indicate a collapsed anticlinal structure, the trace of the axial plane of which coincides with the long axis of the intrusion (Ordonez, Baltosser, and Martin, 1955; Rose and Baltosser, 1966). The Whim Hill breccia on the north side of the open pit (Fig. 9) may be due to magma pulsations during emplacement (Rose and Baltosser, 1966).

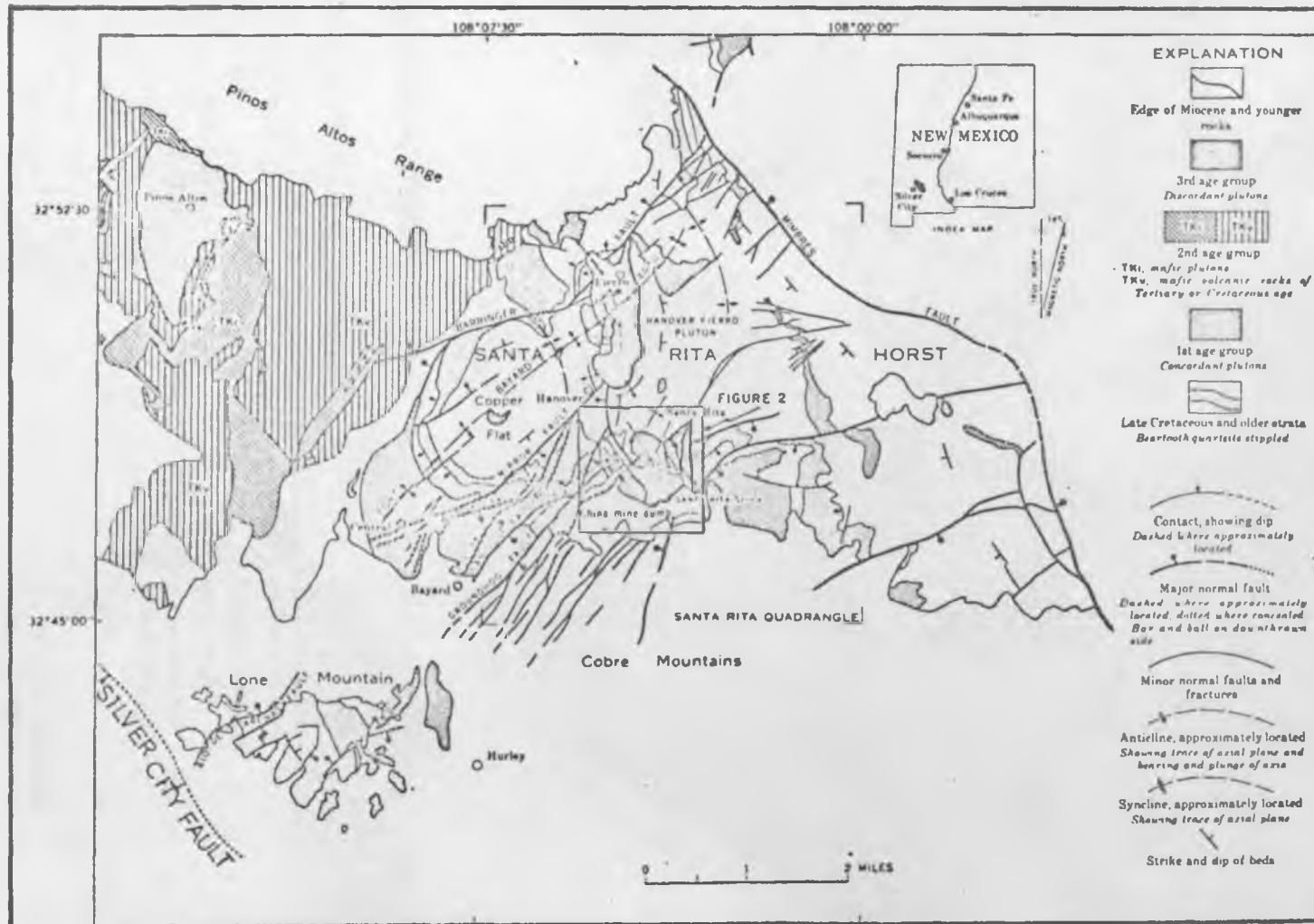


Figure 8. Structural geologic setting of the Santa Rita mining area.--From Jones and others (1967)

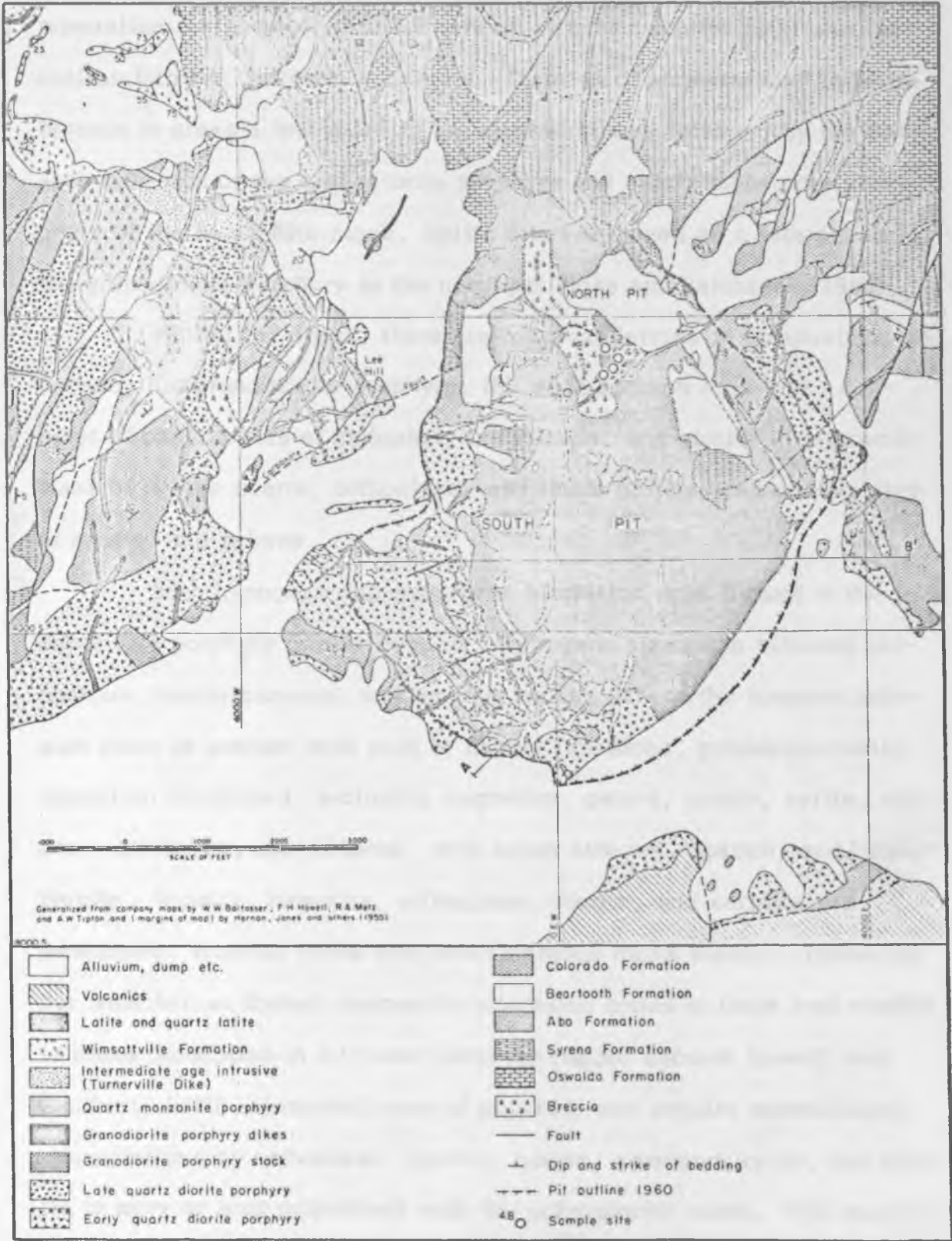


Figure 9. Geologic map of the Santa Rita area, New Mexico.-- After Rose and Baltosser (1966)

The Laramide igneous intrusive events which culminated in mineralization began with the intrusion of quartz diorite sills and laccoliths into the Colorado Formation. Eruption of andesite and andesite breccia in areas a few miles to the northwest was followed by the passive intrusion of the granodiorite porphyry and quartz monzonite porphyry of the Santa Rita stock. Aplite dikes followed as a late phase of the granodiorite porphyry in the north pit (Rose and Baltosser, 1966).

Within the stock, there are local gradations in composition and texture, but granodiorite porphyry, the most common rock type, consists of phenocrysts of andesine, hornblende, and biotite in a groundmass of sparse quartz, orthoclase, and minor biotite, and accessories of apatite and sphene.

Both hypogene and supergene alteration were formed at the Santa Rita porphyry copper deposit. Hypogene alteration affected calcareous, noncalcareous, and igneous rocks. Where the igneous intrusion came in contact with pure or impure limestone, pyrometasomatic alteration developed, including magnetite, garnet, quartz, pyrite, epidote, actinolite, and chlorite, with minor siderite, apatite, and hedenbergite. Locally, hematite, orthoclase, biotite, and sericite are developed. Igneous rocks and noncalcareous rocks reacted differently but nonetheless formed concentric alteration zones in large part similar to those developed in a typical porphyry copper deposit (Lowell and Guilbert, 1970). A central zone of potassic and argillic assemblages characterized by orthoclase, biotite, quartz, montmorillonite, and kaolin is more or less coincident with the granodiorite stock. This central zone alteration, in turn, is followed concentrically outward by a phyllic

assemblage characterized by sericite, quartz, and pyrite, occurring mainly in the margins of the intrusion, in sedimentary rocks, and in quartz diorite sills.

The overall hypogene alteration picture is slightly modified by supergene alteration and apparently, according to Rose and Baltosser (1966, p. 217), "much of the kaolinite and montmorillonite, most of the alunite, some sericite and quartz, and possibly some chlorite are supergene." Supergene alteration affected the phyllic alteration more than the potassic and pyrometasomatic alteration assemblages. This supergene alteration is due to abundance of pyrite and intense fracturing in the phyllic zone. Weak supergene alteration in the potassic alteration assemblage may be due to scarcity of pyrite. Similarly, scarcity of pyrite in addition to the reactivity of carbonate minerals in the pyrometasomatic assemblage may have prevented the development of supergene alteration.

Aplites and Pegmatites. Aplite dikes in the Santa Rita stock were reported by Leroy (1954) to occur in the north pit (Fig. 9). Samples for this study were collected from the "barren island" in the north pit. The "barren island," as indicated by its name, is neither economically mineralized nor affected by hydrothermal alteration.

The entire granodiorite porphyry and quartz monzonite porphyry intrusion and part of the adjoining mineralized sedimentary rocks are included in the Santa Rita open pit. Consequently, any dikes that were present at the surface have been removed by mining. However, Leroy reported that aplite dikes cut granodiorite porphyry in the north pit and that thin horizontal aplite sheets were emplaced along flat-lying joints

developed in the roof of the cooling intrusion. Rose and Baltosser (1966, p. 218) reported that "in the north pit, veins of magnetite and orthoclase are cut by veins or thin aplite dikes containing quartz, orthoclase, calcite, and chalcopyrite." For this study, I was able to locate only five dikes (Fig. 9) in spite of all the help given by the mine geologists. Reconstructing the abundance of aplite dikes reported in the literature and by Baltosser (oral commun., 1972), The Santa Rita intrusion probably contained about 8 to 10 dikes per line mile in the north pit, with an average width of 4 inches, based on width of presently observed dikes which range in width between 3 and 5 inches.

The dikes are pinkish brown, a color that has not been observed elsewhere. Microscopically, dikes show xenomorphic granular texture with an average grain size of 0.5 mm. A large grain size (1-2 mm) aplite is observed in sample 52 (Table 5). Granophyric texture, an intergrowth of quartz and orthoclase, is shown by sample 51. Replacement and vein orthoclase associated with pyrite and chalcopyrite are not uncommon.

Mineral composition is 31-38 percent quartz, 42-56 percent K-feldspar, and 12-21 percent plagioclase. Biotite, magnetite, and pyrite are accessory minerals. The wide compositional range is due to the high content of K-feldspar and low content of quartz and orthoclase in sample 52, which also has larger grains (1.2 mm).

Potassic alteration in sample 52, based on the presence of secondary biotite, vein and replacement K-feldspar, and sericite in plagioclase, is more extensive than that observed in other aplite samples. Quartz forms anhedral, angular, and rounded clear crystals

Table 5. Modal mineralogical composition and grain size of aplites from Santa Rita, New Mexico

Sample No. ¹	Percent by Volume				Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Accessory Minerals	
48	38	42	19	biotite, magnetite, pyrite: ≈ 1	0.50
49	36	44	20	magnetite, pyrite: < 1	0.30
50	35	43	21	biotite, pyrite, magnetite, chalcopyrite: ≈ 1	0.50
51	35	44	21	biotite, magnetite, pyrite: < 1	0.40
52	31	56	12	biotite, pyrite, magnetite: ≈ 1	1.00

1. Sample locations are shown on Figure 9.

with undulose extinction. Coarse-grained quartz occurs in veins with K-feldspar and pyrite. K-feldspar rarely shows carlsbad twinning whereas microcline twinning is absent and perthitic texture is common in twinned and untwinned crystals alike. Based on the presence of carlsbad twinning and the absence of microcline twinning, K-feldspar appears to be orthoclase. Turbid orthoclase forms anhedral to subhedral crystals. Orthoclase, in addition to being a primary aplite mineral, occurs in veins in crystallization association with quartz and pyrite and also in replacement association with plagioclase. Oligoclase (An₁₇) forms anhedral to subhedral crystals with poorly developed twinning. Oligoclase is partly replaced by orthoclase along cleavage planes and also as a discontinuous mantle.

Potassic alteration based on the presence of vein-controlled and replacement orthoclase, sericite in plagioclase, and small greenish-brown flakes of biotite is developed. Pyrite and chalcopyrite are found in veinlets in association with secondary orthoclase or secondary biotite.

Mineralization. Two main types of ore recognized at Santa Rita are the chalcocite secondary enriched ore within igneous rocks, sandstone and shale, and limestone replacement ore, with little or no enrichment. Three zones of relatively high grade ore trend northwesterly, where the widest of them passes about through the center of the intrusion and into the Lee Hill pyrometasomatic ore area, whereas the other two zones are found on the eastern and western margins of the stock. A low-grade zone, which is not mined, forms an island between the north and south pits (Fig. 9).

Supergene mineralization is dominantly chalcocite with minor amounts of covellite. Pyrite and chalcopyrite are by far the dominant sulfide minerals in the hypogene zone, with minor bornite, molybdenite, marcasite, and pyrrhotite.

Sierrita Intrusion

The Sierrita intrusion in the Sierrita Mountains of Pima County is about 20 miles southwest of Tucson, Arizona (Fig. 2). A quartz monzonite facies of this intrusion is spatially related and is believed by Cooper (1960) to be genetically related to the Sierrita, Esperanza, Twin Buttes, Mission-Pima, and Mineral Hill ore deposits (Fig. 10). It comprises an area of 77 square miles with its longest dimension trending

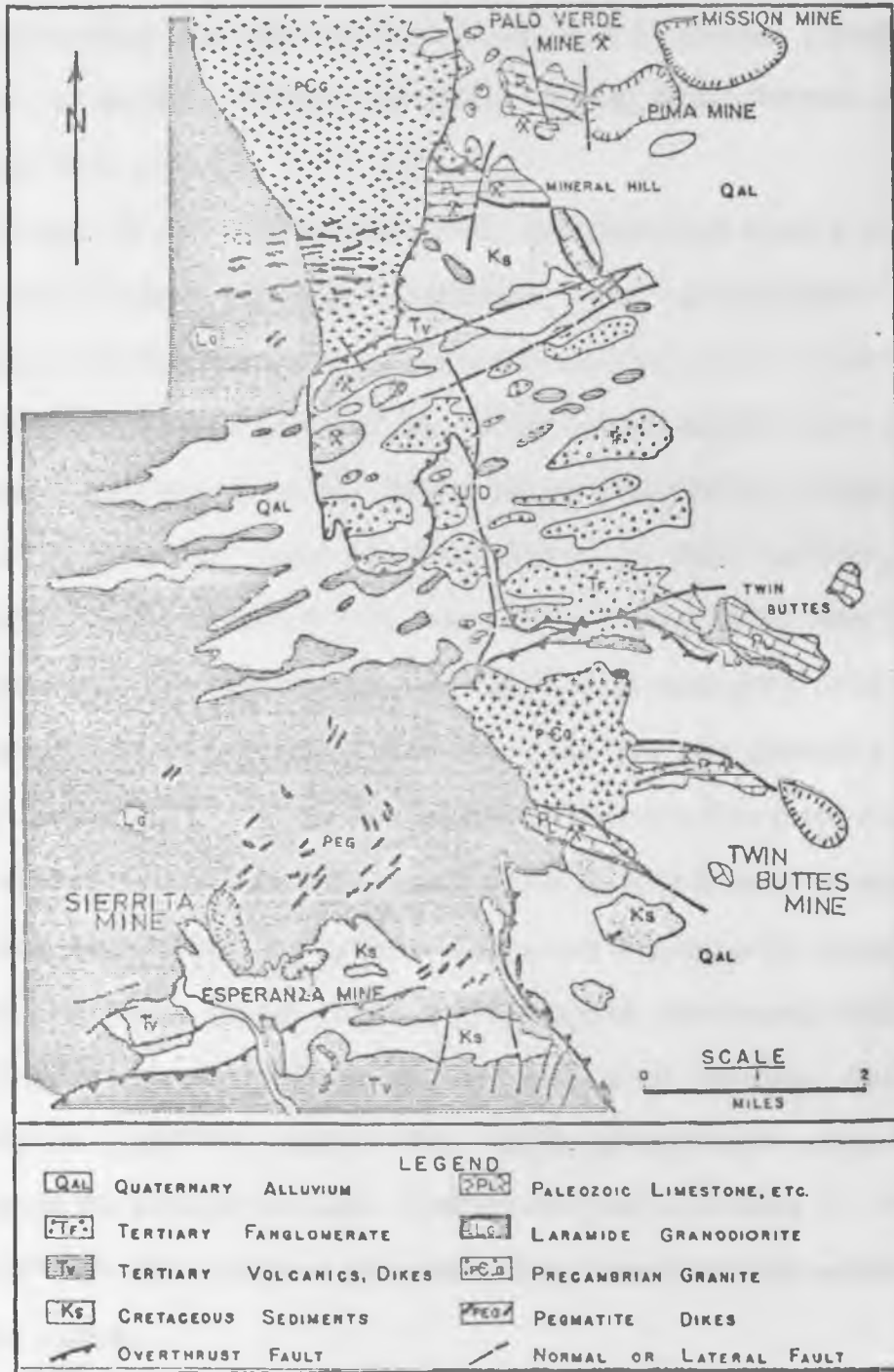


Figure 10. Generalized geologic map of the southeastern part of the Sierrita intrusion, Arizona
 Geology from Lacy and Titley (1962); pit boundary from Cooper (1970)

northwest. The intrusion invaded Precambrian granite, Paleozoic sedimentary rocks, Jurassic(?) Harris Ranch quartz monzonite, and a complex of sedimentary and volcanic rocks assigned by Cooper (1960) to the Cretaceous period. Damon and Mauger (1966) dated Sierrita as 62 m.y. by the K-Ar method.

Cooper (1960) distinguished two deformational events in the district, both of which postdate Cretaceous rocks. An early pre-granodiorite and premineralization orogeny resulted in northwest-trending complex folding and faulting. A late postmineralization and post-Helmet Fan conglomerate event formed large-scale thrust faulting and steep southwest tilting. Lacy and Titley (1962, p. 76), however, proposed another model in which "the major period of thrusting was contemporaneous with the intrusion of the Sierrita batholith" and the "mineralization was essentially post-thrusting and was partially controlled by thrust faults. Post-mineralization faulting has been confined to block subsidence and to minor readjustments which have concentrated in the fringe surrounding the intrusive complex which would have stood as a solid buttress." Lynch (1966) indicated that prominent joint directions strike east-west, north-south, and northwest, dipping, respectively, 40° - 50° N., 60° W., and 55° NE. In the granodiorite about half a mile north of the Esperanza mine, I observed joints striking N. 50° E., dipping 65° - 88° NW. Aplites and pegmatites commonly fill northwesterly striking joints.

The Sierrita intrusive history, according to Cooper (1960) and modified by Lynch (1966), begins with the intrusion of minor diorite followed by granodiorite, quartz monzonite, quartz latite porphyry found

on the southwest side of Esperanza pit, quartz monzonite porphyry, a second diorite, and lastly minor dacite and andesite porphyries. The intrusive history culminated in hydrothermal mineralization (Cooper, 1960; Oakley, 1973). The early diorite is a fine-grained gray rock found in the southern part of the Sierrita intrusion and is composed of 60 percent andesine, 19 percent biotite, and 19 percent hornblende. Accessory minerals include magnetite, sphene, epidote, and apatite.

The Sierrita intrusion is dominantly composed of light-gray granodiorite, which can be divided into three facies: (1) a granodiorite porphyry border facies, (2) medium-grained equigranular granodiorite occurring as zones 0.5 to 2 miles wide along the east side of the intrusion, and (3) a porphyritic granodiorite. According to Cooper (1960), the average constituent minerals are 24 percent quartz, 19 percent perthitic orthoclase, 48 percent oligoclase (An_{30}), 5.5 percent biotite and chlorite, and 3.3 percent hornblende. Zircon, apatite, and magnetite are accessory minerals. Quartz monzonite porphyry is found at the southern end of the Sierrita intrusion in and near the Esperanza mine (Lynch, 1966), near Mineral Hill (Cooper, 1960), in the Pima mine (Cooper, 1960), and at depth near the Mission mine (Richard and Courtright, 1959). The occurrence of quartz monzonite porphyry near several of the ore deposits led Cooper (1960) to suggest a genetic relationship between this rock type and the ore deposits. Mineral composition of the quartz monzonite porphyry includes phenocrysts of perthitic orthoclase, plagioclase, quartz, and biotite in a fine-grained groundmass. The mode is 29 percent quartz, 32-35 percent K-feldspar, 34 percent plagioclase, 4.2 percent biotite and chlorite. Apatite, epidote, and zircon are accessory

minerals. Aplites and pegmatites are associated mainly with the granodiorite.

Hydrothermal alteration at the Esperanza mine can be interpreted in terms of that of the porphyry copper deposits of the Southwest. Taking Sierrita and Esperanza mines together, Oakley (1973) visualized a potassic alteration core with phyllic alteration occurring irregularly outside of it. Potassic alteration, as expressed by the presence of orthoclase along with sericite and silica, is the most prominent alteration. Phyllic alteration of sericite, quartz, pyrite is restricted in distribution, is closely associated with the ore zone, and shows a marked decrease in abundance away from the ore zone, while quartz and K-feldspar remain fairly abundant (Lynch, 1966). Phyllic alteration within the Esperanza mine is practically limited to the igneous intrusive quartz latite porphyry and quartz monzonite porphyry. Weak potassic alteration as orthoclase and biotite is displayed at the sites where aplite and pegmatite samples were collected (Fig. 11).

Ore deposits north of Esperanza mine along the eastern flank of the Sierrita intrusion exhibit alteration assemblages different from that at Esperanza. Alteration at Pima, Mission, and Mineral Hill is principally skarn type in limestone. However, alteration of the argillites, quartzite, and quartz monzonite porphyry at Mission mine produced sericite, clay, biotite, quartz, and orthoclase (Kinnison, 1958).

Aplites and Pegmatites. Aplite and pegmatite dikes occur in the granodiorite and quartz monzonite porphyry, but dikes sampled for this study are located about three-quarters of a mile north of the Esperanza pit in granodiorite (Fig. 11). Veinlets filled by secondary orthoclase and

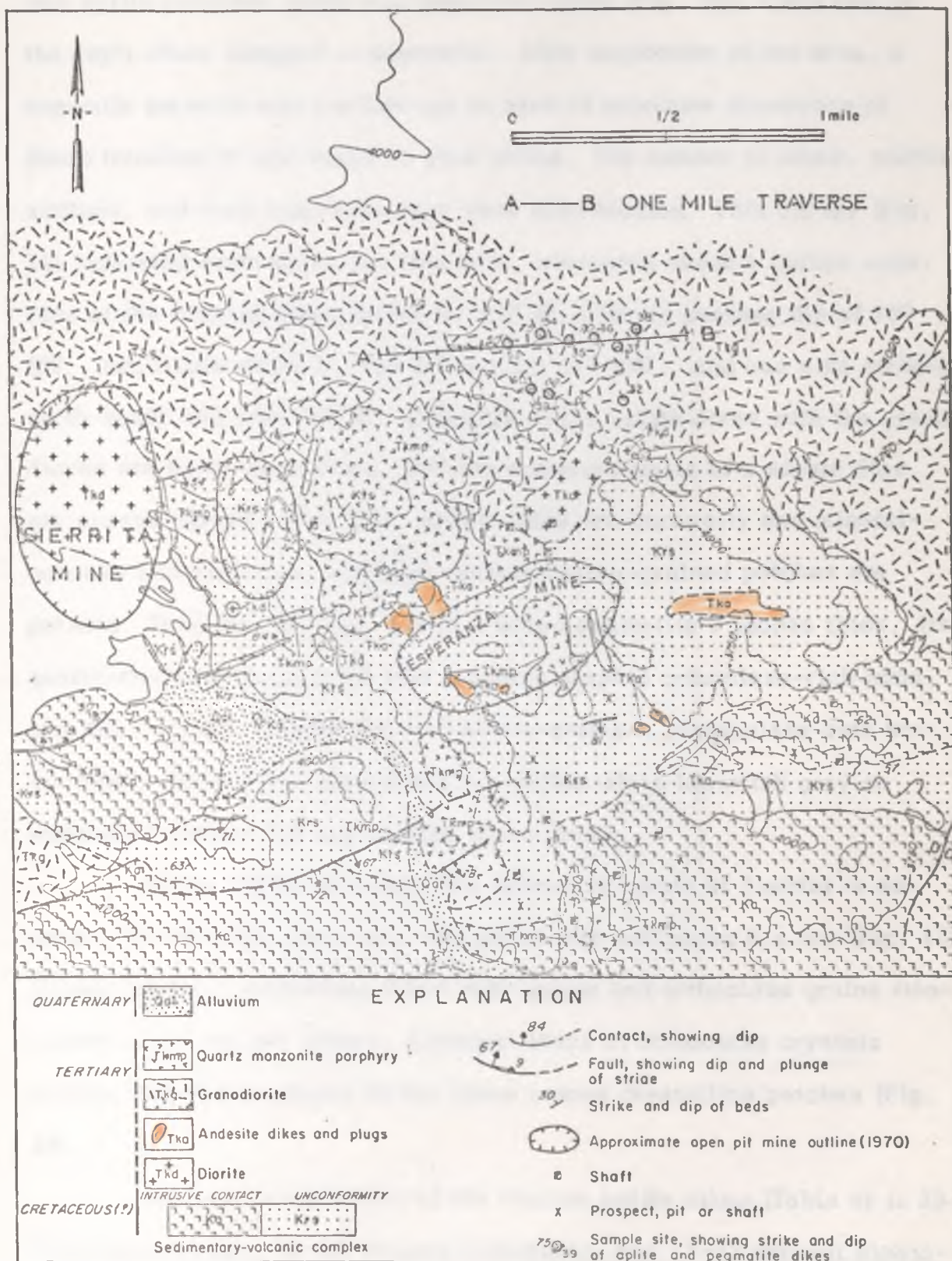


Figure 11. Geologic map of the south part of the Sierrita intrusion, Sierrita Mountains, Arizona.--After Cooper (1960, 1970)

rare pyrite crosscut aplite and pegmatite dikes (Fig. 12). Only one of the eight dikes sampled is pegmatite. After inspection of the area, a one-mile traverse was run through an area of maximum abundance of dikes trending at high angle to their strike. The number of dikes, widths, attitude, and their host-rock type were also studied. This survey (Fig. 11) indicated eight dikes per line mile, averaging about 4 inches wide. Five of the studied dikes strike N. 15° W. with an average dip of 75° SW., two dikes strike N. 30° E. and dip 68° NW., and one dike strikes north-south and dips 70° W. Contacts of the aplite dikes with the granodiorite are knife-edge sharp, and the opposing walls of a single dike are always parallel (Fig. 12). Aplite dikes are texturally and mineralogically homogeneous, although random coarse-grained patches are present. Dike No. 39 (Fig. 11) is a zoned pegmatite 7 inches thick. Its quartz-rich core grades out into a coarse graphic orthoclase-rich zone, and this, in turn, grades out into a fine-grained, plagioclase-rich border zone. Aplites and pegmatites are yellowish to brownish gray on weathered surface but are pinkish where fresh.

Under the microscope, the texture of aplite at Sierrita is sub-croce, xenomorphic granular, with grain size averaging 0.4 mm (Fig. 13). Coarse crystalline patches filled with quartz and orthoclase grains measuring 1.2-2 mm are formed. Euhedral faces of orthoclase crystals project into quartz grains filling these coarse crystalline patches (Fig. 14).

Mineral composition of the Sierrita aplite dikes (Table 6) is 33-38 percent quartz, 41-54 percent K-feldspar, and 12-23 percent plagioclase. Accessory minerals are pyrite, magnetite, biotite, and apatite.



Figure 12. Hydrothermal alteration veinlets (HAV) cross-cutting an aplite dike, southern Sierrita intrusion, Arizona

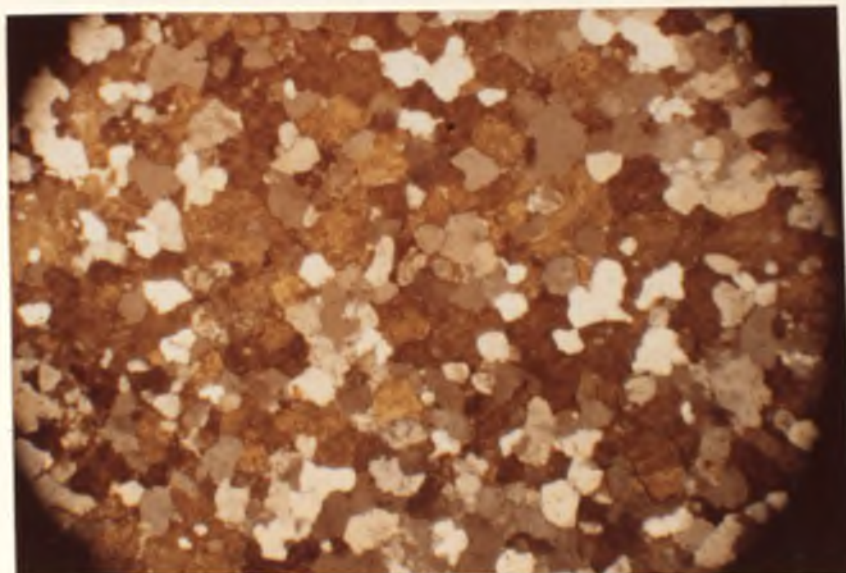


Figure 13. Photomicrograph showing fine-grained, xenomorphic granular texture in aplite dikes, southern part of Sierrita intrusion, Arizona

Stained thin section 33; plane polarized light, X25.

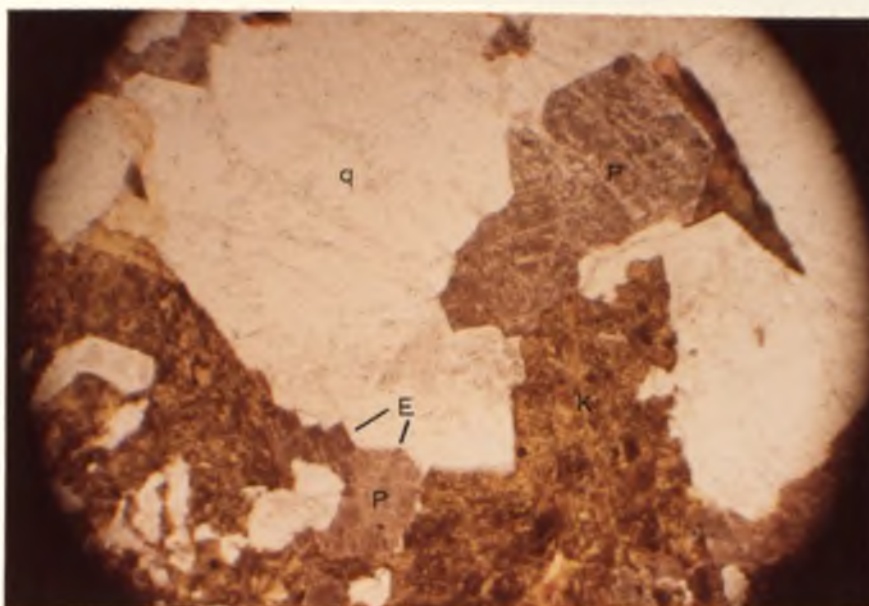


Figure 14. Photomicrograph showing a coarse-grained patch in aplite dike, southern part of Sierrita intrusion, Arizona

Coarse grains of mainly quartz (q), K-feldspar (K), and plagioclase (P), surrounded by fine-grained matrix of same minerals. Euhedral crystal faces (E) project into the coarse-grained patch. Stained thin section 37; plane polarized light, X25.

Table 6. Modal mineralogic composition and grain size of aplites from Sierrita intrusion, Sierrita Mountains, Pima County, Arizona

Sample No. ¹	Percent by Volume				Average Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Accessory Minerals	
32	35	41	23	biotite, magnetite, hematite, pyrite, apatite: ≈ 1	0.40
33	34	54	12	pyrite, hematite: < 1	0.30
34	35	43	22	pyrite, hematite: < 1	0.25
35	37	45	21	pyrite, biotite: ≈ 1	0.25
36	37	43	20	biotite, pyrite, magnetite, hematite: < 1	0.50
37	38	42	20	biotite, pyrite, magnetite, hematite: < 1	0.50
38	35	45	18	biotite, pyrite, magnetite, hematite: ≈ 2	0.35
39 ²	(pegmatite)				3-8
40	33	46	21	biotite, pyrite, magnetite, hematite: < 1	0.40

1. Sample locations are shown on Figure 11.

2. Mineralogic composition of pegmatite was not determined because of its coarse-grained nature.

Quartz forms angular and subrounded, clear crystals showing undulose extinction. K-feldspar forms turbid, anhedral to subhedral crystals and is generally perthitic. Carlsbad twinning, to the exclusion of microcline type, is sparsely developed, indicating that orthoclase forms most of the K-feldspar in this section. Orthoclase is also found in veinlets associated with quartz and pyrite. Subhedral to anhedral plagioclase (An₁₇) is sparsely twinned and slightly sericitized. Locally, they are mantled by orthoclase or replaced along twinning lamellae. Rare equant brown biotite (0.4 mm) is randomly distributed, whereas greenish-brown biotite (0.05 mm) is vein controlled, and both types alter partly or completely to chlorite. Graphic growth (Fig. 15), mutual crystallization boundaries, and scarcity of veins and replacement texture indicate mutual magmatic deposition. Minor, vein-controlled orthoclase, quartz, and biotite with or without pyrite (Fig. 16) indicate secondary origin for these minerals, suggesting minor potassic alteration.

Mineralization. The eastern flank of the Sierrita intrusion and its associated country rocks carry copper, molybdenum, zinc, and lead mineralization. To the southeast are the open-pit copper-molybdenum deposits of Esperanza and Sierrita. About 3.5 miles to the northeast is the Twin Buttes mine. Further north are the Pima and Mission ore bodies (Fig. 10). Ore minerals in Esperanza-Sierrita, Pima-Mission, and Twin Buttes are chalcopyrite, supergene chalcocite where supergene enrichment formed, molybdenite, and pyrite with minor sphalerite and galena. The Mineral Hill deposit to the southwest (Fig. 10) is characterized by significant amounts of sphalerite and galena in addition to chalcopyrite. The ore of the Esperanza mine, with which aplite and pegmatite samples



Figure 15. Photomicrograph showing graphic texture in a pegmatite dike, southern part of Sierrita intrusion, Arizona

Stained thin section 39; plane polarized light, X25.



Figure 16. Photomicrograph showing a veinlet of secondary orthoclase in aplite, southern part of Sierrita intrusion, Arizona

Stained thin section 35; plane polarized light, X25.

are spatially and genetically related, as shall be discussed later, is described by Lynch (1966, p. 275) as

a mixture of hypogene and supergene metallization occurring in veins and as disseminated grains. Roughly surrounding the copper-molybdenum ore zone is an aureole of vein type deposits that was worked for lead, zinc, and silver about the turn of the century. Metallization was associated with more than one intrusive pulse and was followed by a post-intrusive metallization period associated with hydrothermal alteration and potash metasomatism.

Oakley (1973) believes that ore deposition occurred directly after the intrusion of the quartz monzonite porphyry.

Barren Intrusions

Amole Intrusion

The Amole intrusion at the north end of the Tucson Mountains, Arizona, is approximately 20 miles northwest of Tucson (Fig. 2). The exposed portion of the intrusion is about 3 by 4.5 miles across, but the total cross-sectional area may be slightly larger than that showing on the map (Fig. 17), because the northwestern portion of the stock is covered by alluvium. The stock is elongate in a northwesterly direction and intrudes rocks ranging in age from Pennsylvanian to Late Cretaceous (Brown, 1939). Damon, Mauger, and Bikerman (1964) reported a K-Ar age of 73 m.y.

Brown (1939, p. 723) states on the mode of intrusion: "Along the northern contact, the Cretaceous rocks, chiefly the volcanic series, are highly disturbed and altered." This evidence indicates active intrusion of the Amole stock. The stock is strongly jointed in a northeasterly direction parallel to the long axis of the stock and in a northwesterly

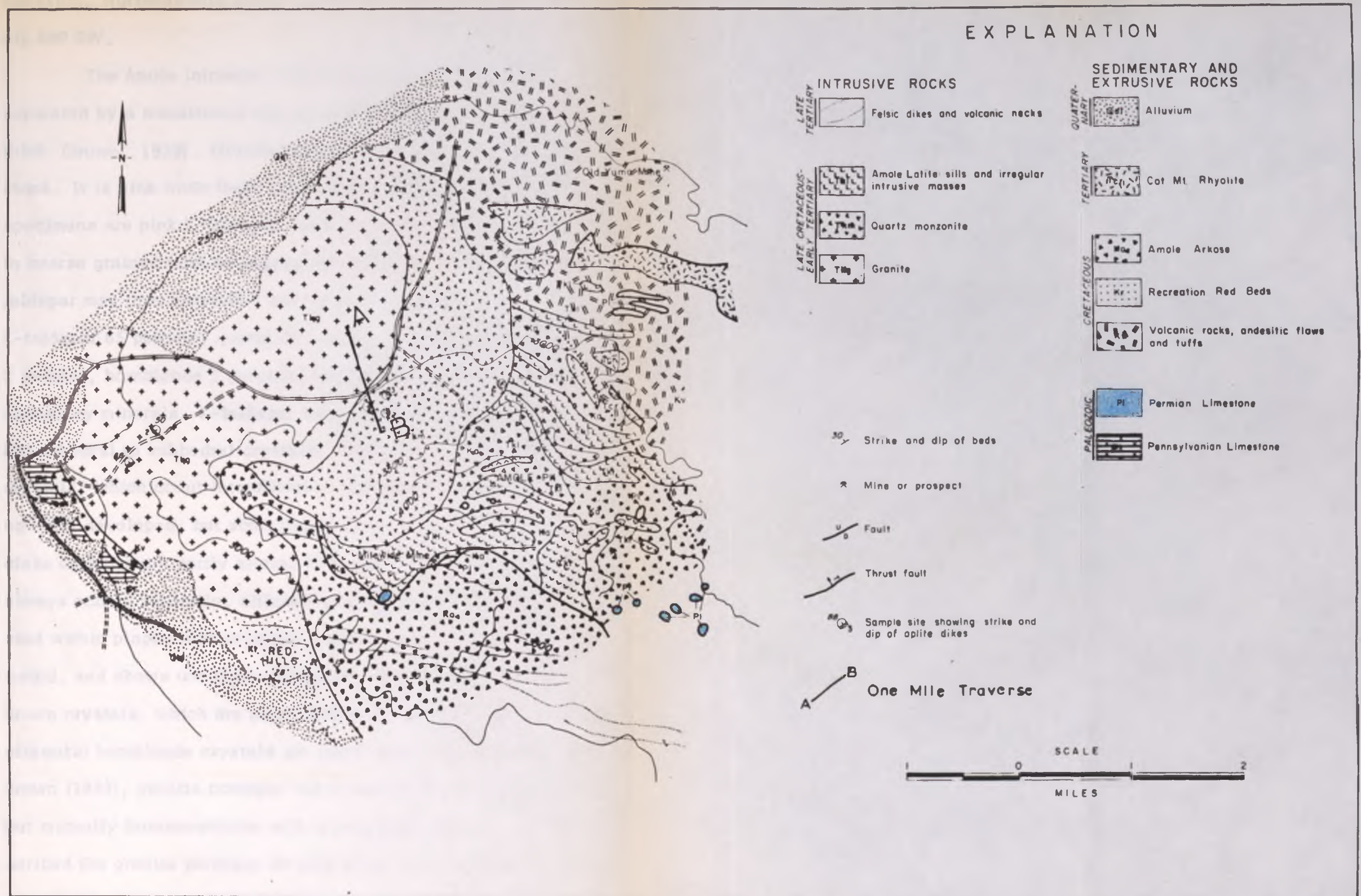


Figure 17. Geology of the Amole stock area, Arizona, showing sample locations.--After Brown (1939)

direction. Northeasterly joints dip 50° SE. and the northwesterly ones dip 88° SW.

The Amole intrusion is formed of granite and quartz monzonite separated by a transitional thin granite porphyry facies 50 to 200 feet thick (Brown, 1939). Granite occupies the western part of the exposed stock. It is pink when fresh and tan when weathered. Visible in hand specimens are pink K-feldspar, quartz, and brown biotite. It is medium to coarse grained with an average grain size of 4 mm, although K-feldspar may form crystals 7 mm long. Its mineral composition is K-feldspar 65 percent, quartz 20 percent, plagioclase 10 percent, biotite 2 percent, hornblende 1 percent, and sphene, apatite, and magnetite as accessory minerals. K-feldspar is perthitic orthoclase which forms turbid anhedral to subhedral crystals. Plagioclase (An_{19}) forms subhedral crystals, which occur interstitial to quartz and orthoclase. Twinning is not well developed, but some plagioclase crystals may be zoned. Plagioclase crystals are partly altered to sericite and minor kaolinite. Sericite always occurs centrally, although in some instances it is evenly distributed within plagioclase crystals. Quartz is round to angular, slightly turbid, and shows undulose extinction. Biotite forms equant greenish-brown crystals, which are partly altered to chlorite and magnetite. Green prismatic hornblende crystals are partly altered to chlorite. According to Brown (1939), granite porphyry has a transitional contact with granite but mutually interpenetrates with quartz monzonite. Brown (1939) described the granite porphyry as pink when fresh but light tan where weathered. Andesine and microperthite phenocrysts occur in an aplite

groundmass of quartz, microperthite, plagioclase, and biotite. Accessory minerals are magnetite, sphene, and hornblende.

Quartz monzonite occurs west and northwest of Amole Peak and encircles the northeasterly portion of the granite (Fig. 17). It is a fine-grained gray rock spotted by dark crystals of biotite and hornblende. Microscopically, it has a hypidiomorphic granular texture with an average grain size of 2.5 mm. Mineral composition is quartz 15 percent, K-feldspar 27 percent, plagioclase 44 percent, biotite 7 percent, hornblende 3 percent, and magnetite 2 percent. Sphene, apatite, and pyrite are accessory minerals. Quartz forms angular anhedral clear crystals with undulose extinction. Orthoclase forms anhedral to subhedral and in rare cases occasional euhedral crystals. It locally forms mantles around plagioclase crystals. Plagioclase (An₂₈) forms subhedral tabular crystals with well-developed albite twinning and common zoning. Few crystals are altered centrally to sericite. Brown biotite occurs as subhedral flakes which alter marginally or along cleavage to chlorite. Green anhedral hornblende crystals alter marginally or along cleavage planes to chlorite with release of magnetite. Sericitic alteration is not guided by veins or fractures and is probably of deuteritic origin.

Aplites and Pegmatite. Except for sample 6 (Fig. 17), aplite and pegmatite dikes sampled for this study are located near the center of the stock in granite and quartz monzonite. Sample 6 was collected near the eastern contact of the stock. Samples 3, 4, and 5 were closest to known mineral prospects and were taken about 1.5 miles from the Mile Wide mine (Fig. 17).

Except for a single pegmatite dike, all dikes encountered in the Amole stock are aplitic. Dikes fill northeasterly and northwesterly striking joints (Fig. 17) and can be traced into ridge-forming sedimentary rocks between granite and quartz monzonite exposures (Brown, 1939). Although sparse dikes about two inches thick may be found everywhere in the stock, the maximum concentration and thickness is found about 1.5 miles west of Amole Peak. Seventeen dikes were counted per line mile (Fig. 17), with widths ranging between 3 and 72 inches. Dikes are generally covered by rubble or pediment gravels, and it was difficult to estimate their lengths. They may form en echelon, and some are observed to taper away and disappear, with no abrupt termination observed.

Contact of dikes against host rock is observed to be sharp at less than 0.05 inch (Fig. 18). Aplite dikes are also homogeneous in texture and mineralogy across their width, except for randomly distributed coarse-grained patches. No chilling effect, as indicated by small grain size, is observed, and similarly there is no apparent exchange in chemical components of aplite or pegmatite dikes and the immediate host rocks. Sharp contacts are marked by abrupt sharp differences in mineralogy and grain size of dikes and host rocks.

Under the microscope, the aplite dikes have a sugary, xenomorphic granular texture with grain size averaging 0.30 mm (Table 7). Some random patches, however, are composed of minerals up to 0.8 mm. in size. Granophyric texture is developed in sample 3 (Fig. 17).

Quartz at 34 percent, K-feldspar at 37 percent, and plagioclase at 28 percent are the principal minerals, with accessory biotite,

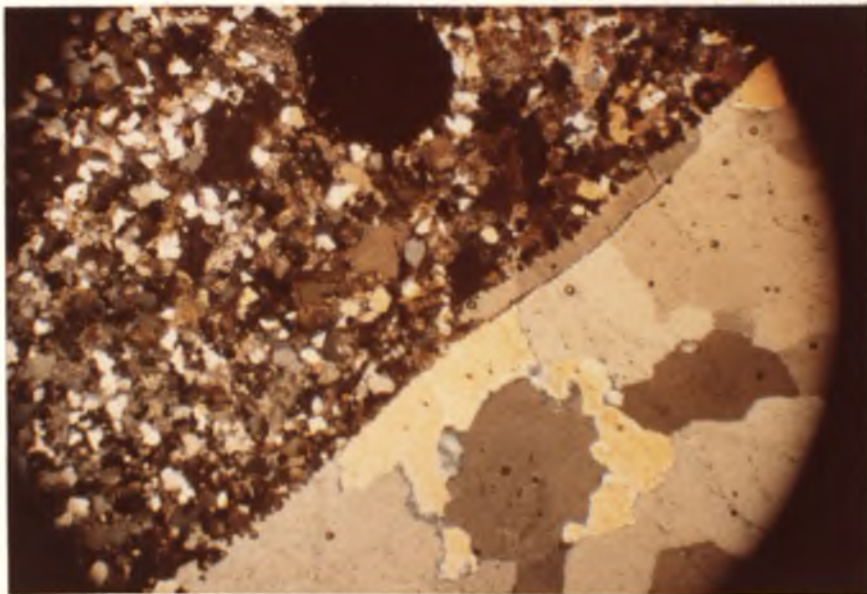


Figure 18. Photomicrograph showing contact relationship between aplite and coarse-grained quartz vein, Amole stock, Arizona

Stained thin section 5; crossed nicols, X25.

Table 7. Modal mineralogic composition and grain size of aplites from Amole stock, Tucson Mountains, Arizona

Sample No. ¹	Percent by Volume				Average Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Accessory Minerals	
1	35	36	29	sphene, biotite, magnetite, pyrite: <1	0.3
2	33	41	25	magnetite, biotite, sphene: ≈ 1	0.28
3	33	36	30	biotite, magnetite: ≈ 1	0.28
4	33	37	28	magnetite, biotite: ≈ 2	0.30
5 ²	(pegmatite)				
6	34	38	35	biotite: magnetite: ≈ 3	0.50

1. Sample locations are shown on Figure 17.

2. Mineralogic composition of pegmatite was not determined because of its coarse-grained nature.

magnetite, and sphene. Clear quartz grains are anhedral angular to rounded and show undulose extinction. Most K-feldspar is untwinned, but those that are twinned show carlsbad twinning only. It is therefore inferred that most of the K-feldspar is orthoclase as anhedral to subhedral turbid crystals. It includes plagioclase and quartz and, in turn, is included by either of the two minerals. Plagioclase (An₁₀) is anhedral to subhedral and twinning is poorly developed. Plagioclase is altered to sericite and is occasionally rimmed with orthoclase. Brown flakes of

biotite are altered along cleavage or peripherally to chlorite. Apparently, alteration is not structurally directed because sericite and orthoclase are not observed to fill veinlets.

Mineralization. The Amole stock has no known significant associated mineral production. Mineral prospects of copper, lead, zinc, molybdenum, and vanadium occur in the sedimentary and volcanic rocks that the stock intrudes (Jenkins and Wilson, 1920; Kinnison, 1958). Pyrometasomatic mineralization principally in Paleozoic and Cretaceous limestone is exposed in the Mile Wide mine (Copper King), the Gould mine, the Copper Bell mine, and other prospects to the east of the Amole stock (Fig. 17). Mineralization includes chalcopyrite, pyrite, malachite, and other minor copper oxides. Fissure veins carrying molybdate and vanadate minerals occur in the Cretaceous volcanic rocks north of Amole Peak (Brown, 1939). Such veins have in the past been worked at the Old Yuma mine.

Time relationships between aplites-pegmatites and mineralization are not clear because the two do not occur together. However, the presence of sericite alteration and scarce malachite in aplite indicate that aplites are older than mineralization.

Swisshelm Intrusion

The Swisshelm intrusion on the west side of the Swisshelm Mountains, Cochise County, Arizona (Fig. 2) is about 7 miles east of the town of Elfrida and 20 miles north of Douglas, Arizona. The main exposed part of the stock comprises a 1.5 square mile area, although the actual area may be larger since the western border is covered by

alluvium (Fig. 19). The stock intruded rocks of late Paleozoic age (Naco Group) and Early Cretaceous age (Bisbee Group) and was dated by Damon (oral commun., 1973) as 30.2 m.y. by the K-Ar method.

Physiographically, the intrusion forms two ridges referred to by Diery (1964) as the north and south spurs (Fig. 19). It is strongly fractured with steeply dipping joints striking northeast and northwest. Fracturing is assigned to more than one age, since a fracture filled by aplite is offset by a later fracture also occupied by aplite (Fig. 20).

Diery (1964) recognized four facies in the quartz monzonite intrusion. According to him a normal quartz monzonite facies includes the northern spur, the eastern part of the southern spur, and other small outcrops to the south of the southern spur (Fig. 19). It is light gray to light pinkish gray where fresh and light brownish gray on weathered surfaces. It is porphyritic with orthoclase phenocrysts in a medium-grained equigranular groundmass. Constituent minerals, according to Diery (1964), are 20-27 percent quartz, 37-45 percent perthitic orthoclase, 23.5 percent plagioclase (An₃₀₋₂₀). Plagioclase is locally altered to sericite or coarse muscovite. Biotite, generally uniformly distributed, constitutes 4-5 percent of the rock. It is partly or completely altered to chlorite and is rarely interlaminated with, or surrounded by, muscovite. Magnetite, apatite, and sphene are accessory minerals. Alteration minerals are fluorite, calcite, sericite, and chlorite.

The "altered" quartz monzonite facies is confined to the western part of the southern spur. Other than its intense weathering and extensive hydrothermal alteration (Diery, 1964), it is similar in mineral composition to the "normal" quartz monzonite facies. Perthitic

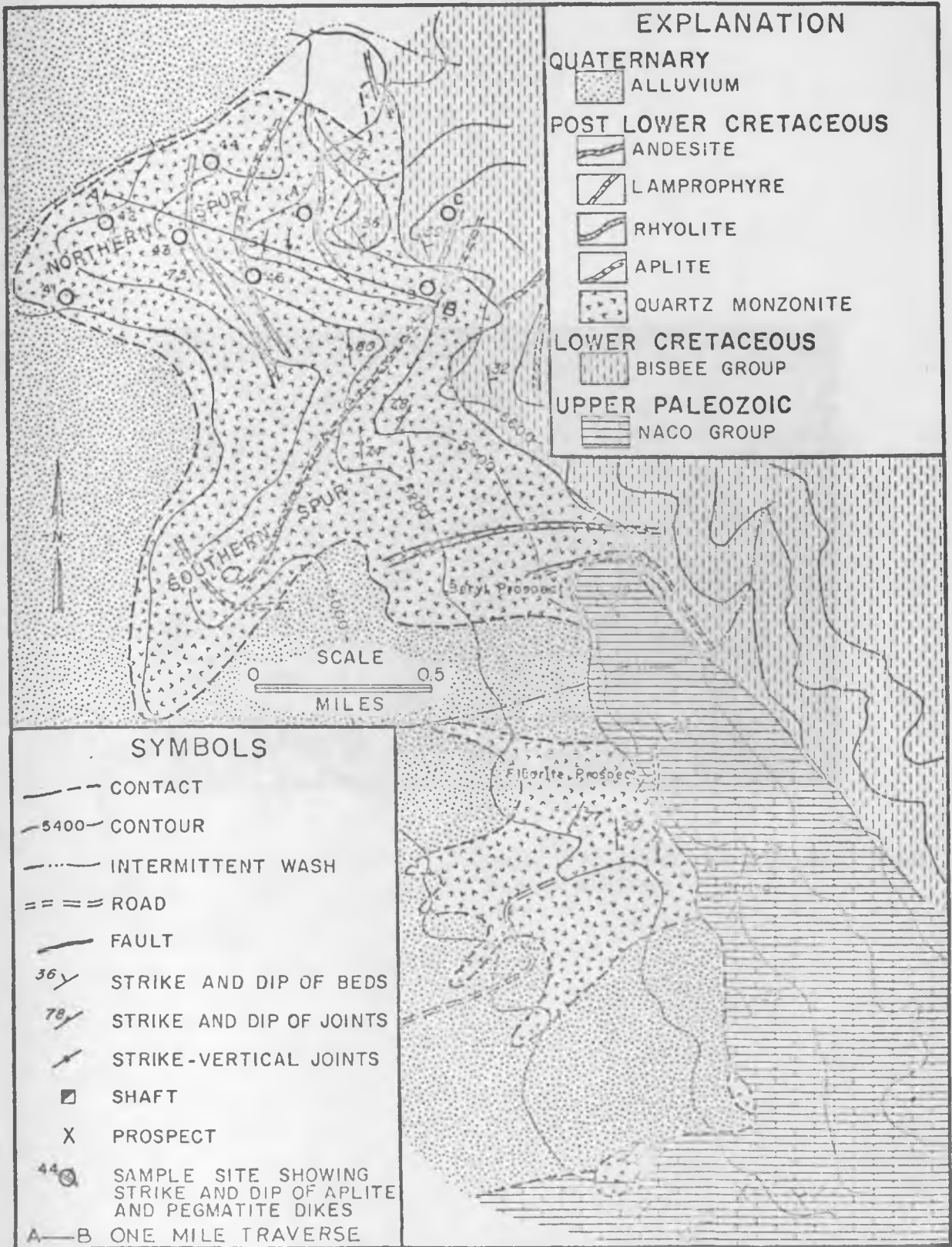


Figure 19. Geology of the Swisshelm stock, Arizona.--After Diery (1964)



Figure 20. Aplite dike filling a joint offset by a younger joint also filled with aplite, Swisshelm stock, Arizona

Sample location 45.

orthoclase is turbid and most of the plagioclase is extensively altered to sericite, muscovite, and minor clay minerals.

A third type is a fine-grained felsic rock associated with the altered quartz monzonite of the southern spur. It is light brownish to light olive gray and is porphyritic with orthoclase and mica phenocrysts. The fine-grained (0.5 mm) groundmass shows graphic texture. Diery (1964) reported its mineralogical composition as 16-22 percent quartz, 41-47 percent orthoclase, 1-2 percent microcline, 11-14 percent oligoclase, 5-8.5 percent mica, mainly muscovite, and 2.5-3 percent magnetite. Accessory minerals are apatite, sphene, zircon, and fluorite. Oligoclase phenocrysts are altered to sericite and muscovite.

A contact facies of diorite, monzonite, and syenite is confined to the contact of the intrusion with the metamorphosed Paleozoic rocks. Desilication and alkali metasomatism of the quartz monzonite are considered by Diery (1964) to have formed these three types of rocks. Diery (1964) believed that the Swisshelm quartz monzonite was derived by differentiation and late-stage alkali metasomatism of a probable quartz diorite magma rich in alkali and volatile constituents.

An inclusion of Bisbee Group in the northern spur of the quartz monzonite (Fig. 19) has an internal structure similar to that of the Bisbee Group and does not show evidence of disturbance. It is therefore considered to be a roof pendant.

Aplites and Pegmatites. Dikes of aplites and pegmatites are scattered all over the Swisshelm stock, particularly the northern spur (Figs. 19 and 21). Samples for this study were collected from this portion of the stock. There is apparently no sulfide mineralization in the



Figure 21. Abundant aplite and pegmatite dike population in the northern spur of the Swisshelm stock, Arizona

Swisshelm stock, but beryl and fluorite prospects are located about a mile to the southwest of the sampled area. Based on petrographic study, fluorite and minor secondary K-feldspar and sericite postdate aplite dikes.

Abundant aplites and pegmatites occur in the Swisshelm stock, with aplite dominant. Mixed aplite-pegmatites are common, with pegmatite usually occupying the centers of dikes. Pegmatite facies in aplite dikes become more common on the northern spur as the eastern contact of the stock with the Bisbee Group is approached. Similarly, grain size increases from 0.4 to 1.4 (Table 8) and muscovite becomes more abundant as the eastern contact of the stock is approached from the east. Aplite dikes in the western portion of the northern spur are pinkish, whereas those to the west are grayish white. Increase of grain size of pegmatite in aplite dikes and of muscovite content as one goes west along the northern spur is taken here to indicate increase of volatile content of the system toward the east, which, in turn, may indicate that the Swisshelm intrusion is structurally higher on the east. The contacts of aplite dikes with quartz monzonite host rock are sharp (Fig. 22) and where pegmatite is absent, aplite dikes are texturally and mineralogically homogeneous across their width, although randomly distributed coarse-grained patches occur in the aplite dikes.

Steeply dipping dikes striking northwesterly and northeasterly fill joints in the quartz monzonite and surrounding rocks. Dikes of at least two ages are observed, as some dikes cut and offset others (Fig. 20).

Table 8. Modal mineralogic composition and grain size of aplites, Swisshelm stock, Swisshelm Mountains, Arizona

Sample No. ¹	Percent by Volume					Average Grain Size (mm)	
	Quartz	K-feldspar	Plagioclase	Muscovite	Accessory Minerals		
41	37	31	32	--	muscovite, biotite, magnetite	<1	0.4
42	33	34	33	--	muscovite, biotite, magnetite	<1	.35
43	32	34	34	--	muscovite, biotite, magnetite	<1	.5
44	35	33	32	--	muscovite, biotite, magnetite	<1	.4
45	36	32	28	3.7	biotite, magnetite, fluorite	<1	1.2
A	32	32	34	2.0	biotite, magnetite, fluorite	<1	1.3
B	33	37	27	2.0	biotite, magnetite, fluorite	<1	1.4
C	31	33	33	3	biotite, magnetite, fluorite	<1	1.4

1. Sample locations are shown on Figure 19.



Figure 22. Sharp contact relationship between aplite and quartz monzonite, Swisshelm stock, Arizona

In thin section, dikes have sugary xenomorphic granular texture. The pinkish aplites have a grain size of 0.4 mm, while the grayish white ones have an average grain size of 1.2 mm. Constituent minerals of the pinkish aplite variety are 32-37 percent quartz, 31-34 percent K-feldspar, and 32-34 percent plagioclase. Accessory minerals are magnetite, sphene, biotite, and muscovite. Clean quartz crystals are anhedral and subrounded to angular with undulose extinction. Turbid perthitic K-feldspar forms subhedral to anhedral crystals and includes minor muscovite. Rare carlsbad twinning indicates the presence of orthoclase; this mineral probably accounts for most of the K-feldspar in the rock. Subhedral to anhedral crystals of oligoclase (An₁₅) are sparsely twinned and contain minor inclusions of muscovite. Oligoclase locally shows sericitic alteration. The grayish-white aplite dikes are composed of 31-36 percent quartz, 32-37 percent K-feldspar, 27-35 percent plagioclase, and 2-3.7 percent muscovite. In contrast to the pinkish dikes, the grayish-white aplite dikes show abundant microcline and their plagioclase is well twinned and has more included muscovite. Fluorite and magnetite are accessory minerals.

Diery (1964) detailed aplite dike compositions in the Swiss-helm stock as being 31-38 percent quartz, 37-51 percent K-feldspar, 10-23 percent plagioclase, 0.5-4.5 percent muscovite, 0.5-1 percent biotite, and 1.5-2.5 percent others. The differing mineral abundances reported by Diery are irreconcilable with those reported earlier by me. Chemical composition calculated from determinations of the new modal mineralogic composition data agrees well with chemical composition of the same rocks determined by atomic absorption. Magmatic texture

including mutual crystallization boundaries, graphic texture, and lack of pervasive hydrothermal alteration are invoked.

Mineralization. No sulfide mineralization has been observed within or outside the stock in the surrounding metamorphosed country rocks. A few fluorite and beryl prospects are found in the southern portion of the stock (Fig. 19). Beryl and fluorite occur as patches or as disseminations in aplite-pegmatite dikes. Their economic significance is doubtful as they have not been extensively prospected or developed.

Texas Canyon Intrusion

The Texas Canyon quartz monzonite intrusion is located about 12 miles northeast of Benson, Arizona, along U.S. Interstate 10 (Fig. 2). The intrusion is very well exposed by the Texas Canyon drainage system and forms the southeastern half of the Little Dragoon Mountains (Fig. 23). Although the full size of this intrusion is probably larger, its outcrop is roughly 4 by 6.5 miles, with the long axis trending northeast.

The Texas Canyon intrusion invaded rocks ranging in age from Precambrian to Late Cretaceous. Livingston and others (1967) dated the intrusion at 47.4-54.2 m.y. by the K-Ar method. Contact relations suggest steep, generally concordant contact walls with the Pinal Schist in the north and northwest and discordant walls where it cuts post-Pinal Schist rocks. Contact relations at the south end of the mass suggest that it has a gently arched irregular roof, which has not been completely uncovered by erosion. Quartz monzonite and associated aplite dikes west of the town of Dragoon (Fig. 23) contain large inclusions that evidently represent roof pendants because their internal structure conforms

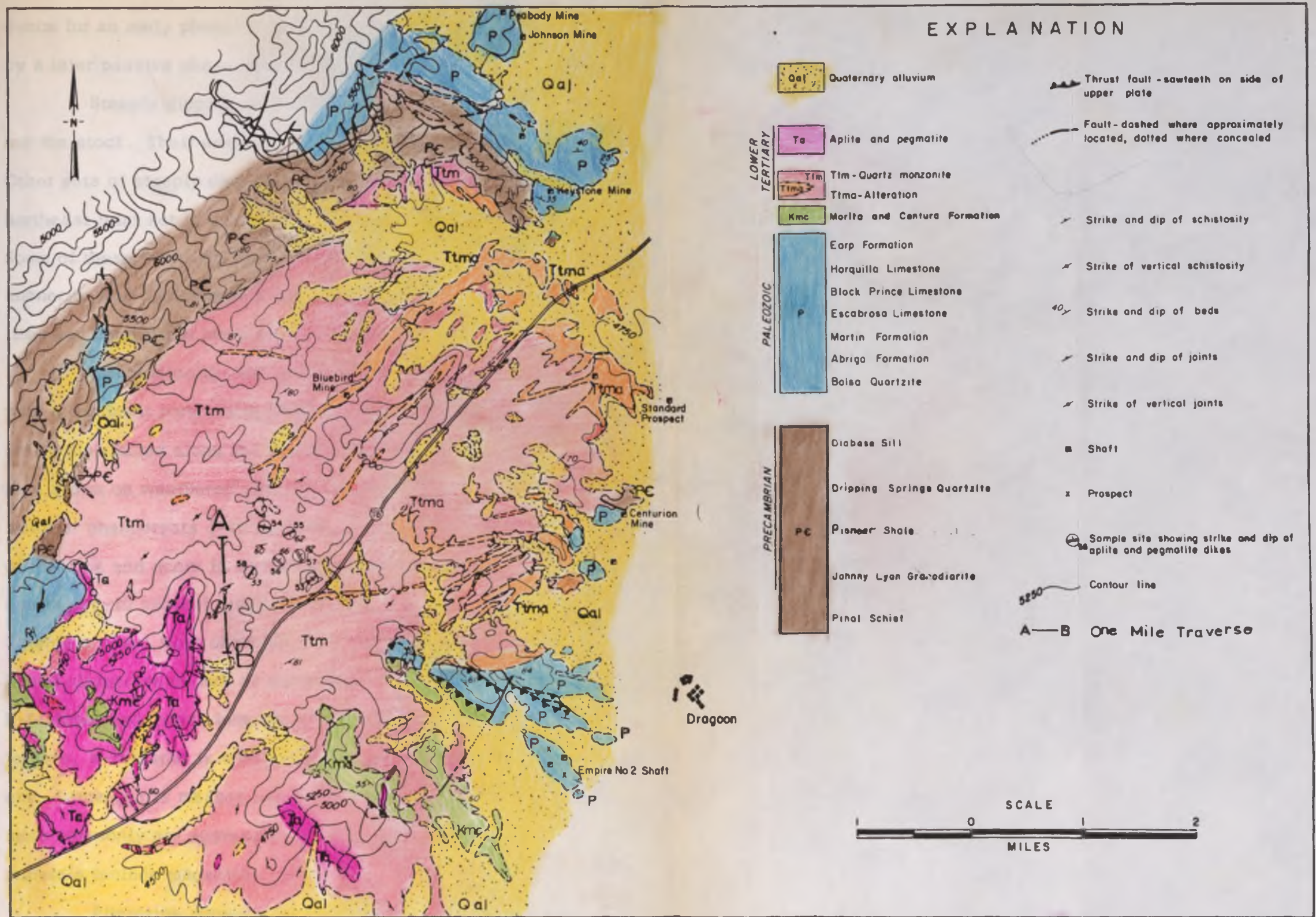


Figure 23. Geologic map of the Texas Canyon stock area, Cochise County, Arizona, showing sample locations.--Modified from Cooper and Silver (1964)

to that of the walls. According to Cooper and Silver (1964), there is evidence for an early phase of forceful injection in the southwest followed by a later passive phase of magmatic stoping in the east.

Steeply dipping northeasterly joints are conspicuous throughout the stock. Their average strike is N. 45° E. with 86° SE. dips. Other sets of steeply dipping joints are developed locally. The dominant northeast joint set is generally parallel to the long axis of the stock. Some of these joints are locally mineralized by veins of quartz in which hubnerite was detected in a few places (Cooper and Silver, 1964). Apatites and pegmatites are also observed to fill these joints.

Lithologically, the Texas Canyon stock is a quartz monzonite with a dominant porphyritic phase and a minor nonporphyritic phase generally distributed along the external contacts. The porphyritic phase is pale brown on weathered surfaces and light gray on fresh fractures. K-feldspar phenocrysts 1-10 cm long, averaging 3-4 cm, form 2-5 percent of the rock and occur in a medium-grained groundmass of 30-35 percent quartz, 30-40 percent plagioclase, 25-30 percent K-feldspar, and about 5 percent mica, most of which is biotite (Cooper and Silver, 1964). Zoned oligoclase occurs as anhedral to subhedral crystals 1-4 cm long. K-feldspar and quartz form the groundmass and give the rock a granitoid texture. K-feldspar is microcline, although orthoclase may also be present. Large quartz masses are in part single subhedral crystals but much more commonly are aggregates of small anhedral crystals. Accessory minerals include magnetite, apatite, and minor zircon.

Alteration minerals form scattered patches and lenses commonly in the northeastern portion of the stock (Fig. 23). Alteration commonly

consists of sericitization of plagioclase and chloritization of biotite. K-feldspar is generally unaltered.

Aplites and Pegmatites. Aplites and pegmatites occur abundantly in the Texas Canyon stock, especially in the southern portion. A one-mile traverse A-B (Fig. 23) intersected 45 dikes, ranging in width from 4 to 23 inches, averaging 13 inches. Dikes sampled for this study are located in the center of the stock, about 2.5-3 miles from the Empire No. 2 shaft and the Centurion mine and 5 miles from the Johnson Camp mine. They show no hydrothermal alteration. Dikes are younger than the quartz monzonite but older than the mineralization. Dikes generally follow the attitude of joints (N. 45° E., 87° SE.). Some dikes bifurcate or suddenly change direction giving rectilinear patterns (Fig. 24). Dikes are also traceable continuously from within the stock into the surrounding country rocks.

Dikes commonly occur as aplite, pegmatite, or a combination of the two, although single aplite occurrence is always dominant. Where both occur in a single dike, pegmatites occur as discontinuous bands located centrally or peripherally (Fig. 25). Dike-host rock contacts are always sharp. Dikes are grayish white.

Texturally, aplite is sucrose, xenomorphic granular. Dikes 53- to 57 (Table 9) located near the center of the stock are coarser grained (0.7 mm average) than dikes 58 to 60 (0.3 mm average) located to the south. Muscovite shows preferred orientation and evidence of strain by the bending of muscovite flakes, bending of plagioclase twinning, and undulose extinction of quartz. A thousand-point count of six stained thin sections indicate a mineral composition of 32-37 percent quartz,



Figure 24. Rectilinear pattern generated by bifurcating aplite dikes that change strike sharply, Texas Canyon stock, Arizona

Sample location 55.

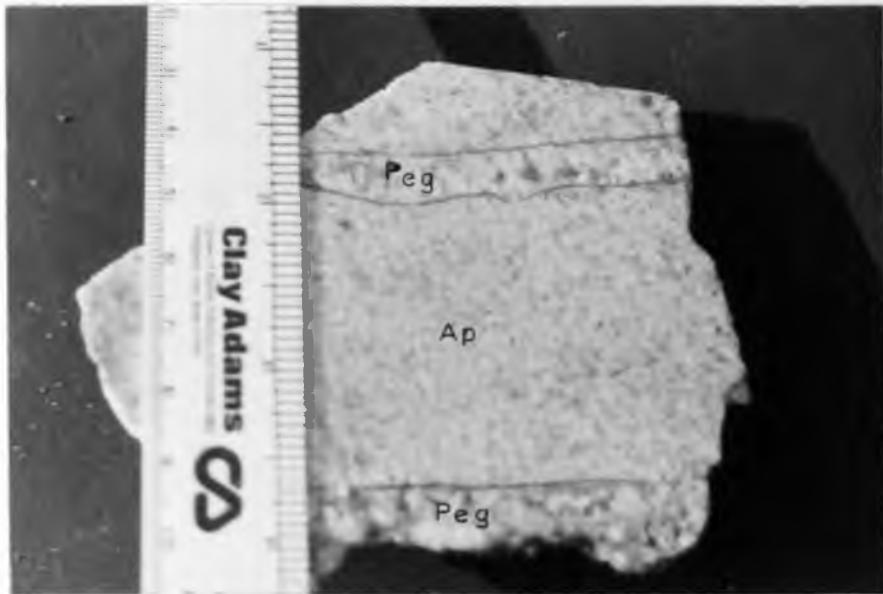


Figure 25. Pegmatite bands (Peg) occurring peripherally in an aplite dike (Ap), Texas Canyon intrusion, Arizona

Sample location 54.

Table 9. Modal mineralogic composition and grain size of aplite dikes, Texas Canyon stock, Little Dragoon Mountains, Cochise County, Arizona

Sample No. ¹	Percent by Volume						Average Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Muscovite	Accessory Minerals		
53	36	18	33	13	magnetite	<1	1.5
54	32	31	31	6	garnet	<1	0.7
55	34	17	37	12	garnet	<1	0.65
56	32	20	36	12	garnet	<1	0.5
57 (pegmatite)							
58	32	24	36	8	garnet	<1	0.3
59	37	29	30	4			0.3
60 (pegmatite)							

1. Sample locations are shown on Figure 23.

17-29 percent K-feldspar, 30-27 percent plagioclase, and 4-12 percent muscovite. Accessory minerals are magnetite and garnet. The wide spread in range of K-feldspar and muscovite is due to the formation of muscovite apparently at the expense of K-feldspar. Mineral composition indicates that wherever values of K-feldspar drop muscovite values pick up and also that combined values of K-feldspar and muscovite are similar among the six thin sections. Quartz occurs as clear anhedral sub-rounded fractured grains and has undulose extinction. Microcline is the principal K-feldspar, although perthitic orthoclase is also developed. Plagioclase (Ang) forms subhedral to anhedral crystals, which include or are surrounded by muscovite. Twinning is generally well developed, sometimes incomplete, and rarely absent. Muscovite occurs as subhedral flakes interstitial to quartz, microcline, and plagioclase and locally included in the last. A magmatic origin of muscovite is based on its equant crystal form, interstitial occurrence to magmatic minerals, and random distribution. Garnet is an accessory mineral not common to all thin sections.

Mineralization. Pyrometasomatic copper and zinc replacement ore deposits at Johnson Camp yielded about 1,130,000 tons of ore valued at \$25,600,000 by the end of 1959 (Cooper and Silver, 1964). Ore minerals are sphalerite, chalcopyrite, with minor bornite in association with pyrite, minor scheelite, and traces of molybdenite (Cooper and Silver, 1964). Other prospects of the Johnson Camp type occur in the surrounding rocks near the eastern contact of the Texas Canyon stock. Intensive mineral exploration is presently going on in the alluvium to the east and northeast of the stock. Although no announcements have

been released, drilling has apparently indicated the presence of two mineral deposits to the east of the stock, the extent and source of which are not yet known.

Whetstone Intrusion

The Whetstone intrusion of the Whetstone Mountains lies about 16 miles southwest of Benson (Fig. 2) and covers an area of about two square miles in the Whetstone Mountains. Whereas the Whetstone Mountains trend northwesterly, the stock itself is elongate in an east-west direction. Although the topography is rugged, access to the intrusion is provided by primitive roads. It intruded Permian carbonate and arenaceous rocks and Cretaceous sandstone, conglomerate, and carbonates, which are overlain by rhyodacite of middle Cretaceous age (Fig. 26). Potassium-argon dating indicates an age of 74 m.y. (Creasey, 1967). The intrusion is strongly jointed, with an east-west striking set of joints parallel to the long axis of the intrusion, dipping about 60° SE. and a northeasterly set striking about N. 20° E., dipping about 68° SE. Sedimentary rocks surrounding this intrusion are disturbed as evidenced by steepening and erratically disturbed strikes of beds. These features indicate that the stock was actively emplaced: The stock and some satellite intrusions were mapped by Creasey (1967) as granodiorite.

V. D. De Ruyter (oral commun., 1971) believes that the intrusion is not homogeneous granodiorite but also includes quartz monzonite. This observation is confirmed by samples collected for this study. Granodiorite is grayish black where fresh, is hypidiomorphic granular and its constituent minerals are 9 percent quartz, 3 percent K-feldspar, 54

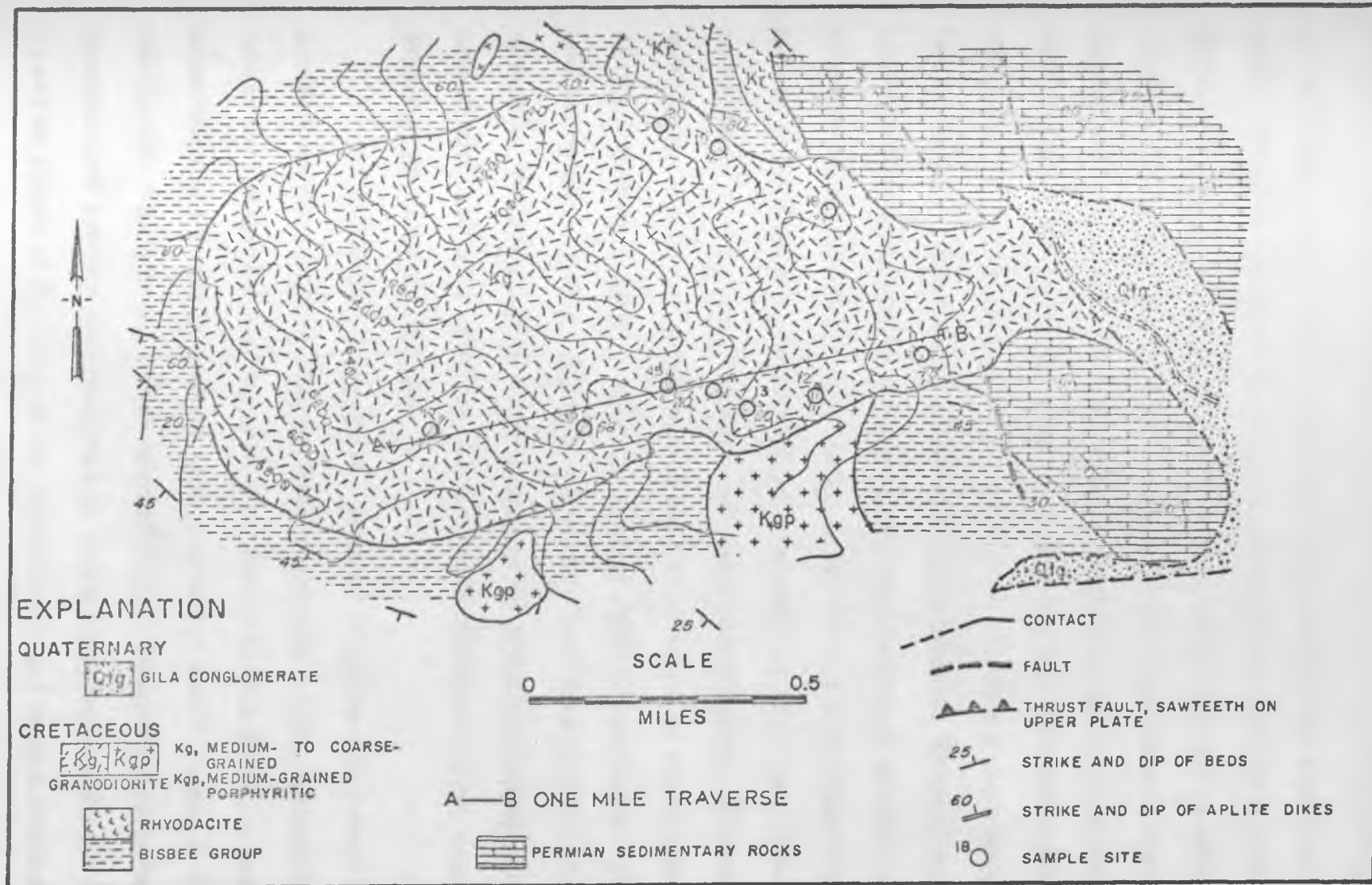


Figure 26. Geologic map of the Whetstone stock, Arizona.--Simplified from Creasey (1967)

percent plagioclase, 14 percent biotite, 13 percent hornblende, and 5 percent pyrite, with sphene, chlorite, and magnetite as accessory minerals. Subhedral plagioclase (An₃₇) is slightly sericitized and discontinuously rimmed with K-feldspar. Orthoclase forms anhedral to subhedral crystals interstitial to plagioclase. Hornblende is fringed by primary biotite and orthoclase. Brown subhedral biotite crystals are slightly chloritized peripherally and along cleavage and are also rarely discontinuously rimmed by orthoclase. Pyrite is disseminated and also clusters most abundantly around ferromagnesian minerals. Quartz monzonite has hypidiomorphic granular texture. Its composition is similar to that of granodiorite except for an increase in quartz and K-feldspar and a decrease in plagioclase, ferromagnesian minerals, and pyrite. Mineral composition is 17 percent rounded and subrounded quartz, 25 percent subhedral orthoclase, 48 percent subhedral to anhedral plagioclase (An₁₇) crystals. 5 percent brown biotite, 2 percent hornblende, and 1 percent pyrite, Sphene, apatite, magnetite, and chlorite are accessory minerals. Potassic alteration is indicated by mantling of plagioclase by orthoclase, partial or complete sericitization of plagioclase, and the presence of secondary biotite.

As indicated by Figure 26, samples of aplite dikes were collected from the southern margin of the Whetstone stock. Although economic mineralization has not yet been located in this stock, a subeconomically mineralized shear zone runs about north-northeast through the locale of sample 16. Weak hydrothermal alteration of secondary K-feldspar and sericite was observed in aplite dikes and their host rocks. Based on filling of fractures in the granodiorite and quartz monzonite,

aplite dikes are younger than these two facies, but as indicated by sulfide and alteration minerals, aplite dikes postdate or in some instances are contemporaneous with these two episodes.

Aplites and Pegmatites. Aplite dikes utterly without pegmatite generally occur along the margins of the Whetstone stock, especially in the south, southwest, and western portions (Fig. 26). Dikes have predominant west-northwest strikes with variable but steep dips. North-easterly striking dikes also occur and dip steeply to the southeast. Contrary to other nonproductive sampled intrusions, the Whetstone shows fewer dikes. A traverse (A-B, Fig. 26) on one mile intersected only 10 dikes, ranging from 4 to 18 inches in wide but averaging 10 inches. The contact with host rock is sharp (Fig. 27), and no change in grain size at the contact is observed. However, the contact at site 16 (Fig. 26) shows a change of color toward the center of the dike and only minor change in grain size (Fig. 27). Going from the margin at the contact toward the center of the dike, a 0.5-inch oil-colored zone gives way irregularly to a pinkish colored rock. Thin sections reveal that the difference in color is due to the presence of clear rather than turbid orthoclase crystals in the oil-colored portion. Aplite collected from site 16 contains less than one percent pyrite and malachite. There is generally no change in grain size or color from one dike to another, except in dike 18, which is grayish white in contrast to the pinkish color of the other dikes. Another difference is that aplite dikes at the southwest (dikes 14 through 17) and also some of the dikes at the northeast portion of the stock show fresh pyrite, although oxidized pyritic halos are not uncommon (Fig. 28).



Figure 27. Sharp contact relationship between aplite and granodiorite, Whetstone stock, Arizona

This specimen also shows the marked change in tone from the granodiorite contact toward the center of the dike.



Figure 28. Oxidized pyritic halos in aplite, Whetstone stock, Arizona

Whetstone sample 16.

Microscopically, aplite has a sugary xenomorphic granular texture in which the average grain size is 0.4 mm (Table 10). Like other aplite dikes in other areas, coarsely crystalline patches greater than 1.0 mm grain size occur. Mineral composition is 33-38 percent quartz, 30-38 percent K-feldspar, and 25-35 percent plagioclase. Accessory minerals are magnetite, biotite, sphene, chalcopyrite, chlorite, sphene, chalcopyrite, and pyrite. Anhedral rounded to subrounded clear quartz grains are fractured and show undulatory extinction. K-feldspar is anhedral to subhedral and is untwinned, except for rare carlsbad twinning indicating the presence of orthoclase. Based on the absence of microcline rectilinear twinning, K-feldspar is also taken to be mostly orthoclase. Perthitic texture has also been observed. Orthoclase is generally turbid except in sample 16, where orthoclase forms clear crystals as the contact of aplite with granodiorite is approached. Plagioclase (An₁₀) occurs as subhedral to anhedral turbid crystals with sparsely developed twinning. Sericite is locally developed in plagioclase, either peripherally or at the center, and mantles of orthoclase are also formed around plagioclase (Fig. 29). Primary biotite forms brown flakes, 2-4 mm in size, whereas secondary biotite of a greenish-brown color occurs as small aligned flakes (0.05 mm). Pyrite in mutual boundary contact and replacement relationship with magnetite is not apparently vein controlled. Textural relationships indicate magmatic crystallization of aplite minerals. Plagioclase is partly replaced by sericite and orthoclase. Absence of extensive plagioclase replacement and of veinlets indicates that the alteration is deuteric.

Table 10. Modal mineralogic composition and grain size of aplites from Whetstone stock, Whetstone Mountains, Arizona

Sample No. ¹	Percent by Volume				Average Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Accessory Minerals	
11	37	30	33	biotite, magnetite: <1	0.4
12	34	37	28	biotite, magnetite, sphene, chlorite: ≈1	.4
13	34	37	38	biotite, magnetite, chlorite: ≈1	.3
14	36	35	28	biotite, sphene: ≈1	.3
15	36	35	27	biotite, magnetite, chlorite: ≈2	.35
16	37	37	26	biotite, chlorite, magnetite, sphene, chalcopyrite, malachite: <1	.4
17	33	32	35	biotite, magnetite, sphene: <1	.4
18	35	37	28	biotite, magnetite, sphene: <1	.5
19	36	36	27	biotite, magnetite, pyrite: ≈1	.4
20	36	38	25	biotite, magnetite, pyrite, carbonate: ≈1	.8

1. Sample locations are shown on Figure 26.

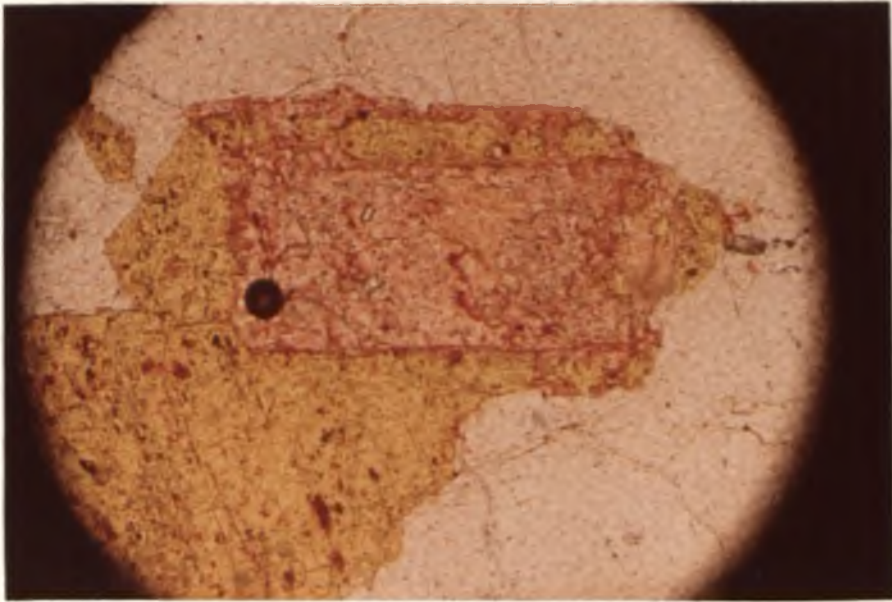


Figure 29. Photomicrograph showing K-feldspar (yellow) mantling and replacing along cleavage of a plagioclase crystal (pink), Whetstone stock, Arizona

Stained thin section 16; plane polarized light, X66.

Mineralization. Drilling of a mineralized zone located close to the center of the intrusion and striking northeasterly indicated the presence of subeconomic copper and molybdenum sulfides (V. D. De Ruyter, oral communic., 1971). Pyrite also occurs irregularly in the intrusion and surrounding sedimentary rocks.

Unclassified Intrusion

Troy Stock

The Troy stock was studied after the completion of the early portion of this research. Results of the early phases indicated a substantial variation in abundance and mineral and chemical compositions of aplites and pegmatites of mineralized and barren intrusions. The Troy stock was selected in order to compare results obtained from its samples against results from other studied intrusions because active mineral exploration is presently being conducted in and around the Troy stock.

The Troy stock is located in the Dripping Spring Mountains about 75 miles north of Tucson (Fig. 2). The stock is pear shaped, with its longest axis trending east-west (Fig. 30), and encompasses an area of about 2 square miles. It has intruded Precambrian and Paleozoic rocks and is dated at 72 ± 2 m.y. (Cornwall, Banks, and Phillips, 1971).

The Dripping Spring Mountains are strongly deformed, mostly by tilting and faulting. As indicated by relationships with the intrusive stocks, several of the major faults formed in the late Precambrian and were later reactivated one or more times, particularly during the Laramide (Cornwall and others, 1971). The Troy intrusion is surrounded by intricately faulted rocks forming small grabens and horsts (Fig. 30) and

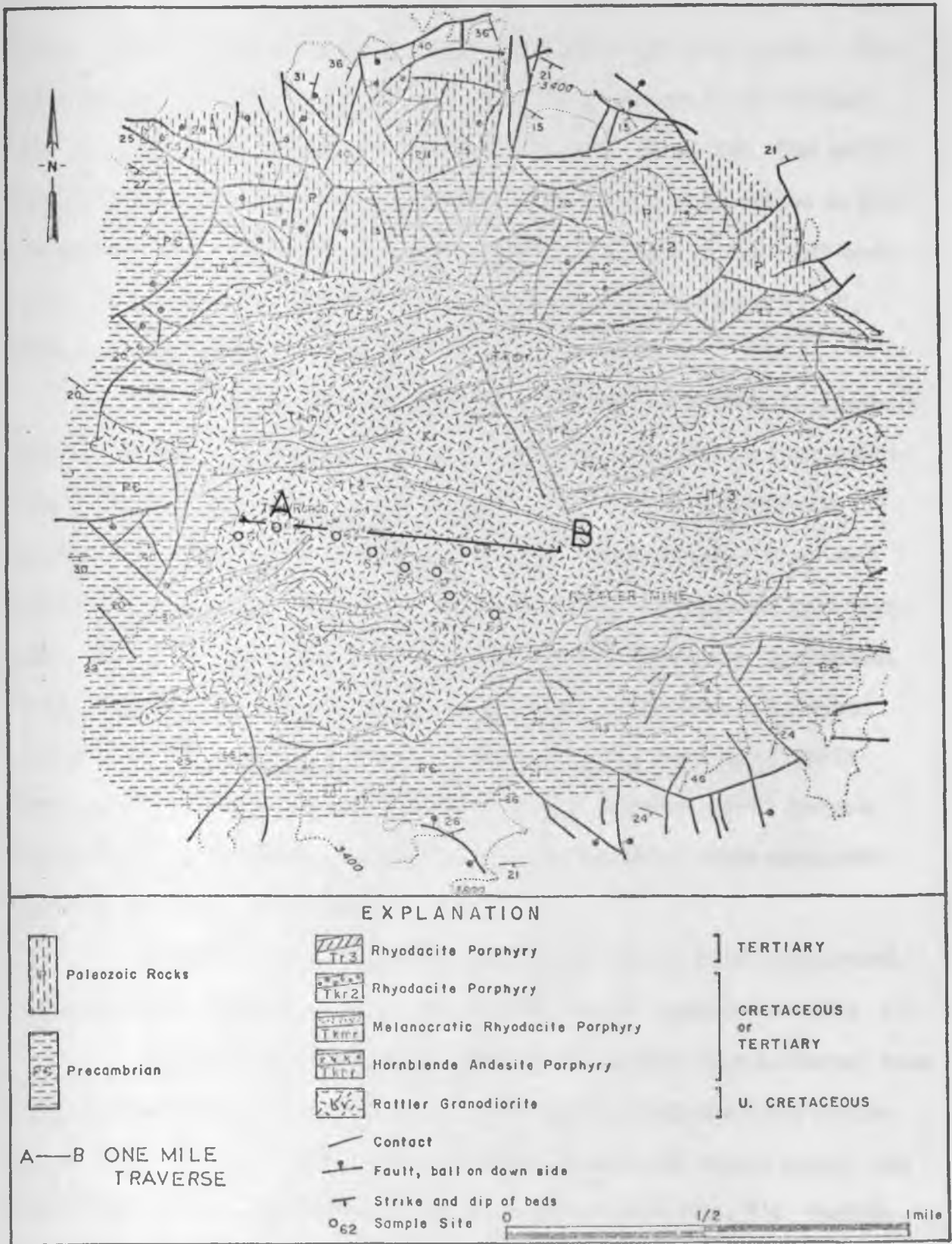


Figure 30. Geologic map of the Troy stock area, Dripping Spring Mountains, Arizona.--Simplified from Cornwall and others (1971)

shows evidence of having been forcefully intruded. At the western contact, wedges of the intrusive granodiorite follow old fault planes. The general west-northwest strike of the country rocks has been modified, and to the south it parallels the intrusive contact (Fig. 30). The southwesterly dips of 25° - 30° are increased to 80° in some locations at the western contact. Islands of Dripping Spring quartzite in the northwest part of the stock have been strongly fractured and brecciated (T. E. Andrews, oral commun., 1973).

The stock itself is strongly jointed and susceptible to weathering and forms a topographic low with respect to surrounding host rocks. Numerous Laramide dikes cut the stock. The stock is a composite intrusion with lithologies varying from quartz diorite to granitic aplites (Cornwall and others, 1971). The main rock type is granitoid granodiorite. The granodiorite consists of 45-66 percent subhedral to euhedral andesine crystals up to 6 mm in length, 15-30 subhedral to anhedral quartz 2-7 mm in diameter, 10-20 percent anhedral orthoclase, 0-13 percent subhedral biotite as much as 5 mm in diameter, 0-11 percent hornblende, 1-4 percent euhedral magnetite-ilmenite, with accessory apatite, sphene, and zircon.

Potassic hydrothermal alteration, not known to be associated with sulfides, occurs as veinlets and plagioclase replacements (Fig. 31).

Aplites and Pegmatites. Samples of aplites were collected from the southwestern part of the stock about 0.5 to 1 mile from the Rattler mine (Fig. 30). No sulfide minerals were observed in aplite dikes, but secondary K-feldspar veinlets transect aplite dikes (Fig. 31). Sulfide mineralization were established by Cornwall and others (1971) to be

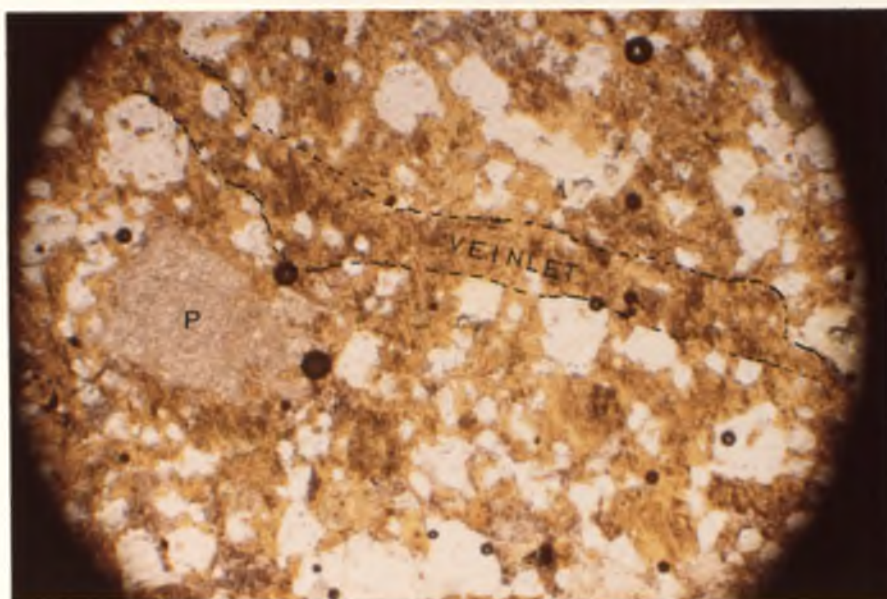


Figure 31. Photomicrograph of aplite showing potassic alteration, Troy stock, Dripping Spring Mountains, Arizona

Secondary orthoclase (yellow) forms a veinlet (---) and also mantles plagioclase (P). Stained thin section 67; plane polarized light, X25.

contemporaneous with alteration. Sampled aplite dikes are therefore considered to be contemporaneous with alteration. Sampled aplite dikes are therefore considered to be younger than the stock granodiorite and to postdate hydrothermal alteration and mineralization.

Present reconnaissance mapping indicated no pegmatites in the Troy stock, although the stock is marked by an abundance of aplite dikes, 17 dikes per line mile, averaging 23 inches thick. Dikes fill radial joints and have steep dips, generally toward the center of the stock. In contrast to the host rock, aplite dikes are fresh with sharp nonchilled contacts. Except for crosscutting quartz and orthoclase veins, the aplite dikes are texturally and mineralogically homogeneous. The aplite dikes are grayish white with scarce ferromagnesian minerals and apparently no sulfides.

In thin section, aplites show xenomorphic sugary textures in which the average grain size is 0.5 mm (Table 11). Mineral composition is 29-33 percent quartz, 41-50 percent K-feldspar, 17-27 percent plagioclase, with accessory biotite, apatite, magnetite, sericite, and hematite. Quartz occurs as anhedral rounded to subrounded crystals ranging in size from 0.2 to 0.7 mm and displaying undulatory extinction. Anhedral to subhedral, generally untwinned turbid K-feldspar varies in grain size from 0.2 to 1.0 mm. The larger grains in many instances are of secondary origin. Minor carlsbad twinning indicates that the K-feldspar present is orthoclase. No microcline twinning was observed in the sections studied. Secondary orthoclase occurs as veinlets or as replacement of plagioclase (Fig. 31). Subhedral to anhedral sodic plagioclase (Ang) occurs as sparsely twinned turbid crystals. Plagioclase is

Table 11. Modal mineralogic composition and grain size of aplites from Troy stock, Dripping Spring Mountains, Arizona

Sample No. 1	Percent by Volume				Average Grain Size (mm)
	Quartz	K-feldspar	Plagioclase	Accessory Minerals	
61	32	46	22	biotite, apatite: <1	1.0
62	31	48	20	biotite, apatite, hematite, sericite: \approx 1	0.5
63	29	45	26	biotite, apatite, magnetite, sericite: <1	0.5
64	29	48	22	biotite, magnetite, chlorite: \approx 1	0.3
65	29	51	20	biotite: <1	0.5
66	29	49	23	biotite, magnetite, sericite: <1	0.8
67	32	41	27	biotite, sericite, chlorite: <1	0.7
68	33	50	17	sericite, chlorite: <1	0.5
68	30	45	25	biotite: <1	0.30

1. Sample locations are shown on Figure 30.

replaced by orthoclase and locally sericite. Both deep-brown primary and greenish-brown secondary biotite is developed in accessory amounts. Apatite, chlorite, magnetite, and hematite are quite rare. Potassic alteration veins without any sulfides cut aplite dikes.

Mineralization. Small deposits of copper sulfides and oxides, occurring in steeply dipping faults and fissures, have been mined in and around the Troy stock (Cornwall and others, 1971). Sparsely disseminated azurite, malachite, chrysocolla, and copper sulfides occur in the eastern part of the stock and in the surrounding country rocks along the southern contact. Cornwall and others (1971) estimate that the Rattler mine (Fig. 30) in Precambrian Mescal Limestone and diabase contains 2,500,000 tons of 1 to 1.5 percent copper, mainly as copper oxides.

Summary of Field Data

The information presented here elaborates upon and summarizes the detailed field work presented in this chapter. This information will be used to discuss the genesis of the dikes and their significance in mineral exploration.

Abundance and Thickness of Dikes

All eight of the studied intrusions contain aplites with or without pegmatites. However a noticeable difference in dike population and thickness has been observed. Aplite and pegmatite dikes in productive intrusions are generally thinner at an average width of 4 inches and relatively more scarce at about 7-9 dikes per line mile (Fig. 32), than nonproductive stocks which contain from 10 dikes per line mile at Whetstone to 45 at Texas Canyon and range in width from 10-24 inches. This

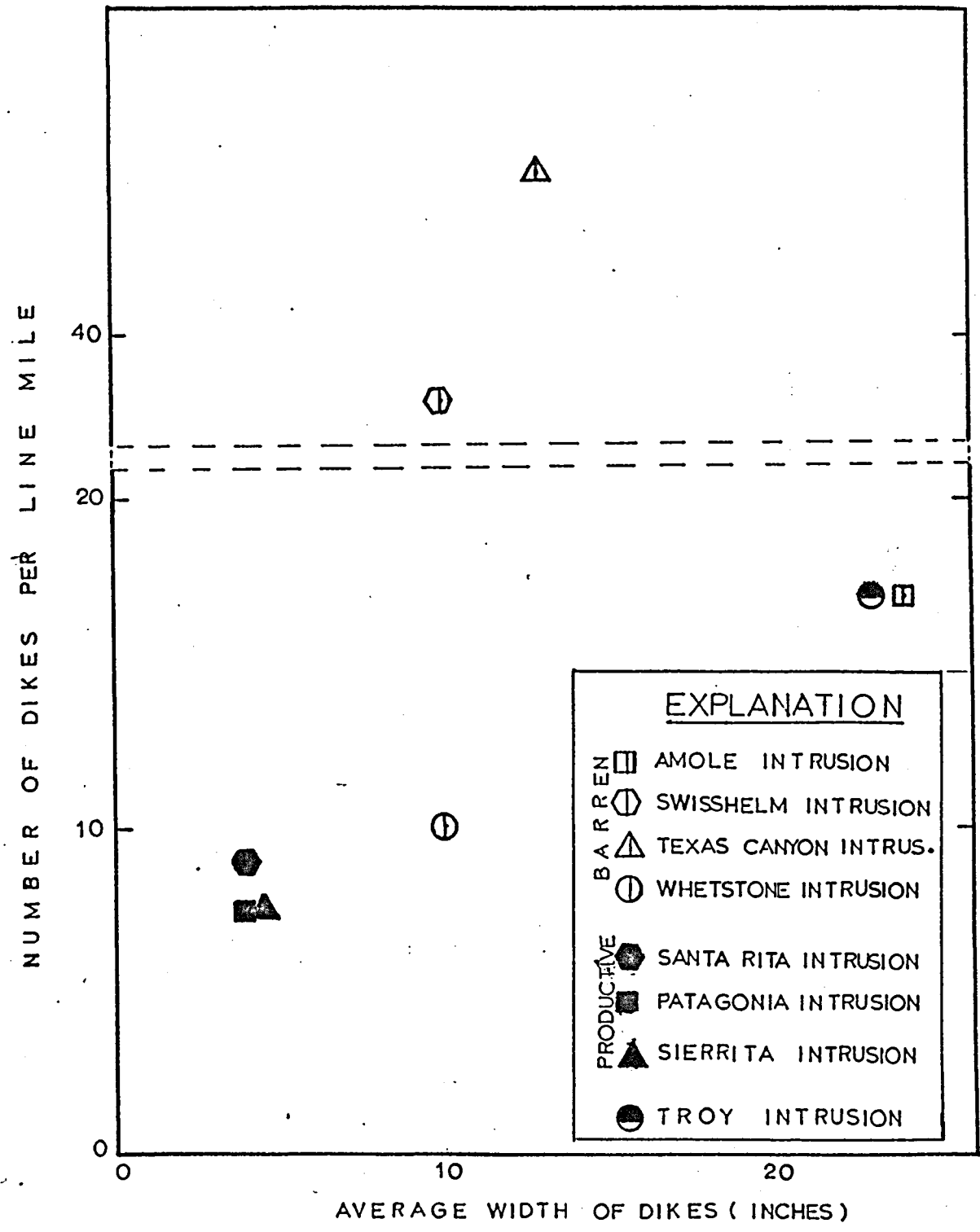


Figure 32. Abundance and average width of aplite and pegmatite dikes in studied intrusions.

relationship has been quantified by the method described earlier. Figure 32 shows that productive intrusions in general have small numbers of thin dikes. The Santa Rita intrusion contains 9 dikes per line mile at about 4 inches wide, whereas the Patagonia and Sierrita intrusions are low and similar at about 7 dikes per line mile which average 4 inches thick. Similar data for the Boulder batholith are not available. Among nonproductive intrusions, the Swisshelm with 38 dikes per line mile and the Texas Canyon with 45 dikes per line mile contain by far the largest relative number of dikes. The average width of dikes in the Swisshelm is 10 and in the Texas Canyon is 13 inches. The Amole and Troy intrusions, which both have 18 dikes per line mile with an average width of about 2 feet, contain the next abundance of dikes. These, in turn, are followed in decreasing dike abundance by the Whetstone intrusion at 10 dikes per line mile averaging 10 inches wide.

Data on the width and number of dikes per line mile in these intrusions will be developed to indicate passive intrusive history for productive intrusions and forceful for the nonproductive ones.

Structure and Texture

The structure and texture of dikes observed in the field are summarized here according to their mode of occurrence and their relationship to fracturing in the host rocks. Their contacts with the host rock and of the textural homogeneity of aplite dikes, mixed aplite-pegmatite dikes, and pegmatite dikes are also described. These data will be subsequently used in a discussion of the origin of aplites and pegmatites in the intrusions under consideration.

Structure. Except for one location at the Texas Canyon intrusion where pegmatite forms a pod (Fig. 33), aplites and pegmatites occur as dikes with long, straight, generally parallel walls. Individual dikes range from an exposed length of 50 feet at the Amole stock to about 3,000 feet at the Swisshelm stock (Fig. 19). They range in width from a fraction of an inch (Fig. 24) to 7 feet. Dikes rarely terminate abruptly but rather pinch out gradually (Fig. 34). Dikes generally maintain a constant strike but occasionally change abruptly. Not uncommonly, they bifurcate and meet again forming a rectilinear pattern (Fig. 24). Fournier (1968) observed similar behavior of dikes and explained it by their forceful intrusion. Although most of the dikes observed are contained entirely within igneous host rocks, they locally are continuous from the intrusions into the surrounding country rocks (Fig. 19).

Texture. Aplite dikes show monotonous textural homogeneity, with grain size averaging 0.4 mm (Tables 3-11). Randomly distributed coarse-grained patches of about 1.2 mm in grain size are found in aplite dikes (Fig. 14). These patches are usually composed of quartz or quartz and K-feldspar, or scarce plagioclase (Fig. 14). Single pegmatites show grain sizes, ranging from 5 mm to 1.5 cm. It is not uncommon, particularly in the Texas Canyon and the Swisshelm intrusions, to find mixed aplite-pegmatite dikes. The pegmatitic material occurs centrally or marginally (Figs. 25 and 35), and contacts of the dikes with the surrounding aplitic material may be either sharp or gradational. Aplites also exhibit the sucrose texture characteristic of published descriptions.

Contacts of dikes with host rock are always sharp, as shown in Figure 27. Observation of the contact of aplite dikes with host rocks



Figure 33. A pegmatite pod in quartz monzonite, Texas Canyon stock, Arizona

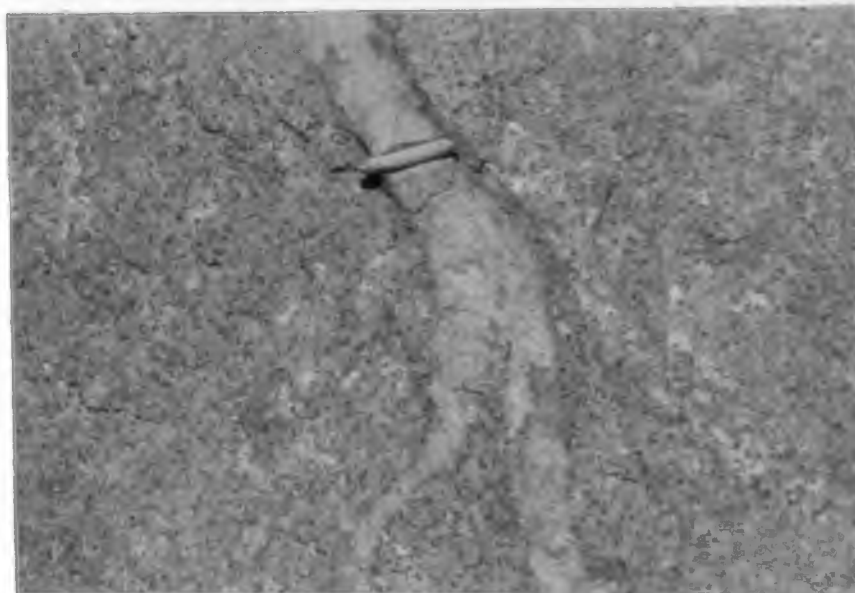


Figure 34. Aplite dike which pinches out in the direction of bifurcation, Texas Canyon stock, Arizona



Figure 35. Mixed aplite-pegmatite dike with aplite located centrally, Swisshelm stock, Arizona

Swisshelm sample location 45.

reveals no change in grain size as a result of chilling. This feature of aplite was also noted by Derry (1931), whereas pegmatites by contrast exhibit this chilling feature.

Color of Dikes

Dikes in the areas under consideration display pink and grayish-white colors. All dikes from productive intrusions are pink with the exception of grayish-pink dikes from the Boulder batholith at Butte. Dikes from nonproductive intrusions are either pink or grayish white. For example, dikes from the Amole and Whetstone intrusions are pink, whereas those from the Swisshelm and Texas Canyon intrusions are grayish white. This color difference is shown in subsequent discussion to indicate a change in the iron content of both the bulk rock and its K-feldspar.

Summary of Petrographic Data

Texture

Microscopic textures confirm the field observations reported earlier. The textural homogeneity observed in the field is also present on a microscopic level. The grain size ranges from 0.2 to 1.5 mm with an average of 0.4 mm (Tables 3-11). Random coarse-grained patches observed in the field are very well displayed in thin sections of aplite dikes (Fig. 14). These patches are composed of grains ranging in size from 1-1.2 mm. Well-developed crystal faces not seen elsewhere in aplites are commonly found in these patches (Fig. 14). Overall, aplite texture is the xenomorphic granular (Fig. 13), similar to that described in the literature. Graphic texture (Fig. 15) is well developed in

pegmatites collected from the Texas Canyon, Sierrita, and Swisshelm intrusions. Granophyric texture (Fig. 7) is also observable in these aplites and is best developed in those from mineralized intrusions. Granophyric texture was defined by Barker (1970) as the intergrowth of quartz and alkali feldspar on a scale from submicroscopic to 1 to 2 mm. While granophyric texture in nonproductive intrusions is observed only in sample 3 (Fig. 17) of aplite from the Amole stock, it is often observed in aplites from productive ones, especially in those from the Patagonia stock (samples 27, 30, 31; Fig. 6). Granophyric texture has been described in plutonic rocks "only from aplites for which rapid crystallization has been postulated" (Barker, 1970, p. 3342). Superimposed on these primary crystallization textures are textures of secondary origin in the form of orthoclase veins (Figs. 16 and 31), mantling of plagioclase by orthoclase and partial replacement of plagioclase by orthoclase along cleavage planes (Fig. 29). The sharpness of dike contacts with the host rocks observed in the field (Figs. 22 and 27) are confirmed by the presence of microscopically sharp contacts (Fig. 20). This sharp contact is defined by variation in grain size of the host rocks and aplite dikes, the latter much smaller, and also by the difference in color of constituent minerals.

Mineral Composition

Quartz, K-feldspar, plagioclase, and muscovite in aplite and pegmatite dikes from Swisshelm and Texas Canyon stocks together constitute 99 percent by volume of the total mineral composition (Tables 3-11). Biotite, magnetite, sphene, garnet, and pyrite are present in accessory amounts.

Single aplite dikes are mineralogically homogeneous, and this homogeneity prevails among different dikes in the same intrusion (Tables 3-11). This mineralogical homogeneity agrees with the chemical homogeneity described later in the chapter on chemical data. Significance of mineralogical and chemical homogeneities of dikes will be subsequently considered. The principal aplite and pegmatite dike minerals include quartz, plagioclase, and K-feldspar.

Quartz. Quartz occurs as about 0.4-mm anhedral grains and as granophyric and graphic intergrowths with K-feldspar (Figs. 7 and 15). Quartz also is found as coarse crystals, averaging 1.2 mm across, in coarse-grained patches in aplite dikes (Fig. 14). The quartz content in the studied aplites and pegmatites ranges from 29 to 37 percent by volume in both productive and barren intrusions (Tables 3-11). The Texas Canyon and Troy intrusions have low quartz content, at about 29 percent, a feature corroborated by the low silica content of bulk rocks (Table 16, Appendix A) collected there. Inspection of Figure 36 indicates that plots of samples of aplite and pegmatite from barren and mineralized intrusions are similar. There is no special correlation of high or low quartz content with barren or mineralized intrusions. The inconsistent trend in quartz in aplites from both productive and barren intrusions makes this mineral a poor mineralogic indicator in the exploration for mineral deposits.

Plagioclase. Plagioclase is present in examined aplites as anhedral to subhedral grains, averaging 0.4 mm in diameter. Plagioclase crystals have interlocking boundary relationships with K-feldspar and quartz. Individual crystals are commonly equant and subrounded but

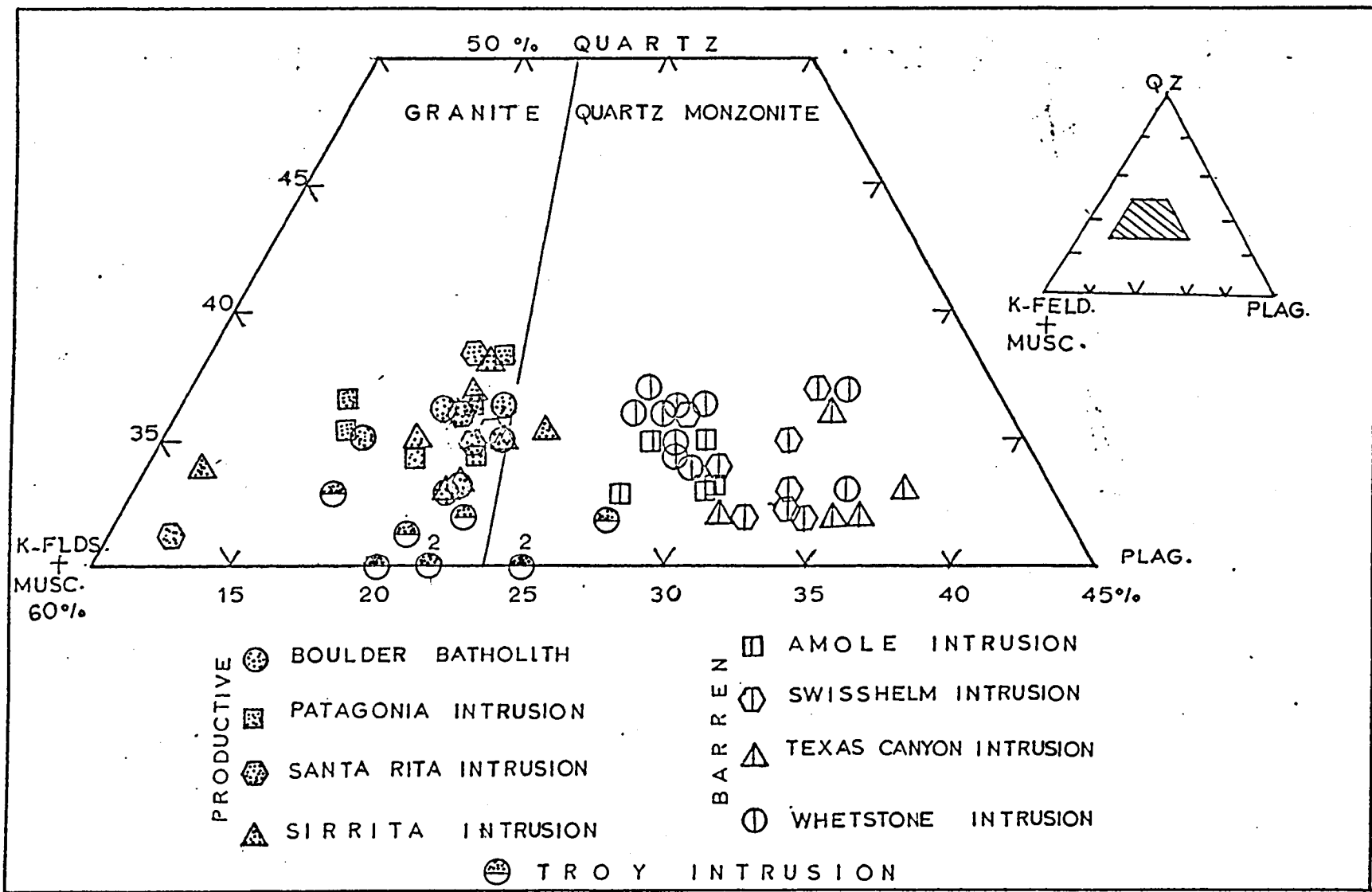


Figure 36. Variation in modal mineralogic composition of aplites from studied Laramide and mid-Tertiary intrusions

elongate crystals are also occasionally present. Its composition, determined by the Michel-Levy method, varies between An₇₋₁₀ in dikes from barren stocks and An₁₀₋₁₇ in those from mineralized ones. This difference is chemically confirmed by the relatively high calcium content of the latter. It has also been observed that twinning is better developed in plagioclase from pegmatites than from aplites. Inspection of Figures 36 and 37 reveals a decrease of plagioclase in dikes from mineralized areas. An inverse relationship of plagioclase to K-feldspar is also clear (Fig. 37).

K-feldspar. Like plagioclase, K-feldspar is present as anhedral to subhedral grains, ranging in size from 0.2 to 1.2 mm, with an average of 0.4 mm. The smallest grains at 0.2 mm are rounded and commonly occur interstitial to plagioclase, quartz, and K-feldspar. The largest grains at 1.2 mm occur in randomly distributed coarse-grained patches and also in and close to secondary K-feldspar veins. However, most K-feldspar occur as 0.4 mm anhedral to subhedral crystals in mutual interlocking boundaries with plagioclase and quartz. Less commonly, K-feldspar displays replacement boundaries with plagioclase.

K-feldspar is generally turbid, except at Texas Canyon where clear K-feldspar is always present. Although particulate hematite was not observed, this turbidity which is always associated with pink K-feldspar could be due to the presence of hematite or Fe⁺⁺⁺ in Al⁺⁺⁺ sites of the feldspar lattice (Andersen, 1915; Wones, 1962; and Boone, 1969). This possibility is supported by a high iron content (0.132-0.175 percent) in pink turbid feldspar in contrast to a low iron content (0.02-0.055 percent) in relatively clear K-feldspar.

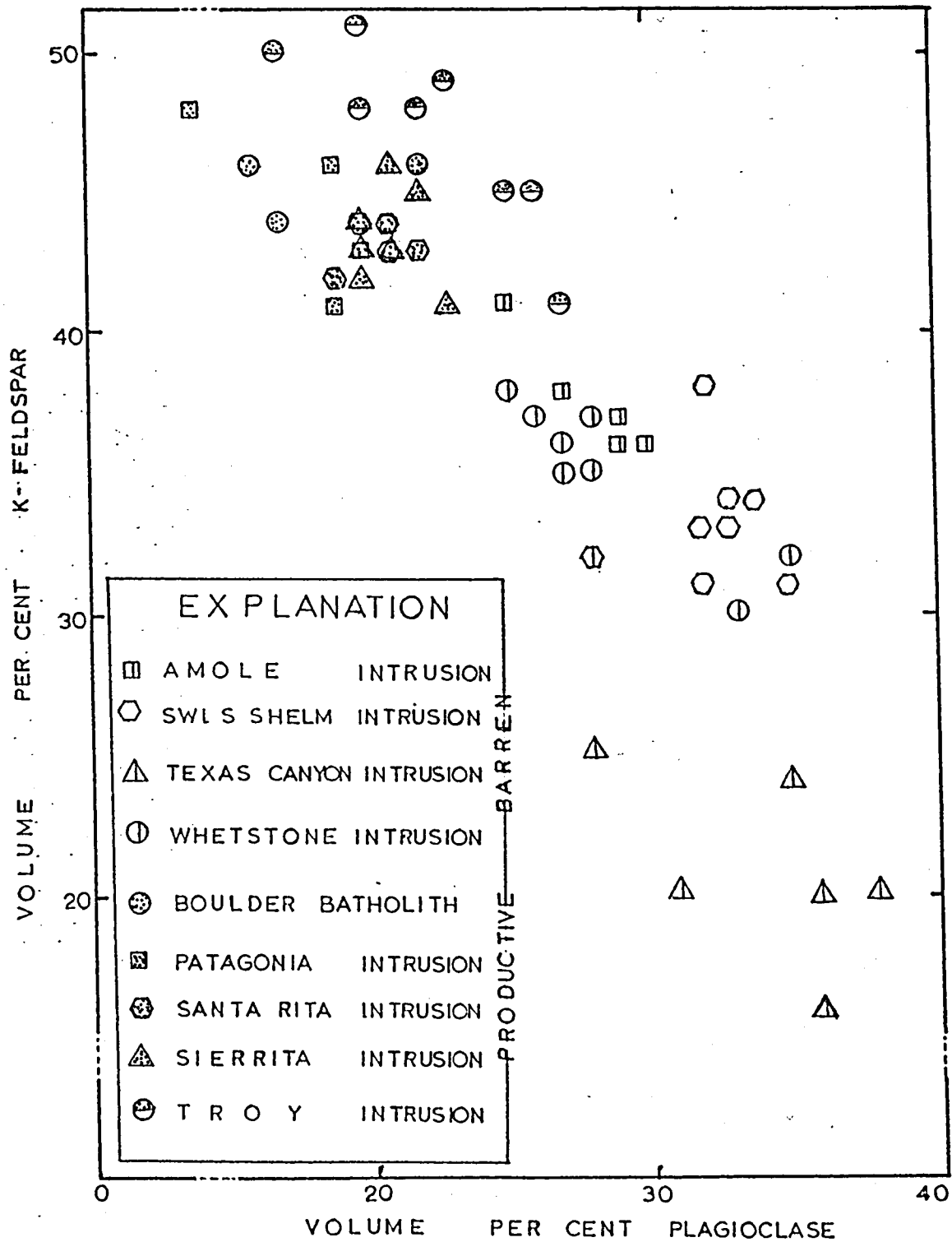


Figure 37. Variation of volume per cent of K-feldspar-plagioclase in aplites from studied Laramide and mid-Tertiary intrusions

Except at the Texas Canyon and Swisshelm intrusions, orthoclase forms the major K-feldspar in aplites. Microcline, whose presence was determined optically, constitutes about 90 percent of the K-feldspar in aplite dikes from Texas Canyon and about 70 percent of the K-feldspar in dikes from the eastern part of the Swisshelm intrusion. This predominance of microcline in Texas Canyon is not readily explainable but is correlatable with the probable greater depth of its formation. The present data, for reasons discussed later, indicate that dikes in the Texas Canyon intrusion probably formed at much greater depth (8 km) than those from other intrusions studied (2-4 km). This depth correlation is in agreement with Dana's (1961, p. 490) statement that "microcline is particularly characteristic of deep-seated rocks and pegmatites, orthoclase of porphyries and hydrothermal veins, and sanidine of extrusive lavas."

Fluid Inclusions

Facilities for studying fluid inclusions became available at the close of this work. Preliminary work had indicated the presence of fluid inclusions in aplite samples, contrasting to their abundance in pegmatites and suggesting that aplite formation environment is not conducive to the formation of fluid inclusions. Primary fluid inclusions in dikes from all mineralized intrusions studied contain halite daughter minerals (Fig. 38), whereas none was observed in dikes from barren areas. Similar observations were made by Roedder (1971). Similarly, on the basis of preliminary information, the liquid-vapor ratio in fluid inclusions in dikes from productive areas is always greater than in dikes from barren areas. Figure 39 from aplites in the Patagonia stock shows



Figure 38. Fluid inclusion with a halite daughter mineral
Boulder batholith, Montana, thin section 21.

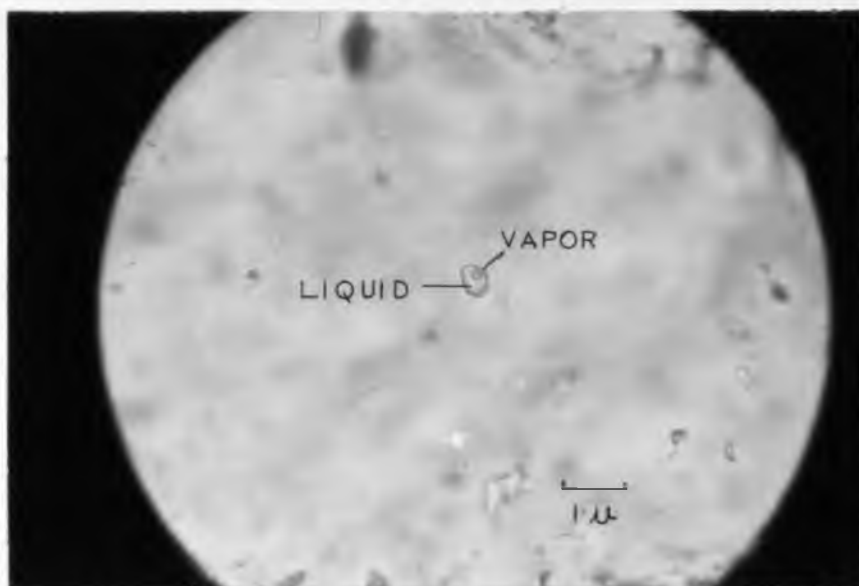


Figure 39. Small vapor phase in fluid inclusion
Sierrita, Arizona, thin section 39.

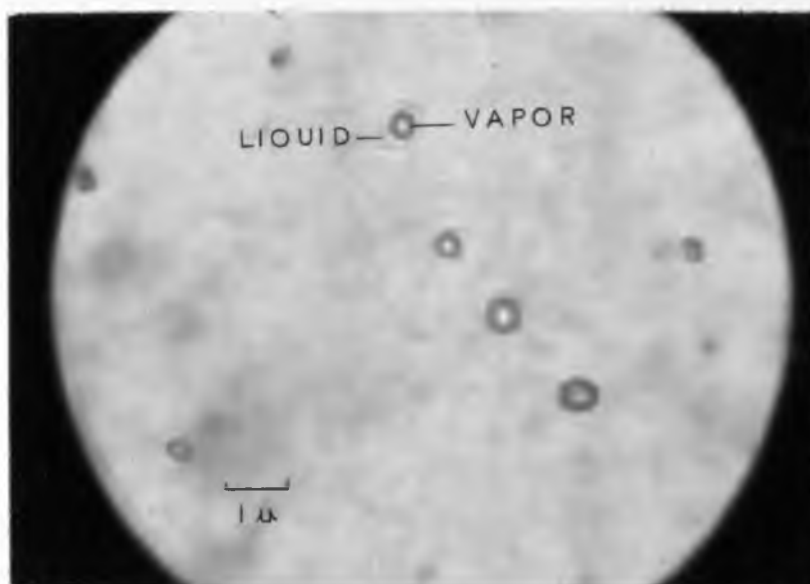


Figure 40. Large vapor phase in fluid inclusion
Texas Canyon, Arizona, thin section 53.

a tiny vapor phase, whereas the vapor phase in samples from Texas Canyon (Fig. 40) are larger.

CHAPTER 5

CHEMICAL DATA

Chemical data of bulk rock and K-feldspars depict the textural and mineralogical homogeneity initially established. They permit the investigation of the behavior of individual elements in productive and barren environments and the calculation of normative minerals and PH_2O . These data will be used to determine depth and temperature of formation of these dikes and their exploration and genetic significance.

Bulk Rock Analysis

All bulk rock and K-feldspar atomic absorption spectrophotometric analyses are listed in Appendix B. The data are grouped by sample location and include analytical values for weight percentage of SiO_2 , Al_2O_3 , total iron as Fe_2O_3 , CaO , Na_2O , and K_2O and ppm of copper and zinc. Elemental abundances calculated from oxides in aplite and pegmatite in each intrusion are averaged. The number of samples per intrusion and the range of analytical values from which these averages are calculated are shown in the figures which accompany the discussions of each element.

Silicon

As predicted by its crystal chemical behavior, silicon concentration in these late-forming dikes is relatively high at 35.38-36.81% Si (Fig. 41A). This high concentration conforms with the high content of

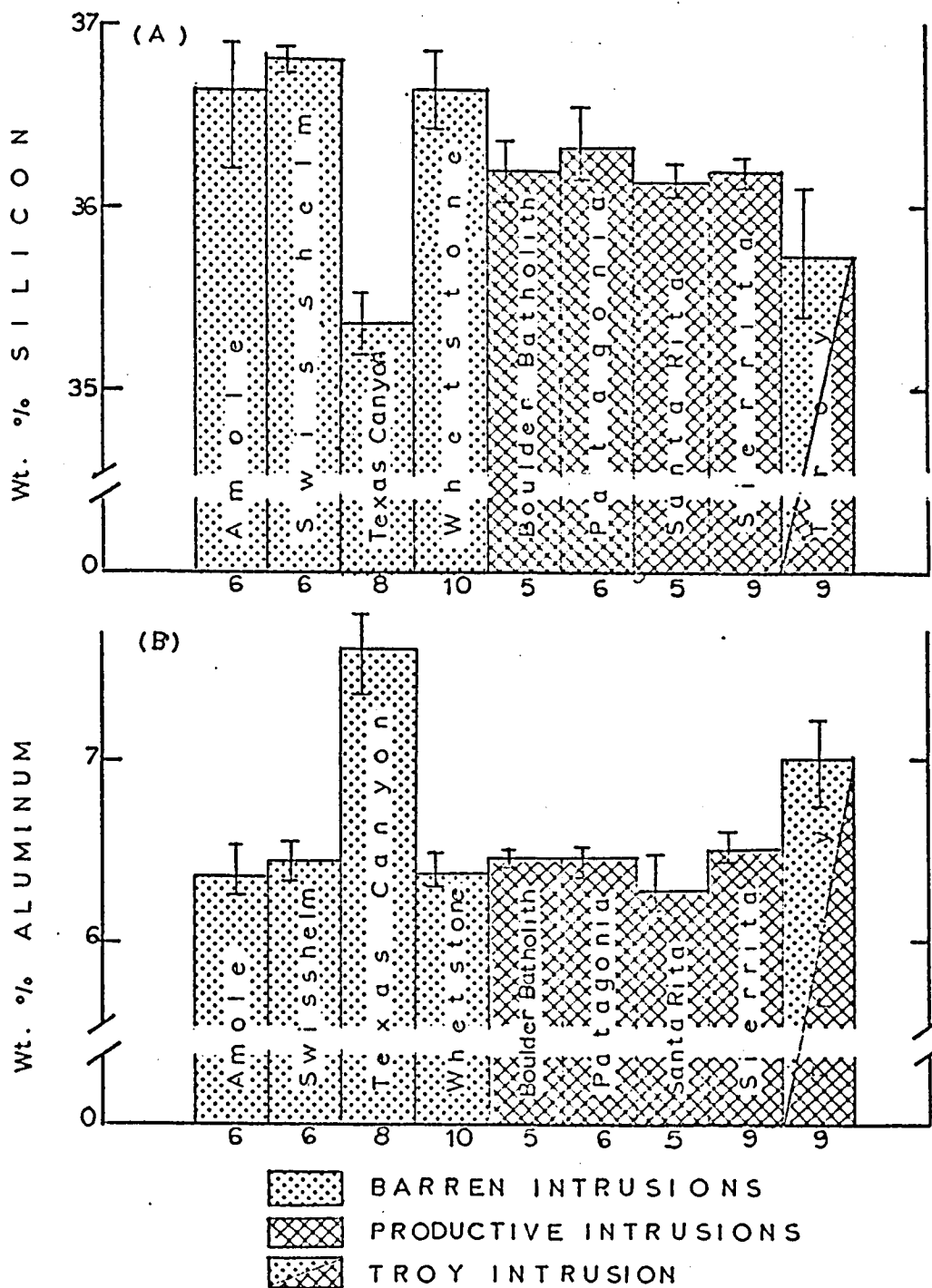


Figure 41. Average concentration of silicon (A) and aluminum (B) in whole-rock samples of aplite and pegmatite in some Laramide and mid-Tertiary intrusions

Vertical bar represents range of values.

quartz in the modal determinations (Tables 3 through 11). Silicon concentration in dikes from barren intrusions at 35.38-36.81% Si is slightly higher than that in dikes from productive ones at 35.16-36.23% Si. Inspection of Figure 41A shows that, taken together, dikes from productive intrusions have silicon values similar to barren ones, except for dikes from Texas Canyon. The low silicon values from Texas Canyon (35-38) and the Troy intrusions (35.61) are consistent with their low modal quartz.

Aluminum

Aluminum, like silicon, does not show any trend correlative to the mineralized or barren status of the intrusions. Except for dikes from the Texas Canyon and Troy intrusions, the overall aluminum contents in dikes from barren and mineralized intrusions at 6.40 ± 0.1 (Fig. 41B) are similar. Because feldspars are the principal carriers of aluminum in the dikes and since the total feldspar content at 63.0-66 percent by volume is similar in productive and barren intrusions, these similar values of aluminum are expected. The high aluminum content of dikes from Texas Canyon at 7.60% Al is in agreement with their high muscovite content (4-13 percent by volume), whereas the high aluminum values in dikes from the Troy stock agree with its high total feldspar content (69 percent by volume).

Iron

Low iron concentration in aplites and pegmatites is predicted from its crystal chemical behavior in silicate melts. Petrographic work indicates that combined iron oxides, sulfides, and ferromagnesian

minerals form less than 2 percent by volume in the dikes under consideration. Figure 42A, however, indicates a higher value of iron at 0.45%-1.16% Fe in productive intrusions and lower iron content in barren ones at 0.30%-0.63% Fe. This high iron content in dikes from productive areas is reflected in the pink color of these dikes. Dikes from the Swisshelm, Texas Canyon, and Troy intrusions are grayish white, correlating with their low iron content. Among the barren intrusions, dikes from the Amole (0.63% Fe) and the Whetstone (0.53% Fe) have high iron contents, also in agreement with their pink color.

Calcium

Crystal chemistry predicts that calcium will be incorporated into early-forming silicates so that minerals crystallizing from residual melts are depleted in this element. This prediction is confirmed analytically by the low average calcium content at 0.21-0.48% Ca in studied dikes (Fig. 42B). Although the calcium content is low in dikes from both productive and barren intrusions, the former show a higher calcium content (0.31-0.48% Ca). Aplites from the Troy intrusion contain as much calcium as that found in dikes from productive ones (Fig. 42B). Except for minor apatite and fluorite (Swisshelm intrusion), plagioclase is the only calcium-bearing mineral seen in thin sections. The relatively higher calcium content in dikes from productive intrusions is confirmed by the presence of a higher anorthite content in plagioclase (An₁₀₋₁₇).

Sodium

As predicted by its crystal chemistry, sodium concentrates in aplites and pegmatites, the products of residual magma crystallization.

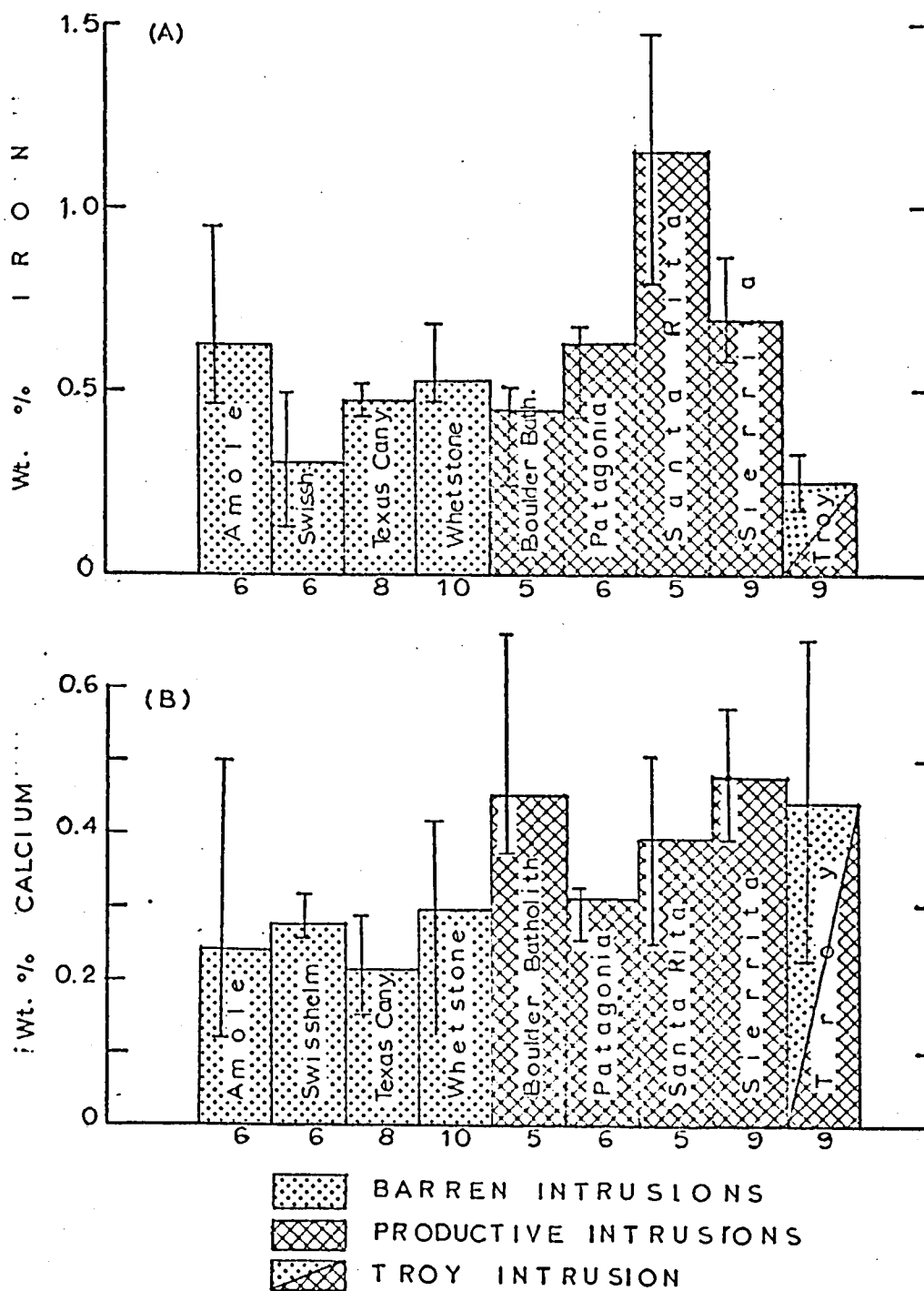


Figure 42. Average concentration of iron (A) and calcium (B) in whole-rock samples of aplite and pegmatite in some Laramide and mid-Tertiary intrusions

Vertical bar represents range of values.

However, it is observed in Figure 43A that dikes from productive areas contain less sodium (1.55-1.82% Na) than those from barren areas (2.28-3.30% Na). This compositional variation is in agreement with petrographic findings. Dikes from productive areas not only contain less plagioclase at 12-23 percent by volume than those from barren stocks, but the albite content of their plagioclase is also low (Ab₉₀₋₈₃). The anomalously high sodium content in dikes from the Texas Canyon intrusion at 2.98% Na (Fig. 43A) and the very low values for the same element from the Santa Rita stock at 1.55% Na are directly proportional to their plagioclase contents. Dikes from the Troy intrusion carry sodium contents intermediate to those from productive and barren areas at 2.12% Na.

Potassium

Like sodium, potassium is concentrated in late-forming aplites and pegmatites. As contrasted to sodium, relatively more potassium at 5.15-5.56% K is present in dikes from productive areas (Fig. 43B). This potassium content is consistent with petrographic findings in which these dikes were determined to carry more K-feldspar, 41-54 percent by volume (Fig. 37), than those from barren intrusions (18-38 percent by volume). Dikes from Texas Canyon have the lowest potassium content at 3.89% K, corresponding to low content of K-feldspar (23 percent by volume) in these dikes. The inverse relationship between sodium and potassium contents in dikes is well expressed by Figures 43A and 43B. An increase of potassium content corresponds to a decrease in the sodium content. Aplites from the Troy intrusion have a potassium content at 5.41% K, comparable to that in dikes from productive intrusions.

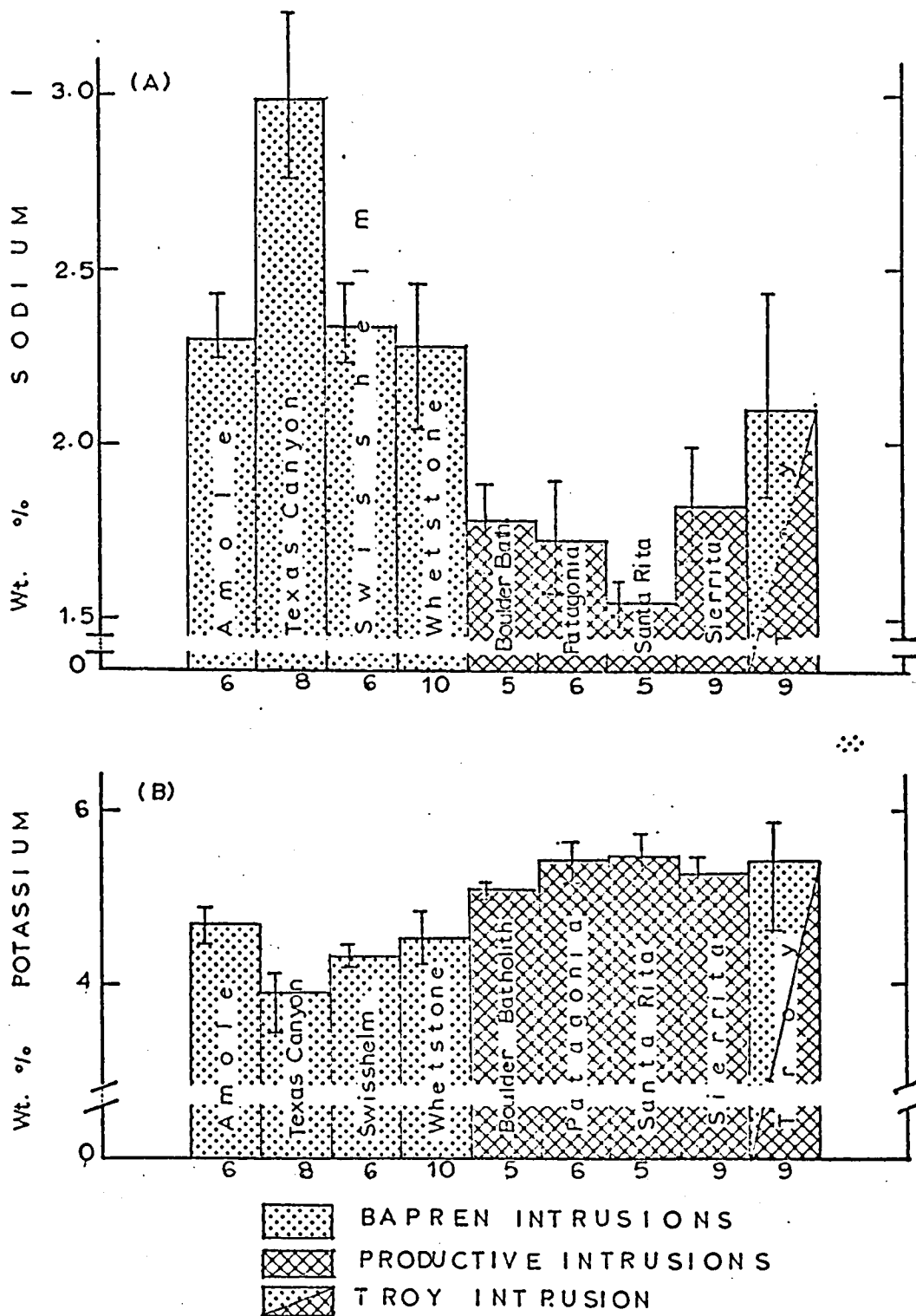


Figure 43. Average concentration of sodium (A) and potassium (B) in whole-rock samples of aplite and pegmatite in some Laramide and mid-Tertiary intrusions

Vertical bar represents range of values.

Copper

As indicated by Figure 44A, copper values are relatively high (10-59 ppm) in dikes from mineralized areas. Dikes from the Boulder batholith and the Whetstone stock are exceptions. High copper content in aplite dikes from the Whetstone intrusion (24 ppm) is mainly due to a single high value (80 ppm). The average copper content drops to 18 ppm with omission of that sample. Nonetheless, all samples from the Whetstone stock are high in copper. Samples from the Boulder batholith at Butte are low in copper (10 ppm), as was also observed by Al-Hashimi and Brownlow (1970), who found that the copper content in biotite from the Boulder batholith is low compared to that of copper-producing intrusions elsewhere. Aplite dikes from the Troy intrusion show low copper content at 12 ppm, similar to values from barren intrusions (Fig. 44A).

Zinc

Considering its geochemical properties, zinc should behave in a manner geologically similar to copper. However, Figure 44B does not confirm this prediction. Concentrations of zinc in aplites and pegmatites are generally irregularly distributed between productive and barren stocks. Aplites from the Patagonia and Santa Rita stocks, however, carry relatively high zinc values, 58 ppm and 73 ppm, respectively, corresponding to similarly high copper values from the same intrusions. Aplites from the Troy intrusion contain zinc concentrations of 28 ppm, which are similar to those from barren intrusions.

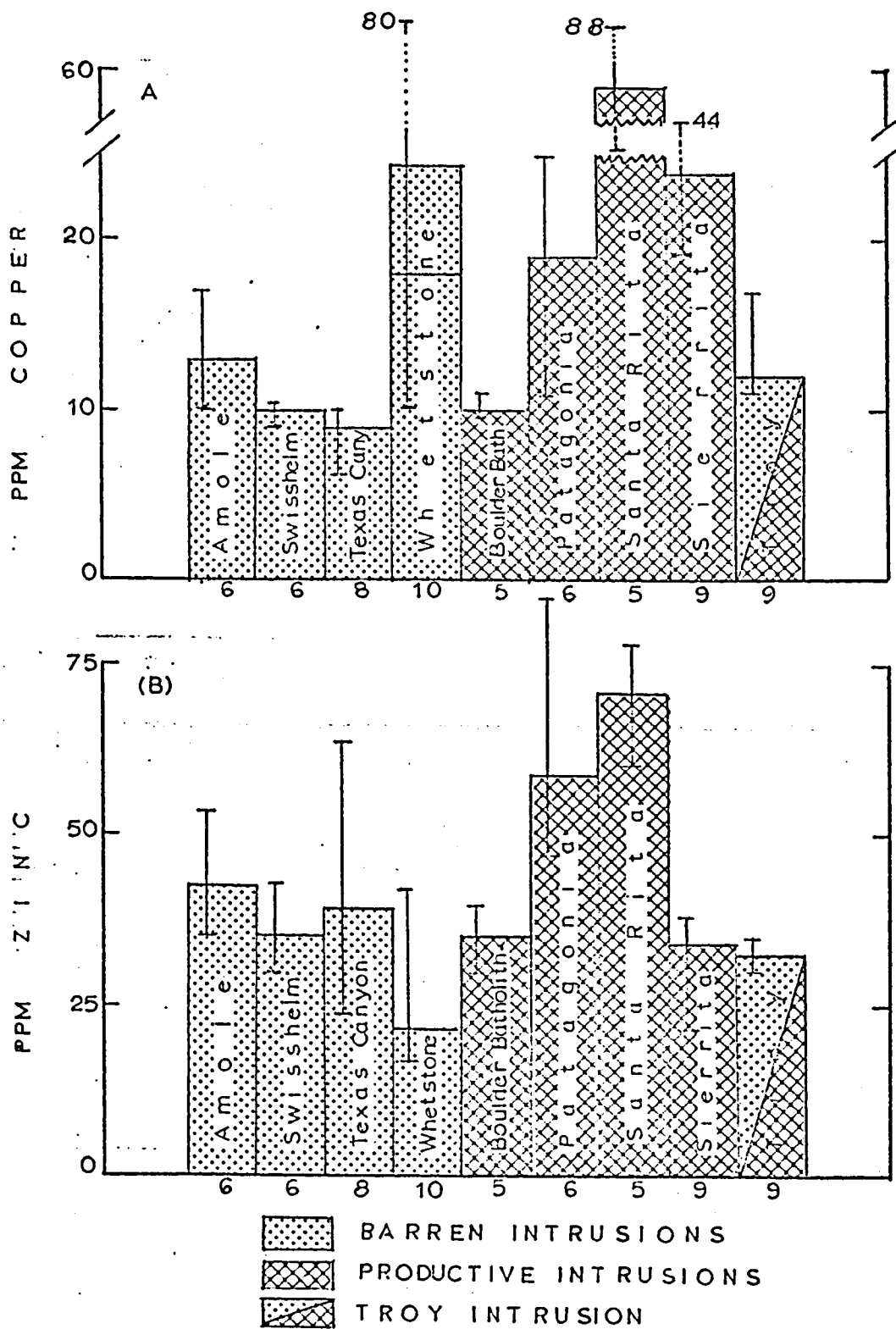


Figure 44. Average concentration of copper (A) and zinc (B) in whole-rock samples of aplite and pegmatite in some Laramide and mid-Tertiary intrusions

Vertical bar represents range of values.

K-feldspar Analysis

K-feldspar, like bulk rock, was analyzed by atomic absorption spectrophotometry. Results are listed in Appendix B and are graphically portrayed in Figures 45-47. The Troy intrusions is not represented here because no attempt was made to separate K-feldspar from its aplites. Results from these analyses do not exhibit pronounced differences in element concentrations between productive and barren intrusions. Since Silicon and aluminum do not show well-developed, distinctive differences between ore-bearing and barren intrusions in bulk aplite and pegmatite analyses, they would not be expected to show distinctions in K-feldspar and thus were not attempted.

Iron

The iron content of K-feldspar in dikes from productive intrusions at 0.08-0.17% Fe is proportionally higher than it was in the bulk rocks. Iron concentrations in samples from the barren Amole (0.14% Fe) and the Whetstone (0.10% Fe) intrusions are sufficiently high, however, to be comparable to those from productive intrusions (Fig. 45A). Again, as in the bulk rocks, K-feldspar separates from the Boulder batholith at 0.08% Fe are low in iron. Analysis also shows that the color of K-feldspar is related to its iron content. K-feldspar in dikes from the Santa Rita stock, which have a deep pink color, contains the highest quantity of iron (0.17% Fe), whereas K-feldspar from dikes from Texas Canyon, which are grayish white, contain the lowest (0.02% Fe). Iron content of the pink K-feldspar from the Amole (0.14% Fe), Whetstone (0.10% Fe), Patagonia (0.14% Fe), and Sierrita (0.13% Fe) intrusions is relatively

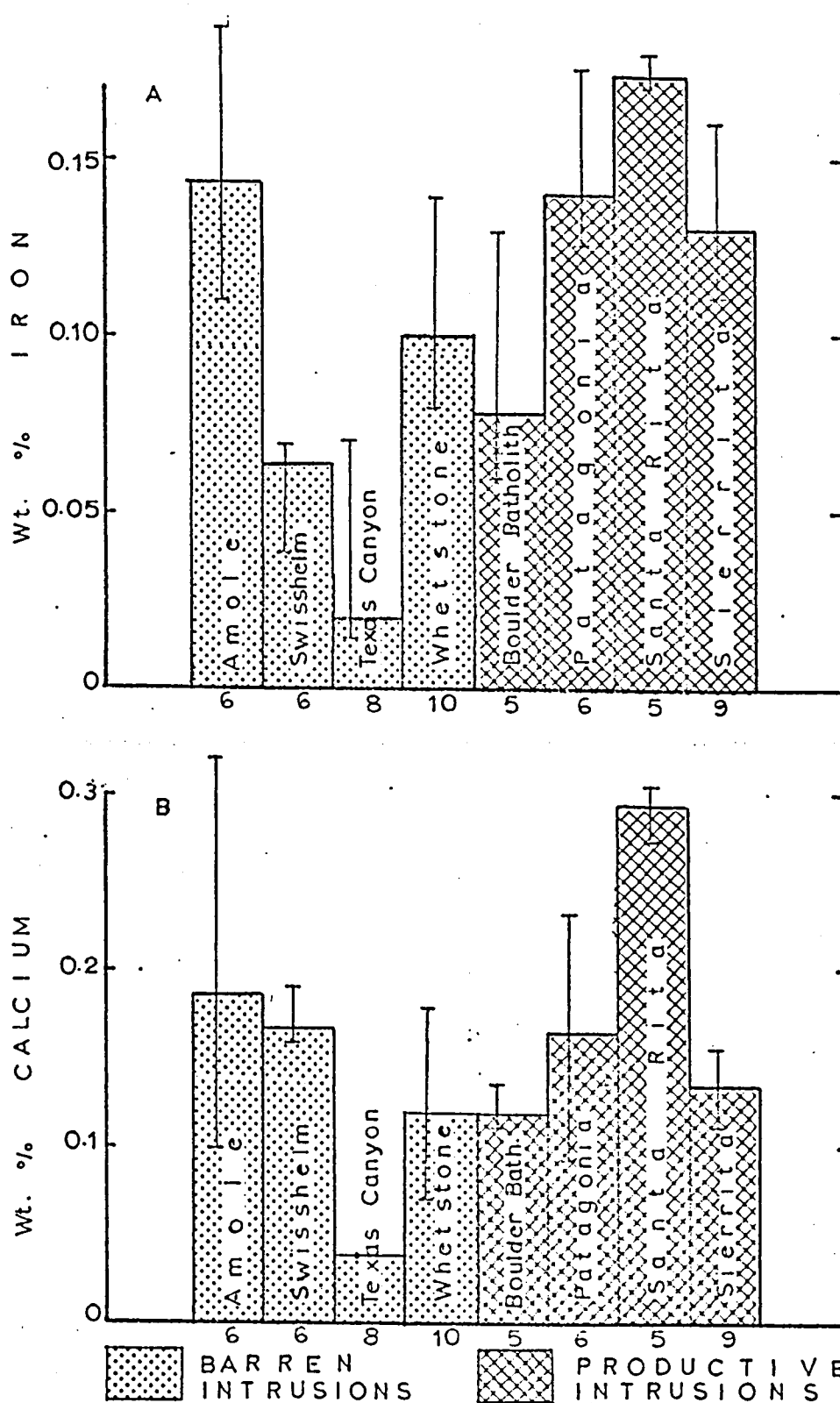


Figure 45. Average concentration of iron (A) and calcium (B) in K-feldspar of apfites and pegmatites in some Laramide and mid-Tertiary intrusions

Vertical bar represents range of values.

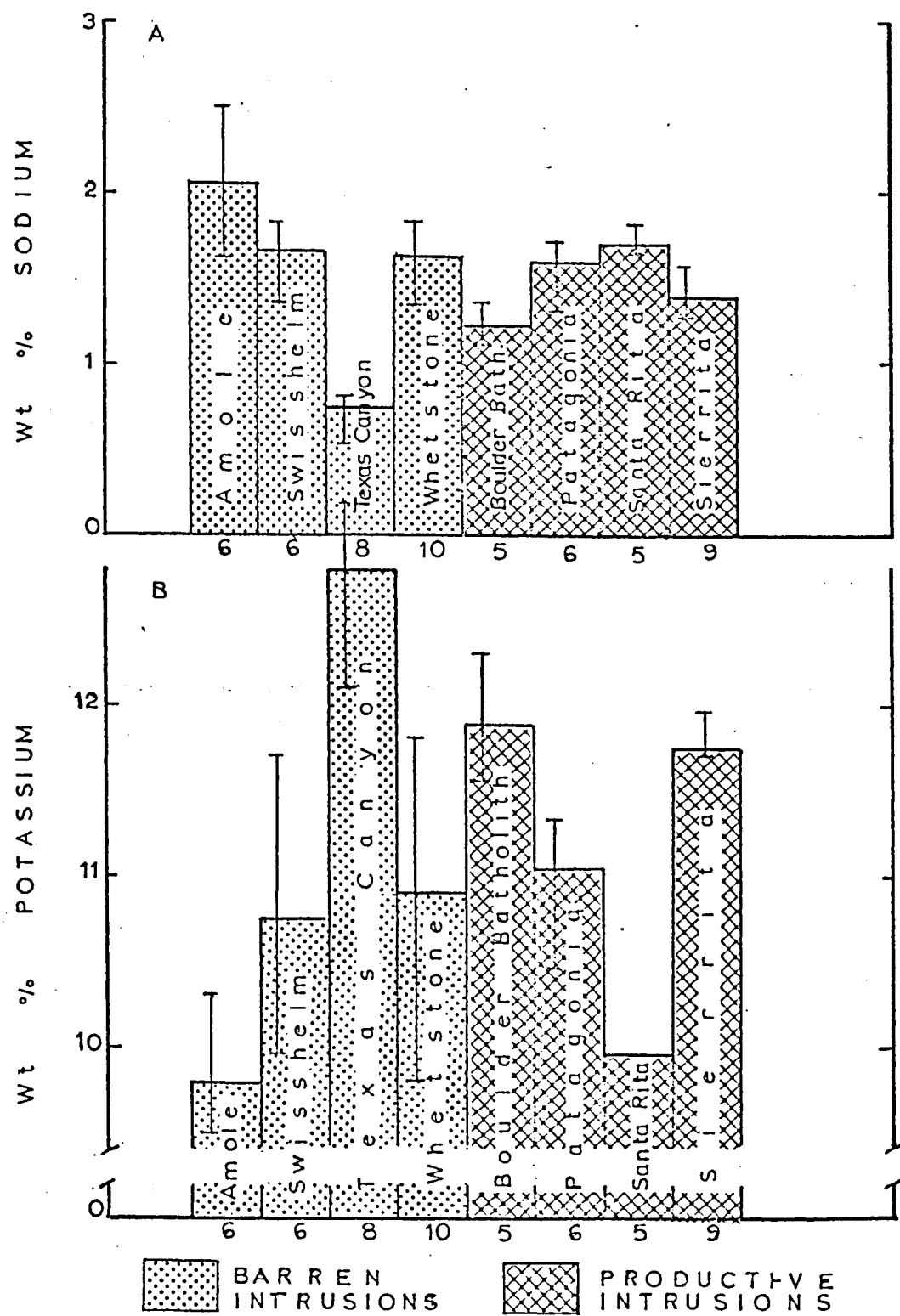


Figure 46. Average concentration of sodium (A) and potassium (B) in K-feldspar from aplites and pegmatites in some Laramide and mid-Tertiary intrusions

Vertical bar represents range of values.

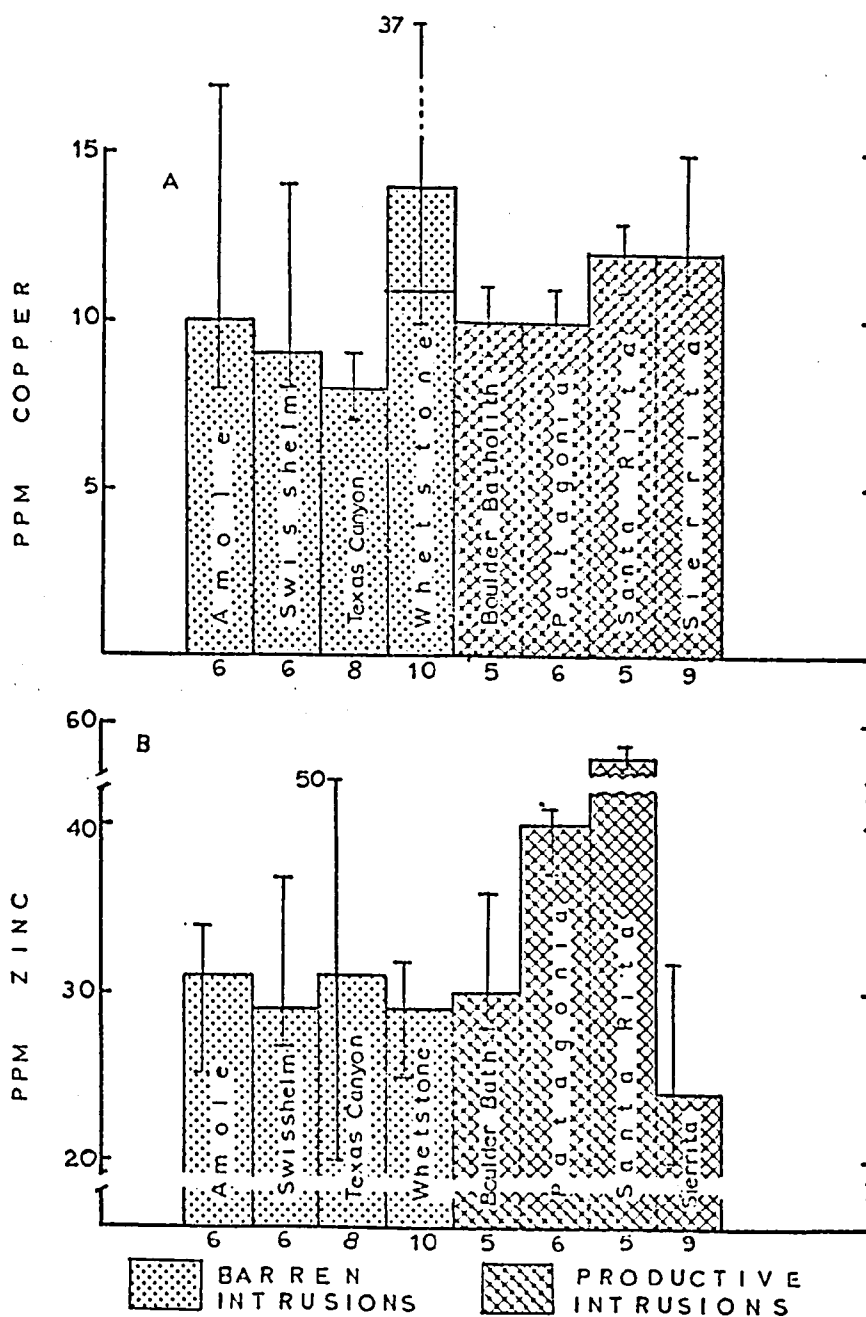


Figure 47. Average concentration of copper (A) and zinc (B) in K-feldspar from aplites and pegmatites in some Laramide and mid-Tertiary intrusions

Vertical bar represents range of values. Lower line represents average without sample 16.

high, while grayish-pink samples from the Boulder batholith contain intermediate iron (0.08% Fe), as indicated by Figure 45A.

Calcium, Sodium, and Potassium

The calcium content in K-feldspar is relatively low, as expected, ranging from 0.03%-0.30% Ca (Fig. 45B). Although calcium is not distinctively different between productive and barren intrusions, both very low (0.03% Ca) and very high (0.30% Ca) values are observed for the Texas Canyon and the Santa Rita intrusions, respectively. Likewise, sodium (46A) shows no trend, but like calcium, K-feldspar in samples from Texas Canyon carries the least (0.73% Na). If samples from Texas Canyon with high potassium (12.80% K) and Santa Rita with low potassium (9.7% K) are excluded, K-feldspar in dikes from productive intrusions at 11.02%-11.90% K are found to carry generally higher potassium contents than those from barren intrusions at 9.8%-10.9% K (Figure 46B). Kuellmer (1960) observed that alkali feldspars from the Lost Gulch quartz monzonite, Globe-Miami, Arizona, from within the area of moderate hydrothermal alteration, contain more orthoclase than specimens from outside this area. He concluded that primary magmatic differentiation or hydrothermal crystallization could be a plausible hypothesis to explain these compositional differences.

Copper and Zinc

Inspection of Figure 47A shows that copper is more concentrated in K-feldspars in samples from productive intrusions at 10-12 ppm. The observed high copper content in K-feldspar from the Whetstone samples at 14 ppm agrees with high bulk rock copper analyses from the same

intrusion. Like bulk aplites, the high average copper value at 14 ppm of the K-feldspar from the Whetstone stock (Fig. 47A) is due to sample 16. When this sample is excluded, the average value drops to 11 ppm copper. The zinc content in samples from barren intrusions is relatively uniform at 29-31 ppm, whereas variable values are observed in samples from productive areas (Fig. 47B). The highest zinc values occur in samples from productive intrusions, the Patagonia at 40 ppm and the Santa Rita at 58 ppm.

Normative Mineral Relationships

Bulk aplite and pegmatite chemical analyses calculated to normative minerals by the CIPW method are given in Appendix B. Normative orthoclase is plotted against normative albite to determine possible trends or distinctive differences in the studied areas and to permit their comparison to modal plots for feldspars. Normative feldspars after recalculation to 100 percent are plotted on a feldspar equilibrium ternary diagram (Bowen, 1956) to determine possible anomalies in their potassium, sodium, and calcium contents. Finally, normative salic minerals, orthoclase, albite, and quartz, after recalculation to 100 percent, are plotted on the isobaric minimum ternary diagram for the system Or-Ab-Q-H₂O (Tuttle and Bowen, 1958) in order to investigate the P-H₂O and temperature conditions at which these aplites and pegmatites formed.

Orthoclase-Albite Ratio

The plot of normative orthoclase versus albite (Fig. 48) depicts a trend similar to that shown by the plot of modal K-feldspar against plagioclase (Fig. 37). Like the relationships shown for modal minerals,

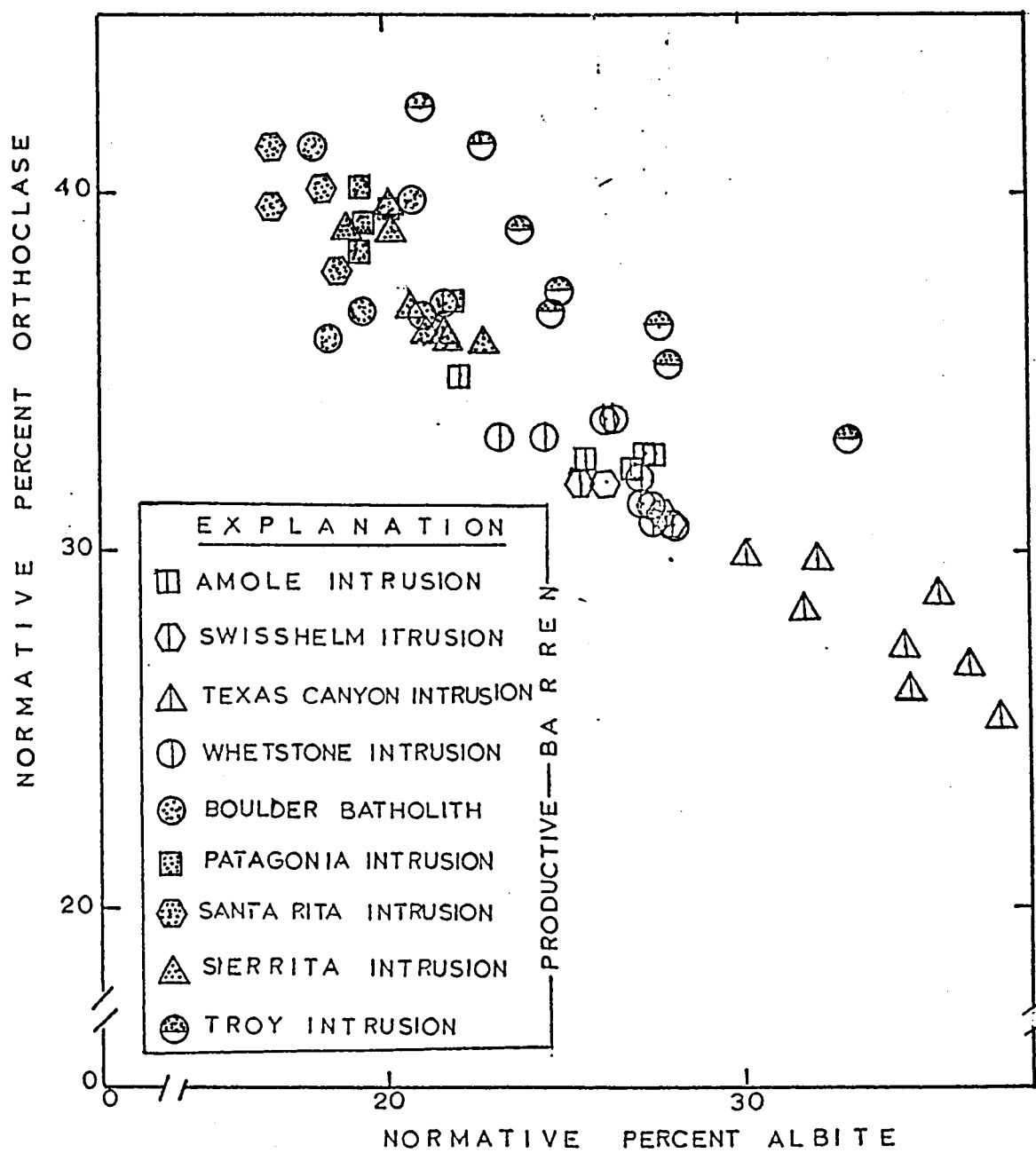


Figure 48. Plot of normative orthoclase against normative albite for dikes from Laramide and mid-Tertiary intrusions

the plots of normative orthoclase and albite show a linear relationship. Plots from productive intrusions cluster at the top left corner at about 40 percent by weight orthoclase and 20 percent by weight albite, whereas plots from barren intrusions spread toward the bottom right corner at 27 percent by weight orthoclase and 34 percent by weight albite. This linear relationship is controlled both by similarity of total feldspar content and the inverse relationship between orthoclase and albite. Since the amount of feldspar is nearly constant, an increase in orthoclase is offset by a decrease of albite and vice versa. It is also observed that samples from the same intrusion cluster together.

Feldspar Equilibrium Diagram

The normative content of feldspar from dikes under consideration is described and will be used to determine the genetic nature of these dikes. Compositions of rock-forming feldspars are expressed as molecular weight percentages of orthoclase, albite, and anorthite and plotted on a feldspar equilibrium ternary diagram (Bowen, 1956). This system is, however, not truly ternary at normal pressures because of incongruent melting of orthoclase to leucite plus liquid; it is actually quaternary (Barth, 1962). A ternary system forms at 30 percent excess silica or at 2,600 atm where water dissolves in an orthoclase liquid up to about 6 percent, from which orthoclase crystallizes directly (Barth, 1962). Bowen (1956) neglected this incongruent melting of orthoclase to facilitate discussion and treated the system as ternary. He constructed the orthoclase, albite, and anorthite diagram (Fig. 49) in which a cotectic boundary curve (ER) separates orthoclase and plagioclase fields.

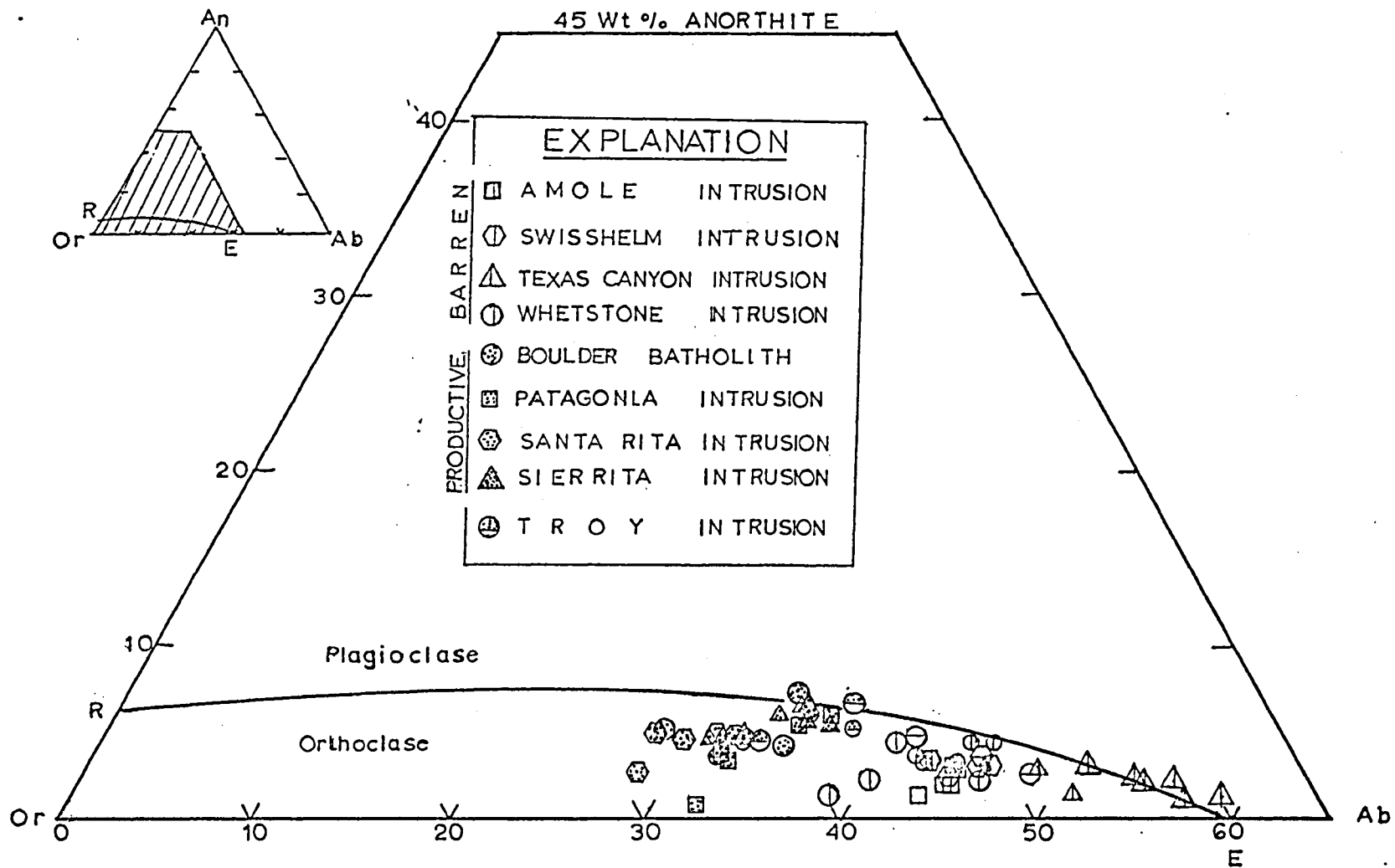


Figure 49. Plot of normative orthoclase, albite, and anorthite for 61 samples, recalculated to 100 percent, on the feldspar ternary diagram of Bowen (1956)

Bowen (1928) contended that all normative feldspars crystallizing from a basaltic magma, for which equilibrium is maintained, must plot in the plagioclase field of the feldspar ternary equilibrium diagram. Rocks whose normative feldspar contents fall in the orthoclase field are potassium rich and could not have formed by fractional crystallization of a basaltic magma (Bowen, 1928; Schairer and Bowen, 1947).

Normative feldspar from bulk chemical analyses of aplites and pegmatites reported here have been recalculated to 100 percent and are plotted on the ternary diagram (Fig. 50). Inspection of this figure shows that with the exception of one sample from the Boulder batholith, one from Troy, and most samples from Texas Canyon intrusions, all samples plot in the orthoclase field. Feldspars from mineralized intrusions plot toward the orthoclase apex. Samples from the Troy intrusion are comparable to those from mineralized areas.

Differentiation Index

The differentiation index (D-1), as described by Thornton and Tuttle (1960), is the sum of the weight percentage of normative quartz, orthoclase, albite, nepheline, leucite, and kalsilite. Since no more than three of these normative minerals can appear in any given norm, the differentiation index pertinent to this work is the sum of the weight percentages of normative quartz, orthoclase, and albite. As "petrogeny's residuum" is the end product of magmatic differentiation and therefore rich in the alkali elements, aluminum, and silicon (Bowen, 1937), the values of the differentiation index of a rock is a measure of how closely it approaches petrogeny's residuum. Thornton and Tuttle (1960)

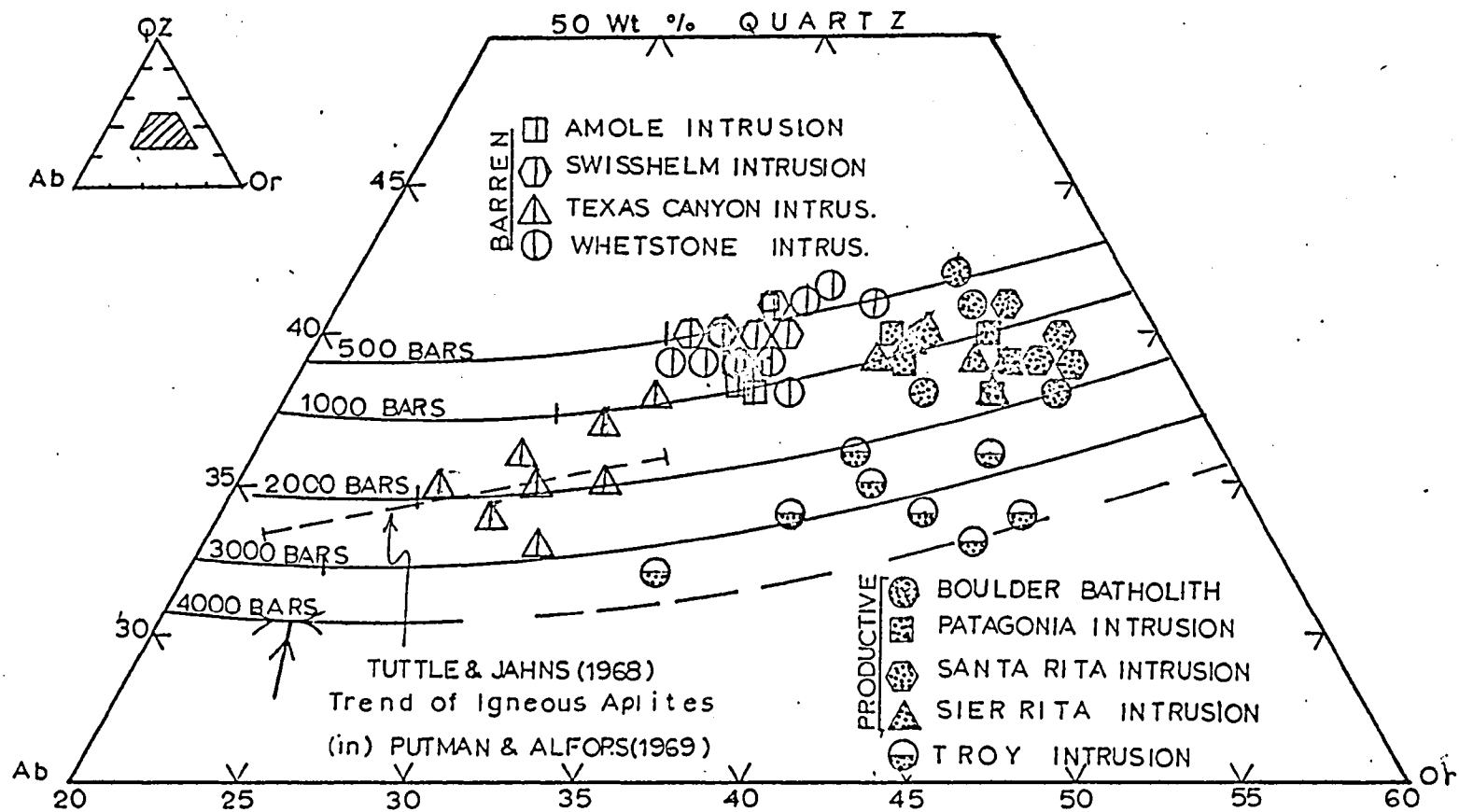


Figure 50. Plot of normative albite, orthoclase, and quartz for 61 samples, recalculated to 100 percent, for the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$

The shift of isobaric minima according to pressure is shown for the system.

calculated the differentiation index of the major igneous rocks of Daly (1914) and found that the differentiation indices of plutonic rocks range from 93 percent for alkali granite to 6 percent for peridotite (Table 12). The differentiation indices of aplites and pegmatites of this work range from 95 to 97 percent. Except for the Texas Canyon and Patagonia intrusions, dikes from productive intrusions have lower differentiation indices at 95 percent than those from barren ones at 95 percent.

Table 12. Differentiation indices for the aplites and pegmatites from this study and for the major plutonic igneous rocks

Aplites and Pegmatites	D-1	Major Plutonic Rock Types ¹	D-1
Amole intrusion	97	Alkali granite	93
Swisshelm intrusion	97	Granite	80
Texas Canyon intrusion	96	Granodiorite	67
Whetstone intrusion	97	Gabbro	30
Boulder batholith	95	Olivine gabbro	27
Patagonia intrusion	97	Peridotite	6
Santa Rita intrusion	95		
Troy intrusion			

1. Data from Thornton and Tuttle (1960).

Water Pressure

The water pressure of the rocks under consideration was calculated in an attempt to determine their temperature and depth of formation. Tuttle and Bowen (1958) studied the system $KAlSi_3O_8$ - $NaAlSi_3O_8$ - SiO_2 - H_2O

experimentally, constructed isotherms and isobars for it, and defined thermal minima for isobars in the system. Winkler (1967) found that the presence of over 5 percent anorthite in this system caused the isobaric minima to shift toward the quartz-orthoclase boundary. He concluded, however, that even if Ab/An is 1.8, the amount of anorthite components in the melt is only about 5 percent and therefore no serious error is made if that small amount is neglected in this discussion. Since the anorthite content of almost all of the rocks reported here is less than 5 percent, the shift of the isobaric minima is negligible and Tuttle and Bowen's (1958) findings are directly applicable.

Normative quartz, orthoclase, and albite of the dikes studied are plotted on the anhydrous base of the quaternary system (Fig. 50) after recalculation to 100 percent. This figure shows that samples from productive intrusions cluster at a P_{H_2O} of about 1,000 bars to the right of the thermal minimum. With the exception of Texas Canyon, samples from barren intrusions group around P_{H_2O} of about 500 bars. Samples from the Texas Canyon intrusion cluster around a P_{H_2O} of 2,000 bars and those from the Troy intrusion plot near a P_{H_2O} of 3,000 bars.

It is evident from Figure 50 that aplites and pegmatites from productive intrusions do not completely conform to the demands of petrogeny's residuum as they do not plot in the "thermal valley."

CHAPTER 6

DISCUSSION

This chapter presents a discussion of the field, petrographic, and chemical data given above with regard to the genesis and geologic significance of aplite and pegmatite occurrences.

Field Data

Within the context of magmatic theory, the presence of aplites and pegmatites indicates the existence of water-saturated silicate melts (Derry, 1931; Andersen, 1931; Emmons, 1940). Other acceptable theories proposed by Emmons (1940), Jahns and Tuttle (1963), Fournier (1968), and Jahns and Burnham (1969) hold that aplites formed as a result of pressure quenching of a water-saturated magma, whereas slow cooling and consequent crystallization of the same melt produced pegmatites. Jahns and Tuttle (1963, p. 90) suggest that aplites and pegmatites are found "almost exclusively in subsolvus granites," and because Tuttle and Bowen (1958) consider that subsolvus granites indicate hydrous environments, one may conclude that aplites and pegmatites form in a hydrous environment. Jahns and Tuttle (1963) also suggest that hypersolvus granites contain few, if any, aplites and pegmatites. Magmas which remain unsaturated with respect to water cannot be quenched by a reasonable drop of pressure. Consequently, such magmas are not likely to develop aplites and pegmatites, except locally where saturation or supersaturation with water has occurred. Fournier

(1968) maintains that a pressure drop may result in saturation or near saturation with water in previously unsaturated magmas so that any further pressure drops may quench the system and develop aplites. Neither can all saturated magmas develop aplites, since conditions favorable to their formation take place only in the event of a rapid pressure drop. This observation is in agreement with the findings of Jahns and Tuttle (1963, p. 91), who state: "The subsolvus granites, on the other hand, may carry large amounts of pegmatitic and aplitic material or none at all, depending on the cooling history of the intrusive." It is thus concluded that absence or scarcity of aplites and pegmatites does not by itself constitute a criterion of attainment or nonattainment of water saturation of a magma. However, the ubiquitous presence of aplites and pegmatites demands the saturation and quench of the melt from which they crystallized. A hydrous environment, as indicated by the presence of aplites and pegmatites, is therefore inferred for the Laramide and mid-Tertiary intrusions studied.

The metamorphic theory of Ramberg (1952, 1956) cannot explain such features as the continuity of dikes from igneous host rocks into the surrounding country rocks. Ramberg (1956) described pegmatites from Greenland and attributed them to metamorphic processes. Notable in his work is the absence of reference to aplite in Greenland. However, where aplite dikes do occur in metamorphic terranes and are considered to have formed by metamorphic processes, this theory runs into serious problems in explaining the contrasting textures of aplites and pegmatites by simple migration of elements into adjoining fractures. The simultaneous

development of these two textures suggests the operation of more than one mechanism.

Data presented above on the abundance and thickness of aplite and pegmatite dikes can shed light upon the mode of intrusion of the host melt if the presence of dikes be taken as evidence of rupturing of the host intrusion at any early stage of its mechanical competence.

In their study of the Little Dragoon Mountains, Cooper and Silver (1964) noted that the Texas Canyon quartz monzonite intruded actively along the southern margin and passively on the east and northeastern borders. They mapped abundant aplite and pegmatite dikes in the southern portion of the intrusion as opposed to a scarcity of them to the east and northeast. I confirmed Cooper and Silver's finding in the field and in addition observed the presence of thicker dikes in the southern than in the northeast portion of the intrusion. There thus appears to be a correlation between the presence of abundant thick dikes with forceful intrusion and scarce thin dikes associated with passive intrusion of the Texas Canyon stock. The consolidated rocks of the Texas Canyon stock appear to have responded differently to the two modes of intrusion. Where the intrusion was forceful, the consolidated part of the stock may have been subjected to stresses which formed many tensional fractures which, in turn, caused rapid decrease of pressure. Water-saturated melt which filled these fractures developed into aplite or pegmatite, depending on further pressure drop. In contrast, only a few fractures per line mile developed in the east where the stock was passively intruded, causing only sparse thin fractures which were subsequently filled with widely separated dikes.

A test of this mode of dike formation is possible by comparing the predicted features to those actually observed. Stringham (1966) contends that 23 of 24 intrusions studied in the porphyry copper environment were intruded passively. Lowell and Guilbert (1970) arrived at the same conclusion and believe that a typical intrusion related genetically to a porphyry copper deposit is passively intruded. Based on the published data, all productive intrusions studied in this research were passively intruded. Of the barren intrusions studied, the Texas Canyon (Cooper and Silver, 1964), Amole (Brown, 1939), and Whetstone (Creasey, 1967) were forcefully intruded. Complete information is not available for the Swisshelm intrusion. Thus, at least three of four nonproductive stocks were intruded forcefully. Based on its disturbance of the structure of the host rocks and the intrusion along preexisting faults, the Troy stock also intruded forcefully.

If the differing intrusive natures assigned to productive and barren intrusions are correct and if the model derived from the intrusive history at Texas Canyon is valid, then correlation of scarcity of dikes with productivity of intrusions becomes readily explainable. Since mineralized stocks intrude passively, it is to be expected that only a few fissures form in the cupola of the shell, resulting in the development of scarce thin dikes. On the other hand, the forceful intrusive nature of barren intrusions caused many fractures which were subsequently filled by melt which ultimately crystallized into aplite and pegmatite dikes. It is concluded here that scarce thin dikes are correlative with productive intrusions mainly because of the passive intrusive nature of the latter. Depth of erosion versus possible zoning of aplites and pegmatites in various

intrusions might also be thought to result in an apparent difference in number of dikes per line mile. Where erosion cuts deeply into an intrusion, most of the dikes are eroded away leaving only scarce dikes. This situation may lead to the misconception that the intrusion originally carried a small number of dikes. If, on the other hand, erosion barely exposes such an intrusion, most of the dikes are preserved, leading to the conclusion that dikes are abundant. In this case, the difference in number of dikes between productive and nonproductive intrusions may be apparent rather than real or genetic. The presence of roof pendants at the Texas Canyon and Swisshelm intrusions indicates that the two intrusions are shallowly eroded and may explain, in part, why both contain abundant dikes.

This erosional level explanation for dike abundance fails when applied to the Amole intrusion where an abundance of dikes occurs even in the absence of roof pendants. The erosional concept for dike abundance may be misleading, however, unless the depth of erosion at each intrusion is well documented. The San Manuel-Kalamazoo deposit, a concealed porphyry copper deposit in Pinal County, Arizona, is for this reason ideal for study. Lowell (1968) and Lowell and Guilbert (1970) do not report the occurrence of aplite-pegmatite dikes. Lowell (oral communic., 1973) confirmed the scarcity of aplite and pegmatite dikes in the Laramide porphyry. Scarce dikes of undetermined age cut the Precambrian Oracle quartz monzonite. R. M. Corn (oral communic., 1973) concurs that aplite and pegmatite dikes at the Red Mountain porphyry copper deposit are uncommon in the exposed igneous intrusion. Aplites and pegmatites are also scarce in the Butte mining district (Meyer and

and others, 1968). Aplites and pegmatites have not been observed in the exposed igneous intrusion at Christmas mine (J. G. Jones, oral commun., 1973).

One may therefore conclude with respect to the areas presently studied that, although depth of erosion may have played a role in the dike population of these intrusions, the original difference is probably genetic and that the mode of intrusion of these stocks plays the major role. Scarcity and thinness of aplite and pegmatite dikes is therefore concluded to be a useful criterion that may be used in conjunction with others to locate porphyry copper deposits.

The mesoscopic and microscopic textural features of aplite- and pegmatite-filled dikes described above also support the concept of a magmatic origin for these aplite and pegmatite dikes. Andersen (1931) and Emmons (1940) visualized these dikes as having formed by permissive draining of pegmatitic magma into fractures, whereas Lindgren (1933), while concurring in their magmatic origin, considered them as having formed by forceful wedging apart of fissures. Ramberg (1952) explained the occurrence of parallel-walled pegmatite dikes in both metamorphic terranes and plutonic rocks by metasomatic replacement spreading outward evenly from a fracture. The metamorphic explanation as given by Ramberg presents difficulties in explaining the simultaneous formation of the different textures of aplites and pegmatites by one and the same mechanism. Cameron and others (1949, p. 9) believe that the shapes of aplite and pegmatite dikes are greatly influenced by the type of host rocks and consider that most of the pegmatites in granite are tabular or branching bodies "obviously formed along joints and

fractures." Fournier (1968, p. 260) contends that ". . . offset of one dike by another, long straight contacts with sharp corners that are commonly accompanied by abrupt changes in the width of the dike, matching walls on opposite sides of dikes . . ." indicate emplacement of dikes by injection.

Texture

The textural homogeneity of aplites in 58 studied dikes can best be explained by a magmatic origin. Vogt (1923) assigned relative viscosities to different silicate melts. He found that iron- and manganese-rich melts are the least viscous and silica- and alkali-rich melts are the most viscous. The relative abundance of water in a granitic melt was determined by Jahns and Burnham (1969) to reduce its viscosity considerably. A water-rich, silica- and alkali-rich melt of low viscosity may be readily injected into preexisting fractures. Subsequently formed fractures cutting older ones cause volatiles from this water-rich melt to escape to the younger fractures, leaving a relatively dry melt of greatly increased viscosity in which chemical diffusion is very slow. Minerals crystallizing from this dry melt draw their components by diffusion from the immediately adjacent melt. If pressure quenching obtains, mineral and chemical homogeneities of the crystallizing viscous melt are inherited in the solid product. Slow crystal growth in the viscous melt coupled with the formation of many crystal nuclei due to a pressure quench would result in fine-grained, xenomorphic granular, texturally homogeneous aplite dikes. The injection of a residual melt chemically different from the composition of the host rock would result in mineral

constituents different from those present in the host rock. Rapid crystallization because of pressure quenching results in a much finer grained texture than is observed in the medium- to coarse-grained host rocks and also prevents the melt from reacting with the wall rock. Sharp contacts of aplite dikes thus form as a result of their mineralogical and textural differences from the host rock and of the hindrance of chemical reactions between the rapidly crystallizing viscous melt and the host rock. Uniformity of grain size and the lack of chilled aplite dike contacts may be explained by filling of preexisting fractures at magmatic temperatures. According to Derry (1931), the recently solidified outer part of a pluton may be essentially at the same temperature as the injected hydrous pegmatitic melt. Another explanation of the textural homogeneity across the dikes is that because aplite dikes are thin tabular bodies, appreciable thermal gradients across them are not likely to develop and dike material will crystallize without any change in grain size. It is also probable that the pressure-quenched melt crystallizes too rapidly to allow observable difference in grain size between the margins and centers of dikes.

The presence of randomly distributed coarse-grained patches in aplites (Fig. 14) is also best explained by the magmatic theory. Growth of these patches must have taken place in a less viscous melt where diffusion of ions was relatively rapid and resistance to crystallization was low. These patches are here considered to have crystallized from a hydrous melt trapped within the rapidly crystallizing viscous melt. Studies of Emmons (1940) and Fournier (1968) support this explanation. The contention that these coarse-grained patches have formed by action

of a hydrothermal solution after solidification is unlikely as evidence for hydrothermal activity, as explained later, is not sufficient.

The presence of mixed aplite-pegmatite dikes in the study areas also supports the magmatic derivation of these dikes. This mixed occurrence of aplite-pegmatite takes place where a fracture filled with pegmatitic magma crystallizes in part to pegmatite, while the remaining melt loses its volatiles and forms aplite within the pegmatite. This view is supported by Emmons (1940), Fournier (1968), and Jahns and Burnham (1969). The last authors suggest that pegmatite within aplite dikes forms where the entire water-rich melt is not pressure quenched to aplite so that the unquenched portions can yield masses of pegmatites within a body of otherwise aplitic rock.

The origin of these mixed dikes is explained hydrothermally in terms of an aqueous solution acting along the contacts of dikes with host rocks or filling fractures in the center of dikes and depositing coarse-grained pegmatitic material (Hess, 1925; Schaller, 1925; and Derry, 1931). The texture and mineralogical and chemical composition of the dikes studied here and discussed later do not support a hydrothermal origin. It is therefore concluded that mixed aplite-pegmatite dikes are formed from a hydrous magma which begins crystallizing to pegmatite with subsequent quenching of the remaining liquid to aplite. Conversely, pockets of hydrous melt may be locally trapped in a viscous, generally anhydrous melt and subsequently crystallize to pegmatite while the viscous melt crystallizes to aplite.

Information presented above on the color of dikes and of their constituent feldspars provides insight into chemical control in the

studied aplite and pegmatite dikes. Chemical analyses of bulk rock and K-feldspars indicate that pink dikes have more iron than grayish-white dikes. Similarly, K-feldspar from pink dikes are pink and contain more iron at 0.1%-0.17% Fe than the grayish-white K-feldspars at 0.02%-0.06% Fe. No grayish-white dike is observed in productive intrusions. It may be thus concluded that the presence of grayish-white dikes in an intrusion is an unfavorable porphyry-copper indicator.

Petrographic Data

Texture

The textural homogeneity observed in thin section confirms that observed in the field and is attributed to the same mechanisms discussed earlier. Both graphic and granophyric textures indicate a magmatic origin and both are found in the dikes under consideration. Granophyric texture is considered by Barker (1970) to form as a result of rapid crystallization. It is commonly observed in devitrifying glass (Schloemer, 1964) and has been described in plutonic rocks from aplites (Barker (1970)). The magmatic origin of granophyric textures is suggested by Barker (1970, p. 3343) when he states: "The restriction of granophyric intergrowth to granitic composition, the intricate texture, and the diminution of grain size of intergrowth with presumed rapid cooling, the lineage structure, and the occurrence in hypabyssal, volcanic, and aplitic rocks suggest that the intergrowths are products of rapid crystallization." Graphic texture is common in granitic plutonic rocks where it is concluded to be a magmatic texture. Its presence in pegmatite has been considered by Jahns (1955) as a result of eutectic crystallization in a silicate melt.

Graphic texture has been considered by Jahns and Tuttle (1963) and Barker (1970) indicative of magmatic crystallization.

Mineral Composition

Plagioclase. With regard to plagioclase composition, the high anorthite content at An_{10-17} in productive intrusions as confirmed by the high calcium content of bulk rock analysis at 0.31%-0.48% Ca may be due to less differentiation of the source material of these dikes. The calculated differentiation indices for dikes from productive areas, averaging 95 percent, contrasting with those from barren intrusions at about 97 percent (Table 12) supports this explanation. Another possibility is that of a chloride-rich solution which has been suggested for reasons discussed later to coexist with melts of productive intrusion carry more calcium in it than chloride-deficient solutions. A silicate melt coexisting with a relatively calcium-rich chloride aqueous phase is also calcium rich, as calcium preferably partitions into the silicate melt (Gammon and others, 1969). Subsequent crystallization of this melt would produce calcium-rich aplites and pegmatites. The rare presence of $CaSO_4$ in fluid inclusions in quartz in porphyry copper deposits indicate that calcium activity in the hydrothermal phase may have been fairly high.

K-feldspar. Point counts and thin section analysis clearly demonstrate the predominance of K-feldspar at 40-48 percent by volume in dikes from productive areas (Figs. 36 and 37) and that this trend is also confirmed chemically by the presence of correspondingly high potassium contents of 5.2-5.6% K in the bulk rock samples and about

11.7% K in corresponding K-feldspar. Figure 40 shows that aplite and pegmatite dikes in mineralized intrusions have granitic compositions, whereas those from barren areas are quartz monzonitic, again indicating the high K-feldspar content of the former. The mineralogical and chemical homogeneities of these dikes, the granitic composition of dikes from mineralized areas, and the predominance of K-feldspar over plagioclase from these same dikes are discussed below and demonstrate their magmatic origin and potential exploration significance.

Bowen (1928) states that anomalously potassium-rich residual melts may form by the differentiation of basaltic magma. He postulated that a reaction between anorthite in a melt consisting largely of orthoclase and anorthite causes the composition of this melt to cross the co-tectic curve of the feldspar equilibrium system (Bowen, 1928, Fig. 59, p. 231) into the orthoclase field. Schairer and Bowen (1947), however, found that this postulated reaction was nonexistent and consequently discredited this conclusion. Considering this reaction of Bowen (1928) to be valid, Noble (1948) assigned a magmatic origin to the anomalously potassium-rich rhyolite dikes in the Homestake mine area, South Dakota. Higazy (1950) concluded that the origin of anomalously potassium-rich rocks might be explained in two ways: (1) by crystallization from a primordial rhyolitic melt or a mixture of rhyolitic and basaltic magmas, the basaltic magma being subordinate, as explained by Fenner (1948); or (2) by crystallization from a granitic magma derived, according to Wahl (1949), by differential remelting of the crust.

If the dikes under consideration formed by fractional crystallization of an intermediate magma, its residual magma should meet the

demands of petrogeny's residua (Bowen, 1937). The residual composition should plot in the system's "thermal valley" (Bowen, 1937) and its feldspar composition should plot in the plagioclase field of the system Or-Ab-An (Bowen, 1928). The dikes studied here do not meet any of the demands stated above and consequently cannot have originated only by normal magmatic differentiation.

It is proposed here that aplites and associated pegmatite in mineralized stocks crystallized from a residual melt that at some time before their injection coexisted with an alkali-base-metal-chloride-rich aqueous phase. Potassium partitions into the melt and sodium into the aqueous phase in ratios controlled by temperatures from 880°C to 250°C (Orville, 1963; Ellis and Mahon, 1967; and Gammon and others, 1969). Within the framework of this magmatic model, the formation of a chloride-rich aqueous phase, its importance in dictating the partitioning of certain elements at high temperatures, and the later reversal in partitioning trend of some of the elements into a coexisting silicate phase in response to a progressive drop in temperature are discussed.

It is fairly well established that where and when an aqueous phase coexisting with a silicate melt develops almost all of the chloride in the silicate melt partitions into this aqueous phase (Burnham, 1967; Kilinc and Burnham, 1972; Holland, 1972). Results of work done by Kilinc and Burnham (1972, p. 233) indicate that

when an aqueous phase separates from a granitic magma much of the chloride it contains also will separate, possibly making the coexisting aqueous fluid a highly concentrated brine. This very saline solution, however, may be diluted with further evolution of water from the magma or may become more saline, depending upon the initial H₂O content of the magma.

Figure 51 from Kilinc and Burnham (1972) shows the variation in chloride content of an aqueous phase coexisting with chloride-bearing, water-saturated melts.

Holland (1972) considers the strong partitioning of chloride ion into the aqueous phase to be an important factor in directing the chemistry of ore-forming fluids derived from magmatic sources. The significance of high concentrations of chloride ion in ore-forming fluids is demonstrated by the high chloride ion content of intrusions genetically related to ore deposits (Stollery, Borcsik, and Holland, 1971). These workers found that the chloride ion content of biotite in the stock which was closely related to base-metal deposits at Providencia, Zacatecas, Mexico, was 0.3-0.5 percent by weight, which was more than the average chloride content of biotites from granitic rocks at 0.1 percent by weight (Dodge, Smith, and Mays, 1969; Dodge and Ross, 1971). Similarly, "the chloride content of biotite from several other stocks associated with base metal deposits is abnormally high" (Holland, 1972, p. 292). Experiments in progress indicate that biotites do not admit chloride ions readily and that the solutions at 800°C must be highly saline to be in equilibrium with biotites containing 0.5% Cl (Holland, 1972).

Alkalies, base metals, iron, calcium, and other metals tend to partition into this chloride-rich aqueous phase (Borina, 1963; Helgeson, 1964; Roedder, 1967, 1971; Burnham, 1967; Gammon and others, 1969; and Holland, 1972). The partitioning of potassium and sodium between a chloride-rich aqueous phase and a coexisting silicate melt is strongly temperature dependent in the range of 880°C to hydrothermal solution temperatures at 250°C (Orville, 1962, 1963; Ellis and Mahon, 1967;

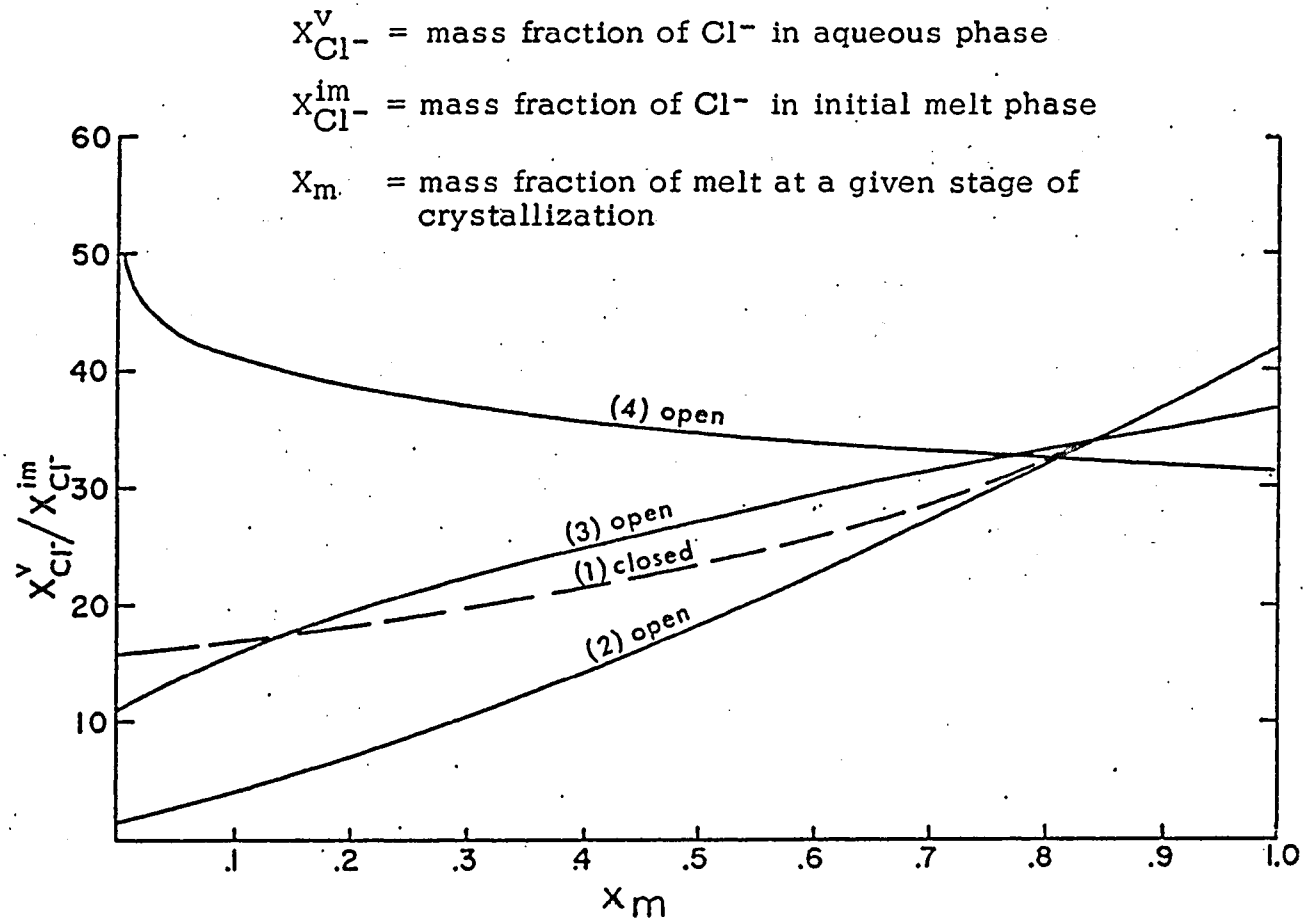


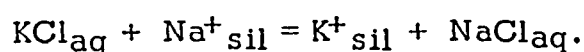
Figure 51. Variation in Cl^- content of the aqueous phase with crystallization of Cl^- -bearing, water-saturated melts

Curve (1) represents aqueous phase compositions in a closed system at 2.0 kb with an initial H_2O content of 6.3 wt. percent. Curve (2) represents open system conditions at the same pressure and H_2O content as (1). Curves (3) and (4) are for open system conditions at 1.0 kb, 4.3 percent H_2O , respectively. Figure taken from Kilinc and Burnham (1972).

Gammon and others, 1969). Ellis and Mahon (1967, p. 519) found that "values of atomic ratio Na/K in solution in contact with rhyolitic rocks ranged from 10-15 at 250° to 4 at 600°C," indicating that a drop in temperature from 600°C to 250°C favors partitioning of sodium into the solution. Orville (1963) found that the ratio (m K aq/m Na aq) in chloride solutions in equilibrium with two alkali feldspars increases with temperature from 0.259 ± 0.006 at 500°C to 0.351 ± 0.007 at 670°C. The work done by Gammon and others (1969) supports Orville's findings and extends it to higher temperatures. They found that the ratio (m K aq/m Na aq) in an aqueous phase in equilibrium with an average granitic melt between 770°C to 880°C and 1.4 to 2.4 kb is 0.57.

Now to consider how the above discussion reflects on the results described earlier in this section. According to the findings of Stollery and others (1971) and Holland (1972), granitic rocks genetically related to base-metal deposits have high chloride concentrations. This observation is also true for dikes from productive areas. Results of work on primary fluid inclusions supports high salinity of fluid trapped in dikes from productive stocks. The presence of halite daughter minerals in dikes from productive areas indicate that the solution from which those inclusions were trapped must have been supersaturated with halides. Roedder (1971) also revealed that fluid inclusions associated with ore also contained daughter crystals of NaCl. Because the partition coefficients of alkali halides into a liquid phase is much greater than into a gas phase (Sourirajan and Kennedy, 1962), fluid inclusions in dikes from productive areas are more saline than those from dikes in barren areas. Accordingly, alkalies, base metals, and iron and calcium partition into

this saline phase (Borina, 1963; Helgeson, 1964; and Burnham, 1967). At a temperature above 880°C, potassium concentrates into the aqueous phase, whereas sodium partitions into the melt. At 880°C, the ratio $m_{K_{aq}}/m_{Na_{aq}}$ is 0.57 (Gammon and others, 1969). As the temperature decreases to 500°C, the ratio in the aqueous phase drops to 0.351 as a result of potassium from the aqueous phase replacing sodium in the silicate melt, according to the equation (Orville, 1963):



Potassium therefore continues to partition into the silicate melt, resulting at magmatic temperature in a potassium-rich melt. Aplites and pegmatites that develop from this melt would thus be anomalously high in potassium and relatively low in sodium, plotting outside the "thermal valley" and in the orthoclase field of the feldspar ternary system. This mechanism readily explains the high content of K-feldspar in dikes from productive stocks, the high content of potassium in their respective K-feldspars, and their granitic composition. Mineralogical and chemical homogeneity of aplite within a given stock is explained by the same mechanism that produced their textural homogeneity.

A continuing drop in temperature below that of aplite and pegmatite crystallization leads to progressive crystallization of K-feldspar down to hydrothermal temperatures of alteration at 250°C (Ellis and Mahon, 1967). In this temperature range, sodium continuously partitions into the aqueous phase, explaining the high NaCl content observed in fluid inclusions in ore deposits.

The modification of aplite and pegmatite dikes by a hypothetical potassium-rich hydrothermal solution, in accordance with the findings of Fenner (1936), Terzaghi (1948), Anderson (1949), Higazy (1949), Stringham (1953), and Peters and others (1966), resulting in a high K-feldspar content in dikes from productive intrusions is apparently unrealistic in the present work. Although hydrothermal solutions have permeated these dikes, as shown by secondary orthoclase veins (Fig. 13) and replacement of plagioclase, the quantity of secondary K-feldspar is not sufficient to account for the observed high K-feldspar content in dikes from productive areas. Addition of at least 10 percent by volume of orthoclase at the expense of plagioclase is needed to upgrade the composition of dikes of quartz monzonite composition from 35 to 45 percent K-feldspar granitic compositions. This amount of "secondary" K-feldspar and the mechanism of its addition are not seen in thin section. The composition of all dikes in a single intrusion is so similar that modification by hydrothermal solution becomes an unreasonable explanation, since hydrothermal replacement cannot be expected to act uniformly to produce such similar compositions. On the contrary, if hydrothermal alteration were the major factor in the high K-feldspar content of dikes, then dissimilarity of composition of dikes would be expected. If the high content of K-feldspar in dikes from productive areas was due to hydrothermal alteration, then according to Meyer and Hemley (1967), a high sodium content should exist in K-feldspar in dikes from productive intrusions. However, the opposite is true where sodium content is lower in K-feldspar in dikes from productive intrusions than in K-feldspar in those from barren ones.

The possibility of a continuum between magmas and ore deposits was considered by Spurr in 1923. Tolman (1931) suggested a continuum between massive quartz or quartz veins and magmatic rocks. Gilluly (1942) indicated that there was apparently no place in the Ajo copper district (Arizona) where a hiatus between pegmatite development and mineralization could be established. Schilling (1956) found molybdenite-bearing pegmatite at the Questa mine (New Mexico). Sales and Meyer (1956) and Meyer and others (1968) described molybdenite in quartz-rich pegmatite cores. Klepper and Robertson (1956, p. 117) in their study of the northern part of the Boulder batholith observed the presence of tourmaline, pyrite, and less commonly molybdenite "in essentially a feldspar-stable (deuteric) environment during the late stage of consolidation of the alaskitic and aplitic rocks." They concluded that "in addition, the presence of abundant tourmaline with feldspar in many aplitic rocks and of tourmaline with feldspar alteration products in many veins suggests a close genetic relationship of late-stage igneous and hydrothermal processes." Lacy (1957) noted the concentration of quartz and orthoclase of aplitic texture in porphyries just prior to ore deposition. Lutton (1959) studied four copper-molybdenite deposits in the vicinity of Tucson, Arizona, and found that molybdenite and chalcopyrite are deposited as early as the pegmatitic stage. He concluded that pegmatite could be the missing link between magmas and hydrothermal ore deposits.

Results obtained during this work indicate a continuum between aplites and pegmatites and genetically related porphyry copper deposits. The texture of oxidized sulfides, uninfluenced by fracturing, and their

occurrence as isolated grains (Fig. 28) indicate that part of the sulfide grains is primary. The presence of sulfides in aplites and pegmatites, the occurrence of identical sulfides in the earliest hydrothermal veinlets, and the breadth of stability fields of these sulfide species across the pressure-temperature range of these environments argue that sulfides continued to crystallize from the aplite-pegmatite stage into the stage of hydrothermal ore deposits.

Orthoclase is found to be an important mineral in establishing this continuum. Orthoclase is common to porphyry copper environment in general (Lowell and Guilbert, 1970) and to the four studied areas in particular. Both secondary hydrothermal (Creasey, 1966) and late magmatic (deuteric) orthoclase (Klepper and Robertson, 1956) have been described in the porphyry copper environment. Results of this work indicate the presence of anomalously high orthoclase content in aplites and pegmatites which are associated with porphyry copper deposits which are considered to be of primary magmatic origin. The anomalously high orthoclase content is explained by crystallization of orthoclase from a residual melt coexisting with a chloride-rich aqueous phase. As a consequence of this condition, orthoclase apparently began to crystallize at magmatic temperatures and continued to crystallize from hydrothermal fluids responsible for the deposition of the ore deposits with no hiatus indicated by field, petrographic, chemical, or experimental data. This observation is in harmony with the experimental work of Orville (1962, 1963), Ellis and Mahon (1967), and Gammon and others (1969). A potassium-rich silicate melt continues to evolve as the temperature of the system drops. Rocks forming from this evolving melt are

anomalously rich in orthoclase. When crystallization of the melt has ceased, K-feldspar continues to crystallize from the hydrothermal solution as orthoclase or microcline in veins or replacing plagioclase.

Chemical Data

The distribution of analyzed elements is discussed below to determine their genetic and exploration significance.

Silicon

The high silicon content in bulk rock at 35.3-36.6% Si confirms the petrographic findings and indicates that the dikes are products of the latest magmatic differentiation. Compared to chemical analyses of plutonic igneous rocks by Washington (1917), these dikes contain higher silicon values than those reported for granite and are comparable to those reported for aplites and pegmatites. The similarity of silicon values in dikes from productive intrusions at 36.2%-36.6 % Si and those from barren ones at 35.2%-36.9 % Si does not render silicon a useful exploration tool.

Aluminum

Like silicon, aluminum cannot be used as an exploration tool, because dikes from mineralized and barren intrusions, except Texas Canyon, show similar values at $6.4 \pm 0.1\%$ Al (Fig. 42). This similarity in aluminum analyses is confirmed by the similarity in the total feldspar content in dikes from these two environments and by the similarity of the content of aluminum in orthoclase at 9.75% Al and in albite at 10.33% Al. The high aluminum content in dikes from Texas Canyon at 7.6% Al is explained by the presence of 4-13 percent by volume of

muscovite carrying 38.5% Al. Relatively greater aluminum at 7.0% Al in dikes from the Troy intrusion is due to the greater abundance of feldspar at 67-72 percent by volume in dikes in this stock as compared to dikes from other intrusions at about 60-67 percent by volume.

Iron

In a volatile saturated or supersaturated residual melt, iron oxidizes to the Fe^{+++} state and possibly behaves as a complex ion (Ringwood, 1955). Because of their similar physiochemical properties, Fe^{+++} substitutes for Al^{+++} . The filling of part of the aluminum sites in feldspars by ferric ions, plus the presence of hematite in crystal defects (Andersen, 1915; Wones, 1962; and Boone, 1969), may cause the observed color in pink feldspars. Pink dikes and their corresponding feldspars contain relatively high iron, confirming, in the scarcity of other iron-bearing minerals in dikes, the probability of this conclusion.

Inspection of Figures 42 and 45 indicates that iron is relatively high in dikes and their corresponding feldspars in productive intrusions. Silicates coexisting with iron-rich chloride solutions, as discussed earlier, may possibly produce feldspars relatively rich in the ferric ion.

High concentration of iron in dikes and their feldspars as an exploration indicator discounts the Texas Canyon and Troy intrusions as having producing possibility. A similar conclusion for Texas Canyon has been reached by dike population, feldspar ratios, and other data in the course of this work. This information casts some doubt on the likelihood that the Texas Canyon stock is the source of metals in the Johnson Camp ore deposit.

Calcium

The low concentration of calcium in aplite and pegmatite dikes under consideration is expected in residual melts, as calcium is captured by early-forming silicate minerals, leading to its depletion in the residual melt. Figure 42 indicates that the calcium content is relatively high in dikes from productive intrusions. However, because the calcium content in dikes is generally low and the difference between calcium in dikes from productive intrusions (0.3-0.5% Ca) and that in dikes from barren intrusions (0.2-0.3% Ca) is small, calcium cannot be considered a good ore indicator. Again, the Texas Canyon aplites and pegmatites are low in calcium, placing it among the barren intrusions. Samples from the Troy intrusion contain relatively high calcium and the intrusion accordingly may be ranked among productive intrusions. The Troy intrusion shows confusing features, since some properties, such as concentrations of potassium and calcium, rank it among productive intrusions, whereas dike population and the concentrations of iron, sodium, copper, and zinc rank it among barren ones.

The reason for the high calcium content in productive intrusions may be that their dikes represent a less differentiated residual melt. Their low differentiation index at 95% supports this conclusion. Burnham (1967, p. 55) reported the presence of calcium along with the alkalis in chloride-bearing solutions and stated: "The Cl equivalent of Na + K + Ca calculated as NaCl, KCl, and CaCl₂, accounts for about 80% of the total Cl." Calcium sulfate has also been reported in fluid inclusions. Gammon and others (1969) found that at temperatures between 800°C-885°C and pressure 2-2.4 kb the "hydrothermal solution

tends to be depleted in calcium relative to the silicate melts with which they are in equilibrium." This relatively high calcium content is explainable if the findings of Gammon and others can be extrapolated to lower temperatures and pressures. Thus, the chloride-rich aqueous phase, postulated earlier, is expected to carry relatively high CaCl_2 . Calcium, according to Gammon and others, is passed to the coexisting silicate melt, and upon its crystallization relatively calcium-rich dikes form.

Sodium and Potassium

Their progressive concentration in a residual melt, coupled with their combined genetic and explorational significance, facilitates discussion of sodium and potassium together. By virtue of their crystal chemistry, sodium and potassium concentrate in residual magmas.

It is significant that these two elements have an inverse relationship when their values in productive and barren environments are compared (Fig. 43). An increase in potassium content corresponds to a decrease in the sodium content in dikes from the same intrusion. Dikes from mineralized intrusions carry more potassium at 5.2-5.6% K than those from barren ones at 3.9-4.6% K. In contrast, dikes from productive intrusions at 1.6%-1.8% Na contain less sodium than those from barren ones at 2.3%-3.0% Na. This relationship is also reflected by the feldspars in the dikes as previously discussed. K-feldspars in dikes from productive intrusions also have higher potassium content than those from barren ones.

The exploration relationships of these elements is significant with respect to the sampling involved for this study. Laramide intrusions

whose aplite and pegmatite dikes have values of sodium and potassium comparable to those in dikes from the studied productive intrusions are excellent exploration targets for porphyry copper deposits.

Copper

An association of anomalously high contents of copper in bulk rock and in their biotite and hornblende separates to apparently genetically related ore deposits has been observed by Parry and Nackowski (1963), Putman and Burnham (1963), Wahab (1968), and Lovering and others (1970). It was concluded that the magma that produced both the igneous rocks and the ore bodies was itself anomalously rich in copper.

Copper commonly substitutes for ferrous ion and magnesium in crystallizing ferromagnesian minerals. Because of the very low content of ferromagnesian minerals in these aplites and pegmatites, their mean copper content (at 20 ppm) is about 15 times less than the mean copper contents in host stock, such as the quartz monzonite at Esperanza with 300 ppm Cu (Lovering and others, 1970). Bulk analyses of aplites and pegmatites from productive areas, except in Boulder batholith, show anomalously high copper contents. Because copper-bearing sulfide and ferromagnesian minerals cannot commonly be discerned in hand specimen or thin section, copper probably occurs mainly in crystal defects as copper metal or sulfide (Tauson, 1958), on intergranular surfaces (Ellis and Mahon, 1967), or as substitutes for calcium and sodium in feldspars. Since copper preferentially partitions into chloride-rich solutions (Holland, 1972) and because productive intrusions are generally chloride-rich, silicate melts coexisting with these solutions are more likely to be

anomalously high in ore metals. Although dikes from nonproductive intrusions are characterized by low copper contents, those from the Whetstone intrusion have copper contents as high as those observed in productive areas due to the presence of malachite and chalcopyrite in sample 16 (Fig. 26) and to the presence of pyrite which may carry copper in solid solution or blebs of chalcopyrite in most of the samples.

Using copper in bulk rock or K-feldspar separates as a pathfinder element to concealed porphyry copper deposits, the Butte ore deposit would certainly be missed whereas the Whetstone intrusion would be taken for a potentially productive intrusion. Dikes from the Amole intrusion show even higher copper contents than those from the Butte district. The Troy stock, presently being explored by several mining companies as potentially productive, has a copper content that places it among the barren stocks (Fig. 45A).

Zinc

Most of the introductory discussion presented for copper applies as well to zinc. The behavior of zinc in these dikes, however, is evidently more irregular (Figs. 44 and 47). While the Patagonia and Santa Rita deposits might be discovered on the basis of their anomalously high zinc contents in aplites and pegmatites, Butte and Sierrita, known to be productive, would be overlooked. The Amole and Whetstone stocks would attract attention on the basis of their zinc content. The Troy intrusion shows zinc contents similar to that observed in barren intrusions. It is concluded here that zinc in aplites and pegmatites is an unreliable indicator for porphyry copper deposits.

Aplite-Alkali Index

The study of aplites and pegmatites from mineralized and barren intrusions has revealed some interesting features. Notable among these features is the chemical variation of potassium, sodium, and calcium. This chemical variation is also observed petrographically in K-feldspar plagioclase relationships (Fig. 37) and the anorthite content of plagioclase. The chemical relationship of these three elements calculated to normative orthoclase, albite, and anorthite has been well expressed by Figure 49. The need for defining the relationship of these three elements by a formula, which could be solved to derive a specific number pertinent to mineral exploration is certainly pressing. This specific number is proposed to be referred to as the aplite-alkali index (AAI) and is expressed by the following equation as

$$\text{aplite-alkali index (AAI)} = \frac{\text{K} + \text{Ca}}{\text{Na}} \times 100$$

in which K = percent potassium in bulk rock aplite and pegmatite

Ca = percent calcium in bulk rock aplite and pegmatite

Na = percent sodium in bulk rock aplite and pegmatite.

This is an empirical formula expressing the relationship between high potassium and calcium and low sodium in productive dikes.

The aplite-alkali index is calculated for 60 analyzed samples of aplites and pegmatites and presented in Tables 13 and 14. Except for samples 6, 28, and 40 from the Amole, Patagonia, and Sierrita stocks, respectively, it is clear that the aplite-alkali index for dikes from barren intrusions at 114-249 is low when compared to an index of 290-409 for dikes from mineralized intrusions. The aplite-alkali index is applicable

Table 13. The aplite-alkali index (AAI) of 56 samples from studied Laramide and mid-Tertiary intrusions

Barren Intrusions	AAI	Mean	Productive Intrusions	AAI	Mean	
Amole	1	196	Boulder batholith	22	330	315
	2	200		23	323	
	3	197		24	298	
	4	203		25	307	
	5	204				
	6	281				
Whetstone			Patagonia	26	347	341
				27	328	
	11	182	213	28	286	
	12	190		29	402	
	13	197		30	333	
	14	199		31	350	
	15	249				
	16	200	Sierrita	32		316
	17	224		33	294	
	18	235		34	352	
19	237		35	290		
20	220		36	337		
Swisshelm				37	311	
	41	186	200	38	338	
	42	208		39	330	
	43	204		40	275	
	44	188				
45	214	Santa Rita	48	409	387	
			49	405		
			50	352		
Texas Canyon	53	164	140	51	379	
	54	114		52	383	
	55	134				
	56	128				
	57	155				
	58	134				
	59	154				
	60	137				

Table 14. The aplite-alkali index (AAI) of 9 samples from the Troy stock

Troy Stock ¹		AAI	Mean
Troy	61	269	289
	62	342	
	63	291	
	64	260	
	65	323	
	66	311	
	67	224	
	68	384	
	69	170	

1. Sample locations are shown on Figure 30.

only where petrographic examination indicated primary crystallization of the K-feldspar and plagioclase (albite). Samples collected from the Troy intrusion displayed aplite-alkali indices ranging from 170, typical of barren intrusions, to 384, similar to that observed in productive ones. This anomalous behavior of the Troy samples is explained by the introduction of petrographically observed substantial amounts of secondary K-feldspar in some of the samples.

Provided that the origin of K-feldspar is known, the AAI will prove to be an important criterion in the search for new mineral resources.

Normative Minerals

Several phenomena can be effectively treated from a consideration of the normative mineral calculations.

Orthoclase-Albite Ratio

The orthoclase-albite relationship as seen in Figure 48 is readily explainable in terms of a magmatic origin for these dikes. The mechanism by which K-feldspar predominates over plagioclase in productive intrusions, as previously explained, remains true here also. The explanation presented earlier includes the partitioning of potassium into the silicate melt coexisting with the alkali chloride-rich aqueous phase at a temperature of 880°C and lower. Sodium simultaneously partitions into the aqueous phase. Consequently, the silicate melt is enriched in potassium and impoverished in sodium in response to falling temperature. Dikes solidifying from this melt are consequently rich in orthoclase with respect to albite. The explorational significance of the orthoclase-albite relationship is also evident from Figure 48. Laramide igneous intrusions are considered to have potential for the development of porphyry copper deposits if, among other encouraging features, the ratio of normative orthoclase to albite is about 2:1. By such a measure, the Boulder batholith and the Patagonia, Santa Rita, and Sierrita intrusions have mineralization potential, whereas the Amole, Swisshelm, Texas Canyon, and Whetstone intrusions do not. However, the Texas Canyon intrusion is known to be spatially related to the Johnson Camp ore deposit and other similar prospects flanking it on the east. That the Texas Canyon intrusion is the source of the Johnson Camp ore deposit and related

prospects is not known and is subject to some doubt, according to the orthoclase-albite relationship. The orthoclase-albite ratio of the Troy intrusion is equivocal as a mineralization indicator. The ambiguity displayed by the Troy samples is due mainly to the effects of hydrothermal alteration as observed before. If the secondary feldspar introduced by hydrothermal alteration is excluded, all samples would plot among barren intrusions.

Feldspar Equilibrium Diagram. With regard to the feldspar equilibrium diagram (Fig. 49), the plotting of most of the samples within the orthoclase field indicates that they are poor in calcium (at about 3.5 percent anorthite) and rich in orthoclase at 65 percent by weight. This trend confirms petrographic findings discussed earlier. Since Bowen (1956) has determined that feldspars crystallizing from a basaltic magma fall in the plagioclase field of the feldspar ternary diagram, an additional mechanism acting with differentiation must have operated to produce these dikes. Neither hydrothermal nor metamorphic mechanisms, for reasons discussed earlier, have contributed substantially to this anomalous feldspar composition. The magmatic theory for reasons previously discussed explains this situation best. A residual pegmatitic magma is believed to have coexisted with an alkali chloride-rich aqueous phase. As a result of partitioning of sodium and potassium into the aqueous phase and residual melt, respectively, in response to decreasing temperature below 880°C, a resultant silicate melt will contain anomalously high potassium and plot in the orthoclase field of the feldspar ternary diagram.

Differentiation Index

The differentiation indices at 95-97 percent for the dikes in the study area are higher than that for alkali granite at 93 percent, indicating that these dikes are probably the product of residual magma which differentiated beyond granite. According to their differentiation indices, dikes from mineralized intrusions are probably less differentiated than those from barren intrusions. The crystal chemistry of calcium indicates that the calcium content in a silicate melt decreases with differentiation. This fact is consistent with the seemingly anomalous high calcium content in dikes from productive intrusions.

Water Pressure

The fact that the plots of samples from productive intrusions, as discussed earlier in the section on petrography, are not in the thermal valley of petrogeny's residuum has significant genetic and exploration implications. Genetically, this high potassium content is explained best by a magmatic theory of origin for these dikes. As discussed below, dikes from productive intrusions formed in a higher P_{H_2O} environment than did dikes from barren intrusions and were also probably emplaced at greater depths.

Depth. It is possible to estimate the depth of crystallization by comparing the composition of aplites and pegmatites with position of the quaternary isobaric liquidus minimum in the synthetic system Ab-Or-Q-H₂O (Tuttle and Bowen, 1958). Results obtained by this method must be treated with caution, as noted by Putman and Alfors (1969, p. 63):

Unfortunately, direct comparison or extrapolation of experimental data (including work on the rocks themselves) to natural plutonic rocks is usually subject to some degree of limitations since nature: (1) provides plenty of chemical components; (2) probably always provides for dynamic changes in physical conditions during formation of the rock or pluton; (3) provides a relative immensity of time and scale in which to carry out a variety of processes; and (4) leaves the final product in various stages of alteration and exposure with some components missing, depleted, transferred, or enhanced.

Comparing chemical data of the aplites and pegmatites under consideration with the isobaric minimum (Fig. 50), a P_{H_2O} of 1 kb and 0.5 kb for dikes in productive and barren intrusions, respectively, is indicated. If the P_{H_2O} of the saturated residual melt equals a lithostatic pressure of 1 kb, P_{H_2O} and a depth of 4 km (Krauskopf, 1967), then respective depths of 4 and 2 km are inferred for dikes from mineralized and barren intrusions. The accuracy of this estimate is subject to some uncertainty. A plot of normative salic minerals for representative igneous aplites forms a straight line near the trend of the minimum in the "granite" system (Fig. 50) and intersects it at a point corresponding to about 2 kb P_{H_2O} (Tuttle and Jahns, 1968). Compositions of aplites and pegmatites from productive stocks plot away from this trend. This feature raises doubts about the use of aplites and pegmatites in productive stocks for estimating P_{H_2O} . The presence of volatiles other than water in the residual melt would also lead to inaccurate estimates. In addition to these problems, Bateman and Wahrhaftig (1966) questioned the validity of the equivalence of P_{H_2O} and P_{load} . The possible influence of tectonic stresses and sequential rupturing leading to devolatilization also must be considered.

The estimated depths of formation of dikes from mineralized areas, however, compares well to the 5.5-7 km depth of crystallization of aplites in the Rocky Hill stock (Putman and Alfors, 1965, 1969). A 4-km depth (13,000 feet) is geologically unrealistic with respect to the 5,000-10,000-foot deep environment of porphyry copper deposits (Lowell and Guilbert, 1970). Rose and Baltosser (1966) concluded on the basis of the structure and stratigraphy of the area that the Santa Rita stock intruded to within 1,500 feet of the surface. These geologic findings and the manner in which these dikes differ from those in the data given by Jahns and Tuttle (reported by Putman and Alfors, 1969) cast doubt on the accuracy of depth obtained by this method. Influence of absolute water pressures at the time of crystallization cannot be unequivocally established with the data at hand, although the real chemical differences between dikes from mineralized and barren intrusions may be used to infer distinctly different environments of formation. These differences may be ascribed to depth only with the attendant uncertainties mentioned above.

Formation of aplites and pegmatites in mineralized intrusions at relatively deeper levels than in barren ones may have a bearing on their respective dike populations. All conditions equal, relatively shallow intrusions are likely to develop more fractures than deeper ones because of their closeness to the surface. The filling of these fractures with injected melt causes an abundance of dikes in shallow intrusions.

Temperature. The temperatures of formation of aplites and pegmatites are estimated by comparing their normative salic minerals to similar norms in experimental work. The normative Or-Ab-Q for the different areas is recalculated to 100 percent, then plotted on the isobaric

equilibrium diagrams of the system $\text{KAlSi}_3\text{O}_8\text{-NaAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$ projected onto the anhydrous base of the Or-Ab-Q- H_2O tetrahedron (Tuttle and Bowen, 1958, Figs 22 and 23). At $P_{\text{H}_2\text{O}} = 1$ kb, a temperature of 720°C is indicated from mineralized areas, whereas dikes from barren areas indicate a temperature of 760°C at a $P_{\text{H}_2\text{O}}$ of 0.5 kb. These temperatures are slightly high, but as mentioned below, geologically realistic. Although experimental work by Putman and Alfors (1969) on aplites from the Rocky Hill stock indicated a crystallization temperature between 700°C and 750°C , the authors accepted a temperature of 650°C as realistic because of the presence of HF in the system. Orville (1960) has reported a temperature of 710°C to 740°C for pegmatites from the Black Hills, South Dakota. Jahns and Burnham (1969) proposed a temperature of 700°C for formation of rocks with pegmatitic and aplitic texture and also referred to temperatures as high as 800°C for the pegmatitic phase of crystallization. A summary given by Jahns (1955) suggests that pegmatites form between 400°C and 700°C with 600°C most common.

CHAPTER 7

SUMMARY

The derivation of magmatic aplites and pegmatites from a water-saturated magma has been proposed by Derry (1931), Andersen (1931), Emmons (1940), Jahns and Tuttle (1963), Fournier (1968), and Jahns and Burnham (1969). It is also believed that a hydrothermal solution is derived by "second boiling" of a silicate melt which attains supersaturation with respect to water and other volatiles. Metallic components of ore deposits can be derived from a magma and be transported to their present location by hydrothermal solutions (Holland, 1972). A close genetic relationship between aplite-pegmatite and hydrothermal solutions has been observed by many workers and is well summarized and discussed by Lutton (1959). Assuming this genetic relationship between aplites and pegmatites and hydrothermal solution to be valid, the study of these rocks in mineralized and barren intrusions is scientifically and explorationally rewarding in terms of understanding the processes and environments linking aplites and pegmatites to hydrothermal solutions and in locating new porphyry copper deposits.

Sixty-two samples were collected from eight Laramide stocks and one mid-Tertiary intrusion. Four productive intrusions, the Boulder batholith, Butte district, the Patagonia intrusion, and the Santa Rita and Sierrita intrusions near the Esperanza mine have been considered. The Amole, Swisshelm, Texas Canyon, and Whetstone stocks were studied

as barren intrusions. The Troy stock, which is presently attracting mineral exploration, was studied to evaluate its mineral potential by comparing it with the other intrusions studied in this research.

A metamorphic model for the origin of the studied aplites and pegmatites has been considered and rejected in light of the following negative evidence:

1. Occurrence of aplite and pegmatite dikes in igneous plutons.
2. Independence of aplite and pegmatite composition from that of the host rock.
3. Continuity of dikes from the igneous plutons into surrounding host rocks.
4. Absence of fringing of dikes by mafic minerals.
5. Difficulty of reconciling the formation of fine-textured aplite and coarse pegmatite by the simple migration of chemical elements into preexisting fractures.
6. Presence of knife-edge sharp contacts.

Evidence collected during this study denying a hydrothermal origin for these dikes includes:

1. Absence of hydrothermal replacement textures.
2. Absence of "pocket minerals" commonly formed by hydrothermal solutions.
3. Matching of opposite walls of aplite or pegmatite dikes.
4. Presence of textural, mineralogical, and chemical homogeneity across a single aplite dike and among dikes in a single intrusion.

5. Presence of knife-edge sharp contacts.
6. Absence of sufficiently great amounts of secondary K-feldspar to explain the difference in mineralogical and chemical composition of dikes in mineralized and barren intrusions.

A residual magmatic origin for these dikes is proposed based on evidence collected during this research, which includes:

1. Occurrence of dikes within or around exposed plutons with which they are thought to be genetically related.
2. Continuity of aplite and pegmatite dikes from the intrusion into the surrounding host rocks.
3. Lack of influence of composition of host rocks upon the composition of the enclosed aplite and pegmatite bodies.
4. Emplacement of aplite and pegmatite dikes by forceful injection.
5. Presence of textural, mineralogical, and chemical homogeneities across width of aplite dikes and among dikes in a single intrusion.
6. Presence of granophyric and graphic textures.

Within the context of the magmatic theory, the presence of aplites and pegmatites in an igneous intrusion indicates that the melt from which they crystallized is saturated or nearly saturated with water and other volatiles. Aplites are considered to form as a result of pressure quenching of water-saturated magmas, whereas the slow cooling and subsequent crystallization of the same magmas favors the production of pegmatites. Pressure quenching is caused by a sudden drop in pressure caused primarily by fracturing of the cooling and shrinking of

the crystallized shell of the intrusion and also to tectonic stresses. Not all saturated magmas can develop aplites; however, conditions favorable to their formation are present only in the event of a rapid pressure drop. Jahns and Tuttle (1963, p. 91) state that "the subsolvus granites, on the other hand, may carry large amounts of pegmatitic and aplitic material or none at all, depending on the cooling history of the intrusive."

The differences in dike populations and average widths in mineralized and barren stocks is dependent primarily on the mode of intrusion of the stock and its relative depth. Mineralized stocks intrude passively and also, because of their deeper location, develop fewer fractures. This contrasts to the forceful and relatively shallow stocks which develop abundant fractures. These fractures are subsequently filled by residual melt which develops into aplite and pegmatite. Stringham (1966) has observed that an overwhelming majority of the porphyry copper stocks intruded passively. Depth of erosion as the cause of apparent variation in abundance of dikes seems unlikely because intrusions associated with those porphyry copper deposits known in three dimensions do not have an abundance of dikes.

Vogt (1923) suggested that in the absence of water and other volatiles a residual silicate melt composed of silicon, aluminum, and alkalis is the most viscous natural melt. However, Jahns and Burnham (1969) indicate that the abundance of water in a granitic melt varies its viscosity considerably. The textural and mineralogical homogeneity of aplites is best explained by relatively high viscosity of the melts from which they crystallize. Where fractures form in the host rock a hydrous low-viscosity melt is injected into them. Subsequent fractures cutting

ones previously injected with melt causes volatiles from this water-rich melt to boil off, leaving behind a dry viscous melt in which chemical diffusion is very slow. Because of slow diffusion rates in the viscous melt, crystallizing minerals must draw their components from the immediately adjacent melt. Because of the pressure quench, mineral homogeneity of aplites is achieved. Slow crystal growth in the viscous melt, coupled with the formation of many nuclei as a result of the sharp rise in the temperature of the liquidus for the system, results in fine-grained, xenomorphic granular, texturally homogeneous aplites. The sharp contact of aplite and pegmatite dikes with their host rock is reflected by differences in their mineral composition, grain size, and absence of chemical reaction with the host rock. Randomly distributed, coarse-grained patches probably represent a hydrous melt trapped within the rapidly crystallizing viscous melt. Aplite within pegmatite dikes forms from a melt which initially crystallizes in part to pegmatite while the remaining melt subsequently loses its volatiles rapidly and forms aplite. Pegmatites within aplites, on the other hand, form where the entire water-rich melt is not pressure quenched to aplite, so that the unquenched portions yield masses of pegmatite within a body of otherwise aplitic rock.

For chemical-mineralogical reasons, it is proposed here that aplites and pegmatites in mineralized intrusions crystallized from a residual melt which before its injection coexisted with an alkali-base metal-chloride-rich aqueous phase. Potassium partitioned into the melt and sodium into the aqueous phase in response to decreasing temperature from 880°C to 250°C.

Where an aqueous phase coexisting with a silicate melt develops, most of the chloride in the silicate melt partitions into this aqueous phase (Burnham, 1967; Kilinc and Burnham, 1972; and Holland, 1972). The significance of high concentrations of chloride in ore-forming fluids is demonstrated by the high chloride content in intrusions genetically related to hydrothermal ore deposits. Alkalies, base metals, iron, calcium, and other metals partition into this chloride-rich aqueous phase. The distribution of K^+ and Na^+ between a chloride-rich phase and coexisting silicate melt is temperature dependent in the range from 880°C to 250°C. As the temperature drops from 880°C to 250°C, potassium partitions into the silicate melt and sodium simultaneously partitions into the aqueous phase. The partitioning of sodium into the aqueous phase explains the high NaCl content observed in fluid inclusions found in ore deposits. Aplites and pegmatites that form from this potassium-enriched silicate melt are therefore anomalously rich in potassium and relatively low in sodium. Preliminary work on fluid inclusions from the dikes under consideration indicates that apparently primary fluid inclusions in quartz in dikes from all mineralized areas studied, in contrast to those from barren ones, contain halite daughter minerals. This feature indicates that dikes from mineralized stocks developed in a highly saline environment.

A continuum between magmas, aplite-pegmatite, and porphyry copper deposits is established primarily by the continuous crystallization of K-feldspar at magmatic temperature (880°C) to hydrothermal ore deposition temperature at 250°C. The crystallization of secondary orthoclase in porphyry copper deposits is a manifestation of this continuum.

The relatively high Fe^{+++} , Ca^{++} , and Cu^{++} in aplite-pegmatite dikes from productive intrusions is probably a result of the coexistence of the silicate melt from which these dikes formed with a chloride-rich aqueous phase anomalously rich in these elements. Filling of part of the aluminum sites in feldspar by ferric ion and the possible presence of hematite in crystal defects accounts for the pink color in aplite and pegmatite feldspar.

Comparison of the composition of aplites and pegmatites with the position of the quaternary isobaric liquidus minimum in the synthetic system Ab-Or-Q-H₂O (Tuttle and Bowen, 1958) indicates respective $P_{\text{H}_2\text{O}}$ of 1 and 0.5 kb for the crystallization of dikes from mineralized and barren intrusions. Equating $P_{\text{H}_2\text{O}}$ of a saturated melt with lithostatic pressure at 1 kb, depths of 4 km and 2 km are indicated, respectively, for crystallization of dikes from mineralized and barren stocks. A depth of 4 km for productive intrusions, like the Santa Rita stock, is geologically unrealistic, as the latter is estimated to have intruded to 1,500 feet (0.5 km) from the surface. Comparison of the chemical composition of aplites and pegmatite dikes with the position of the isobaric liquidus minimum in the system Ab-Or-Q-H₂O in order to determine $P_{\text{H}_2\text{O}}$ and depth poses great difficulty.

CHAPTER 8

CONCLUSIONS

The results of this research have led to the following conclusions:

1. Because of textural and mineralogical homogeneities, channel is of no significant preference to chip sampling of aplite dikes. In view of ease of sampling, chip sampling may be preferable.
2. Since aplite and pegmatite dikes collected from a single stock have similar compositions, 5 to 10 samples adequately represent the composition of the dikes in the stock.
3. Scarcity and narrowness of dike populations in productive stocks is directly related to the passive intrusion of these stocks and to their relatively deep level of intrusion. This feature constitutes a useful porphyry copper deposit indicator.
4. In view of their identical chemical and mineralogical composition, the aplites and pegmatites under consideration are the product of chemically identical melts crystallized under different water pressures. Pegmatites are the products of crystallization of water-saturated residual magmas, whereas aplites are the pressure-quenched equivalent of the same saturated residual magmas.
5. The predominance of K-feldspar over sodic plagioclase in dikes from mineralized stocks is a useful feature in the search for

porphyry copper deposits. The anomalously high K-feldspar content of these dikes is due to crystallization of K-feldspar from a silicate melt which coexisted with a chloride-rich aqueous phase in response primarily to falling temperatures between 880°C and 250°C.

6. There is an inverse relationship between potassium and sodium and calcium and sodium. Where the potassium content is high in aplite and pegmatite dikes from productive intrusions, the sodium content is low. The opposite relationship is true for dikes from barren intrusions. The calcium content is also high in dikes from productive intrusions.
7. Potassium content of K-feldspar in dikes from productive intrusions is higher than that in dikes from barren ones.
8. The aplite-alkali index, $\frac{K + Ca}{Na} \times 100$, is higher, almost double, in dikes from productive stocks and is an excellent exploration tool.
9. The total iron content of aplites from productive intrusions is higher than the content of iron from barren ones.
10. This research has not revealed significant variations in the silicon and aluminum contents in dikes from productive and barren intrusions.
11. Whereas evidence for the value of K-feldspar-plagioclase abundance and potassium-sodium relationships as porphyry copper indicators is compelling, evidence for iron and copper is only permissive and of zinc is nonindicative.

12. Although the Texas Canyon intrusion is spatially related to the Johnson Camp ore deposit, evidence from this work indicates that the Johnson Camp deposit may not be genetically related to it.
13. Based on its dike population and copper, iron, and zinc contents, mineralization of the Troy stock is not indicated. Over half of the samples from this intrusion indicate a K-feldspar to plagioclase ratio similar to that from mineralized intrusions. By eliminating the influence of secondary K-feldspar in these samples, this ratio becomes similar to that in nonproductive intrusions.

APPENDIX A

ANALYTICAL TECHNIQUE

Preparation of Standards

It is recommended in atomic absorption analysis that the matrices of standards and unknown be matched as closely as possible to reduce errors due to differing chemical and physical characteristics of solutions, such as viscosity. The importance of matching standards and unknowns was observed by Slavin (1968) and Graybeal (1972). Graybeal found that considerably higher values of manganese and iron were obtained when these elements were dissolved in 3% HNO₃ in the absence of dissolved silicates than in their presence.

In the absence of natural aplite-pegmatite and K-feldspar standards, artificial standards were prepared. These artificial standards were prepared from chlorides, carbonates, and oxides of the major elements. Silica was prepared by crushing a clear quartz crystal to -65 mesh, leaching it overnight in a hot 50% HNO₃ to remove iron from grinding and iron oxides. Ten grams of artificial standards were prepared such that the major element compositions bracketed the range of concentration of elements found in granitic aplite-pegmatite and K-feldspar. All salts and oxides were pulverized in an agate mortar and dried overnight at 80°C. Quartz, Al₂O₃, Fe₂O₃, CaCO₃, NaCl, and KCl were weighed and mixed by shaking in a plastic vial which contained an aluminum oxide ball. These oxides were then pulverized in an aluminum oxide Pica ball mill for 6 minutes and stored in glass bottles. Careful weighing and preparation of standards yielded very regular working curves. Blanks for individual elements were prepared by omitting that particular element from one standard. Concentrations of copper and zinc in aplites and pegmatites was too low to permit preparation of their standards in the same

way as that used for the major elements. Instead, standards of these two elements were prepared by dissolving zinc metal and copper nitrate in 50% HNO_3 . Zinc and copper nitrate were weighed and dissolved in HNO_3 so that their concentration was 2,000 ppm of metal in each. These 2,000-ppm solutions were stored as stock solutions. Working standards were freshly prepared on the day of each run by proper dilutions with 3% HNO_3 , so that values of copper and zinc in the digested unknown were bracketed by these standards. It was found that values of copper and zinc in the USGS standard G-2 were consistently less than that found by the present curves. This discrepancy is due to the difference in the matrix of the standards and the unknown.

Prepared samples were taken into solution, using a lithium metaborate (LiBO_2) fusion technique for use with the atomic absorption spectrophotometer as modified by Medlin and others (1969) and adapted by Graybeal (1972) for use in the Laboratories of Economic Geology of The University of Arizona. To take a sample into solution, 0.1000 gm of it is mixed with 0.5000 gm of lithium metaborate on a piece of weighing paper. After careful mixing, the sample was transferred to a pre-ignited graphite fusion crucible and fused in a muffle furnace for 15 minutes at about 1050°C . The molten bead was then swirled to gather uncoalesced beads of the melt and immediately poured into a 250-ml nalgene beaker containing 40 ml of 3% HNO_3 .

Pre-ignited graphite crucibles (ultra carbon A-2260, YU-40) were used. Graybeal (1972) observed that some of the bead would invariably stick to the bottom of the crucible during the first fusion if crucible were not pre-ignited at about 700°C for 10-15 minutes.

Dilutions

Dilution of dissolved samples is necessary to bring them to the optimum concentration for analysis by atomic absorption. For analysis of sodium and potassium, an aliquot of the fusion solution is diluted with demineralized water, whereas for silicon, aluminum, iron, and calcium, the aliquot solution is diluted with a 1% solution of lanthanum nitrate (LaNO_3). Lanthanum nitrate acts as a releasing agent and prevents the formation of refractory substances in the flame. Copper and zinc are determined directly from the fusion solution. Dilutions used here are those recommended by Medlin and others (1969) and are listed in Table A-1.

Table A-1. Instrumentation and dilution

Element	Wavelength (Å)	Flame	Burner Position	Sample Dilution	Diluent
Si	2516	$\text{N}_2\text{O}-\text{C}_2\text{H}_2$	parallel	1:6	La
Al	3093	$\text{N}_2\text{O}-\text{C}_2\text{H}_2$	parallel	1:6	La
Fe	2483	Air- C_2H_2	parallel and perpendicular	1:6	La
Ca	4227	Air- C_2H_2	parallel	1:6	La
Na	5890 5896	Air- C_2H_2	parallel	1:40	H_2O
K	7665	Air- C_2H_2	parallel	1:40	H_2O
Cu	3247	Air- C_2H_2	parallel	none	
Zn	2139	Air- C_2H_2	parallel	none	

Instrumentation

The analyses were obtained by using a Perkin-Elmer model 403 atomic absorption spectrophotometer. Data were read and recorded in absorbance units. Percent oxides in unknowns were interpolated from generally linear working curves drawn by plotting the absorbance values against the known percent oxide of the standards. Drift in the instrument was noticeable for Si and Al and was continuously monitored and corrected by zeroing the instrument after running every 2 to 5 unknowns. Burner clogging was a problem when using a nitrous oxide-acetylene mixture, and it was necessary to clean it every time a glowing carbon residue started to form. This cleaning was done after running each batch of 2-5 unknowns.

Precision and Accuracy

The precision of the analytical procedure was determined by making 8 to 12 replicates of the Amole 6 sample. The precision for individual elements is reported in Table A-2 as percent by weight deviation and also as relative percent deviation. Relative percent deviation is the percent the deviation represents of the total amount of the given oxide or element in a sample. With the exception of Fe_2O_3 and CaO , the relative deviation of other oxides is less than 2 percent. Copper and zinc have low precision at 11 and 7 percent, respectively. The reason for this low precision is the low concentration of Fe_2O_3 , CaO , Cu , and Zn in aplites and pegmatites; consequently in the resulting fusion solution, they are near the lower detection limit.

Table A-2. Analytical precision

Oxide or Element	Deviation	Percent Relative Deviation
SiO ₂	0.112 wt%	0.145
Al ₂ O ₃	.147 wt%	1.19
Fe ₂ O ₃	.049 wt%	4.58
CaO	.025 wt%	3.35
Na ₂ O	.034 wt%	1.24
K ₂ O	.087 wt%	1.46
Cu	1.41 ppm	11
Zn	2.58 ppm	7

The accuracy of the analyses is dependent on the accuracy of the artificial standards. Their accuracy was checked by analyzing USGS standard rock G-2 and the National Bureau of Standards standard 73a provided through the courtesy of Dr. D. E. Livingston of the Department of Geosciences, The University of Arizona. The analyses of these standards are shown on Table A-3. Comparison of the results on this table indicates an error in the results obtained for Al₂O₃ and Fe₂O₃. The Al₂O₃ used to prepare the artificial standards was apparently hygroscopic. Hall (1972) reported that the weight of Al₂O₃ increased considerably while weighing the necessary amount of standards. Fe₂O₃ was observed to stick to the wall of the Pica mill, apparently causing loss of it from the standards. Both Al₂O₃ and Fe₂O₃ were corrected by multiplying

values of all unknowns by a coefficient derived by dividing reported contents of these oxides in USGS G-2 by their values reported here.

Table A-3. Analytical data for USGS G-2 and NBS 73a

Oxides and Elements	USGS G-2		NBS 73a	
	Measured	Present	Measured	Present
SiO ₂	69.19 wt%	70.25 wt%	67.10 wt%	68.30 wt%
Al ₂ O ₃	15.34 wt%	17.65 wt%	17.90 wt%	19.72 wt%
Fe ₂ O ₃	2.52 wt%	1.98 wt%	0.075 wt%	0.067 wt%
CaO	1.98 wt%	1.93 wt%	0.11 wt%	0.10 wt%
Na ₂ O	4.15 wt%	4.15 wt%	2.55 wt%	2.50 wt%
K ₂ O	4.51 wt%	4.69 wt%	11.80 wt%	11.80 wt%
Cu	11 ppm	10 ppm	---	---
Zn	75 ppm	73 ppm	---	---

APPENDIX B

BULK APLITE, PEGMATITE, AND
K-FELDSPAR ANALYSES

Table B-1. Chemical analyses and norms of aplites and pegmatites from Laramide and mid-Tertiary intrusions, by district

Sample No.		AMOLE					
		1	2	3	4	5	6
Rock Type		Aplite	Aplite	Aplite	Aplite	Pegmatite	Aplite
<u>Chemical Analysis</u>							
SiO ₂	%	78.89	78.46	78.50	78.00	79.00	77.50
Al ₂ O ₃	%	11.97	12.12	11.99	12.17	11.82	12.34
Fe ₂ O ₃	%	1.00	0.712	0.814	0.840	0.649	1.400
CaO	%	0.35	0.38	0.25	0.28	0.17	0.72
Na ₂ O	%	3.25	3.27	3.25	3.19	3.04	2.60
K ₂ O	%	5.40	5.52	5.52	5.55	5.52	5.90
Cu	ppm	11	10	17	13	13	13
Zn	ppm	53	48	41	40	36	36
<u>Norms</u>							
Q		38.60	37.26	37.95	37.62	39.87	38.13
Or		32.12	32.70	32.74	32.49	32.63	34.89
Ab		27.47	27.63	27.46	26.99	25.67	22.23
An		1.72	1.84	1.24	1.39	0.83	3.57
C		0.14	0.04	0.25	0.39	0.14	0.31
He		1.00	0.71	0.81	0.84	0.65	1.40

Table B-1. Chemical analyses and norms.--Continued

Sample No.	WHETSTONE									
	11	12	13	14	15	16	17	18	19	20
Rock Type	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite
<u>Chemical Analysis</u>										
SiO ₂ %	78.20	78.36	78.60	78.40	78.90	78.00	78.55	78.86	78.00	78.22
Al ₂ O ₃ %	11.95	12.14	11.95	11.95	11.95	12.30	11.95	11.99	12.08	12.25
Fe ₂ O ₃ %	0.789	0.992	0.687	0.712	0.661	0.712	0.712	0.750	0.878	0.674
CaO %	0.28	0.55	0.45	0.38	0.17	0.58	0.42	0.56	0.26	0.47
Na ₂ O %	3.25	3.34	3.25	3.22	2.72	3.25	3.02	2.90	2.75	3.10
K ₂ O %	5.20	5.20	5.32	5.40	5.90	5.30	5.70	5.60	5.60	5.70
Cu ppm	20	14	19	13	18	80	18	10	27	16
Zn ppm	28	42	29	21	21	17	19	13	18	21
<u>Norms</u>										
Or	30.75	30.75	31.37	31.92	35.37	31.34	36.69	33.15	33.14	33.69
Ab	27.46	28.19	27.25	27.20	22.95	27.46	26.52	24.52	23.27	26.20
An	1.39	2.73	2.22	1.89	0.83	2.82	2.03	2.78	1.28	2.34
Q	38.10	37.91	38.37	38.24	39.71	37.60	38.65	39.34	40.01	37.42
C	0.62	0.01	0.06	0.11	0.76	0.20	0.04	0.11	1.00	0.10
He	0.79	0.99	0.69	0.71	0.66	0.71	0.71	0.75	0.88	0.67

Table B-1. Chemical analyses and norms.--Continued

		BOULDER BATHOLITH				
Sample No.		21 ^a	22	23	24	25
Rock Type		Pegmatite	Aplite	Aplite	Aplite	Aplite
<u>Chemical Analysis</u>						
SiO ₂	%	77.46	77.74	77.65	77.50	77.30
Al ₂ O ₃	%	12.25	12.30	12.17	12.10	12.32
Fe ₂ O ₃	%	0.81	0.70	0.66	0.66	0.37
CaO	%	0.90	0.52	0.52	0.52	0.94
Na ₂ O	%	3.08	2.21	2.30	2.50	2.58
K ₂ O	%	5.30	6.08	6.20	6.20	6.25
Cu	ppm	10	10	10	11	11
Zn	ppm	34	29	38	33	40
<u>Norms</u>						
Or		35.87	35.97	36.70	36.66	36.97
Ab		31.06	18.85	19.44	21.12	21.80
An		26.03	2.56	2.59	2.59	4.67
Q		4.58	39.11	38.75	37.81	35.33
C		1.51	2.91	1.45	1.12	0.99
He		0.81	0.69	0.65	0.65	0.37

a. Analysis of a piece of a pegmatite dike not considered representative of this dike.

Table B-1. Chemical analyses and norms.--Continued

		PATAGONIA					
Sample No.		26	27	28	29	30	31
Rock Type		Aplite	Aplite	Aplite	Aplite	Aplite	Aplite
<u>Chemical Analysis</u>							
SiO ₂	%	78.20	77.56	77.65	77.40	77.79	77.53
Al ₂ O ₃	%	12.00	12.17	12.17	12.16	12.25	12.30
Fe ₂ O ₃	%	0.65	0.97	0.97	0.95	0.89	0.92
CaO	%	0.40	0.40	0.45	0.47	0.42	0.45
Na ₂ O	%	2.30	2.40	2.60	2.10	2.30	2.25
K ₂ O	%	6.80	6.70	6.25	6.75	6.50	6.65
Cu	ppm	16	11	12	13	48	25
Zn	ppm	86	52	58	54	38	47
<u>Norms</u>							
Or		40.20	39.64	26.97	39.91	38.42	39.31
Ab		19.44	20.28	21.96	17.76	19.44	19.65
An		0.50	1.97	3.32	2.31	2.10	2.22
Q		38.58	27.13	37.65	38.35	38.69	37.61
C		0.60	0.20	0.27	0.53	0.64	0.49
He		0.65	0.97	0.96	0.95	0.89	0.96

Table B-1 Chemical analyses and norms. --Continued

		SIERRITA								
Sample No.		32	33	34	35	36	37	38	39	40
Rock Type		Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Pegmatite	Aplite
<u>Chemical Analysis</u>										
SiO ₂	%	77.40	77.30	77.40	77.57	77.80	77.60	77.23	77.49	77.40
Al ₂ O ₃	%	12.00	12.58	11.91	12.17	12.25	12.25	12.43	12.43	12.25
Fe ₂ O ₃	%	0.95	0.90	0.92	1.18	0.94	1.25	0.97	0.84	0.99
CaO	%	0.65	0.80	0.55	0.66	0.80	0.75	0.60	0.55	0.66
Na ₂ O	%	2.30	2.57	2.25	2.57	2.25	2.47	2.38	2.40	2.70
K ₂ O	%	6.25	6.08	6.60	6.10	6.10	6.20	6.70	6.60	6.05
Cu	ppm	34	26	22	33	24	44	21	18	18
Zn	ppm	38	34	34	36	34	38	36	34	34
<u>Norms</u>										
Or		36.97	35.97	39.03	36.08	36.08	36.70	39.64	39.03	35.88
Ab		19.44	21.75	19.02	21.70	21.27	20.16	20.12	20.28	22.84
An		3.13	3.98	2.73	3.28	3.98	3.73	2.77	2.73	3.28
Q		38.71	37.33	37.88	37.90	38.12	37.88	36.56	37.11	37.10
C		0.24	0.29	0.08	0.09	0.02	0.08	0.16	0.33	0.02
He		0.95	0.91	0.92	1.18	0.91	1.25	0.97	0.84	0.99

Table B-1. Chemical analyses and norms.--Continued

		SWISSHELM				
Sample No.		41	42	43	44	45
Rock Type		Aplite	Aplite	Aplite	Aplite	Aplite
<u>Chemical Analysis</u>						
SiO ₂	%	78.90	78.84	78.72	78.75	78.70
Al ₂ O ₃	%	12.25	11.99	12.17	12.34	12.20
Fe ₂ O ₃	%	0.71	0.64	0.36	0.56	0.18
CaO	%	0.37	0.37	0.31	0.42	0.40
Na ₂ O	%	3.31	3.00	3.10	3.32	3.00
K ₂ O	%	5.20	5.26	5.40	5.20	5.40
Cu	ppm	9	9	9	10	9
Zn	ppm	34	30	34	34	43
<u>Norms</u>						
Or		30.57	31.11	31.92	30.76	31.92
Ab		27.98	27.98	26.20	28.05	25.57
An		1.83	1.84	1.53	2.09	1.97
Q		38.98	38.74	39.40	38.89	39.76
C		0.54	0.17	0.62	0.47	0.68
He		0.71	0.64	0.35	0.56	0.18

Table B-1. Chemical analyses and norms.--Continued

		SANTA RITA				
Sample No.		48	49	50	51	52
Rock Type		Aplite	Aplite	Aplite	Aplite	Aplite
<u>Chemical Analysis</u>						
SiO ₂	%	77.19	77.25	77.50	77.30	77.60
Al ₂ O ₃	%	11.70	11.82	11.73	12.26	12.10
Fe ₂ O ₃	%	2.11	1.98	1.87	1.18	1.15
CaO	%	0.35	0.61	0.60	0.60	0.70
Na ₂ O	%	2.00	2.00	2.20	2.16	2.10
K ₂ O	%	7.00	6.70	6.40	6.80	6.60
Cu	ppm	54	50	45	66	70
Zn	ppm	69	70	78	88	65
<u>Norms</u>						
Or		41.40	39.64	37.87	40.20	39.03
Ab		16.91	16.91	18.60	18.37	17.76
An		1.75	3.03	2.97	2.97	3.78
Q		37.98	38.69	38.94	37.44	38.60
C		0.17	0.14	0.07	0.22	0.20
He		2.11	1.98	1.87	1.18	1.15

Table B-1. Chemical analyses and norms.--Continued

		TEXAS CANYON							
Sample No.		53	54	55	56	57	58	59	60
Rock Type		Aplite	Aplite	Aplite	Aplite	Pegmatite	Aplite	Aplite	Pegmatite
<u>Chemical Analysis</u>									
SiO ₂	%	76.50	75.40	75.35	75.49	76.06	76.00	75.50	75.30
Al ₂ O ₃	%	13.90	14.56	14.56	14.34	14.34	14.34	14.34	14.56
Fe ₂ O ₃	%	0.58	0.76	0.62	0.54	0.65	0.62	0.62	0.62
CaO	%	0.38	0.21	0.20	0.30	0.40	0.30	0.30	0.35
Na ₂ O	%	3.56	4.40	4.30	4.07	3.75	4.08	3.10	4.20
K ₂ O	%	4.88	4.28	4.50	4.40	4.80	4.65	5.04	4.85
Cu	ppm	9	7	10	8	8	9	9	10
Zn	ppm	35	49	46	64	28	23	31	32
<u>Norms</u>									
Or		29.86	25.30	26.63	26.02	28.41	27.42	29.82	28.69
Ab		30.08	37.20	36.36	34.37	31.70	34.48	32.12	35.49
An		1.89	1.06	0.97	1.49	1.99	1.49	1.08	1.94
Q		36.34	33.02	32.71	34.37	35.03	33.85	33.65	31.59
C		2.06	2.32	2.26	2.37	2.29	2.03	2.21	1.75
He		0.58	0.76	0.62	0.54	0.65	0.62	0.62	0.62

Table B-1. Chemical analyses and norms.--Continued

Sample No.	TROY									
	61	62	63	64	65	66	67	68	69	
Rock Type	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite
<u>Chemical Analysis</u>										
SiO ₂ %	76.00	76.15	67.04	77.00	76.60	75.76	76.26	77.40	76.70	
Al ₂ O ₃ %	13.38	13.21	13.38	12.70	13.21	13.64	13.38	12.69	13.21	
Fe ₂ O ₃ %	0.45	0.41	0.25	0.33	0.29	0.42	0.32	0.39	0.30	
CaO %	0.93	0.52	0.80	0.67	0.60	0.58	0.65	0.65	0.35	
Na ₂ O %	2.95	2.50	2.28	2.92	2.48	2.69	3.30	2.12	3.90	
K ₂ O %	6.30	7.18	6.60	6.20	6.75	7.00	6.05	7.00	5.60	
Cu ppm	16	14	11	12	11	13	11	12	11	
Zn ppm	33	35	30	30	33	33	33	33	31	
<u>Norms</u>										
Or	37.25	42.48	39.03	36.70	39.92	41.42	36.20	41.42	33.14	
Ab	24.94	21.12	23.84	24.68	20.96	22.74	27.88	17.92	32.96	
An	4.62	2.59	3.98	3.34	2.97	2.87	3.23	3.23	1.75	
Q	32.75	33.01	32.64	34.82	35.09	32.11	32.53	36.88	31.82	
C	0	0.36	0.12	0.09	0.71	0.55	0.20	0.42	0.07	
He	0.45	0.41	0.25	0.33	0.29	0.42	0.32	0.39	0.30	

Table B-2. Chemical analyses of K-feldspar from aplites and pegmatites of certain Laramide and mid-Tertiary intrusions

Sample No.	SiO ₂ (%)	Al ₂ O ₃ (%)	Total Fe (as Fe ₂ O ₃) (%)	CaO (%)	Na ₂ O (%)	K ₂ O (%)	Cu (ppm)	Zn (ppm)
AMOLE								
1	66.90	17.90	0.255	0.45	2.73	11.80	8	28
2	66.53	18.07	0.150	0.27	3.18	11.90	8	25
3	69.00	16.25	0.278	0.16	2.20	11.60	17	31
4	67.00	17.45	0.190	0.14	2.53	12.40	9	34
5	66.90	18.25	0.215	0.20	3.40	11.00	10	34
6	66.30	18.28	0.150	0.33	2.77	12.20	9	31
WHETSTONE								
11	66.25	18.25	0.201	0.17	2.49	12.75	14	32
12	66.00	18.25	0.104	0.18	2.20	13.45	10	25
13	65.92	18.42	0.190	0.12	1.80	13.75	14	32
14	65.96	18.16	0.160	0.17	2.10	13.45	11	25
15	68.00	17.73	0.182	0.10	1.90	11.80	12	28
16	68.18	15.90	0.142	0.16	2.22	13.40	37	28
17	67.00	17.64	0.140	0.25	3.13	11.45	10	28
18	65.80	18.42	0.120	0.20	1.89	13.90	10	32
19	67.00	18.34	0.140	0.11	1.90	13.92	11	32
20	65.80	18.25	0.115	0.20	2.46	13.10	10	32

Table B-2. Chemical analyses of K-feldspar.--Continued

Sample No.	SiO ₂ (%)	Al ₂ O ₃ (%)	Total Fe (as Fe ₂ O ₃) (%)	CaO (%)	Na ₂ O (%)	K ₂ O (%)	Cu (ppm)	Zn (ppm)
BOULDER BATHOLITH, BUTTE DISTRICT								
21	65.48	18.42	0.085	0.10	1.68	14.20	10	29
22	64.80	18.96	0.092	0.18	1.50	14.82	9	28
23	64.48	18.96	0.092	0.16	1.70	14.62	10	29
24	64.88	19.18	0.100	0.18	1.57	14.10	9	29
25	63.85	20.09	0.192	0.16	1.81	13.93	10	36
PATAGONIA								
26	65.47	18.25	0.18	0.17	2.24	13.70	10	37
27	66.80	17.56	0.19	0.12	1.75	13.20	9	39
28	64.99	18.95	0.21	0.33	2.92	12.60	9	39
29	65.12	18.20	0.20	0.16	1.78	13.60	10	40
30	65.00	18.30	0.25	0.32	2.01	13.40	10	38
31	66.10	17.95	0.18	0.27	2.25	13.60	10	41

Table B-2. Chemical analyses of K-feldspar.--Continued

Sample No.	SiO ₂ (%)	Al ₂ O ₃ (%)	Total Fe (as Fe ₂ O ₃) (%)	CaO (%)	Na ₂ O (%)	K ₂ O (%)	Cu (ppm)	Zn (ppm)
SIERRITA								
32	65.72	17.99	0.19	0.20	1.82	14.10	11	25
33	65.54	17.99	0.180	0.22	1.87	14.10	13	25
34	65.62	17.99	0.180	0.17	1.80	14.10	11	32
35	64.74	17.99	0.18	0.20	1.69	14.15	14	25
36	65.37	18.08	0.19	0.20	1.95	14.15	13	25
37	65.35	18.08	0.23	0.16	1.80	14.40	13	25
38	65.57	17.99	0.18	0.16	1.80	14.20	15	20
39	65.00	18.34	0.18	0.16	2.13	14.10	11	27
40	65.60	18.08	0.16	0.22	1.95	14.00	11	32
SWISSHELM								
41	65.30	18.25	0.10	0.22	1.80	14.10	8	31
42	65.25	18.25	0.10	0.22	1.80	14.10	9	30
43	67.83	17.38	0.10	0.25	2.45	12.10	8	27
44	66.00	17.90	0.10	0.27	2.15	13.40	8	31
45	67.32	17.82	0.05	0.22	3.05	11.30	8	37

Table B-2. Chemical analyses of K-feldspar.---Continued

Sample No.	SiO ₂ (%)	Al ₂ O ₃ (%)	Total Fe (as Fe ₂ O ₃) (%)	CaO (%)	Na ₂ O (%)	K ₂ O (%)	Cu (ppm)	Zn (ppm)
SANTA RITA								
48	66.45	18.30	0.26	0.42	2.27	11.60	12	58
49	66.60	18.34	0.25	0.40	2.24	11.64	12	58
50	67.00	18.25	0.24	0.41	2.28	11.50	11	59
51	66.60	18.34	0.24	0.41	2.42	11.90	13	59
52	66.50	18.32	0.23	0.40	2.29	11.70	13	59
TEXAS CANYON								
53	65.10	18.95	0.07	0.10	2.08	13.70	8	37
54	64.30	18.95	0.032	0.03	0.80	15.90	9	30
55	64.00	19.12	0.020	0.03	0.83	15.85	7	30
56	64.25	18.95	0.03	0.03	0.75	15.85	7	22
57	64.84	18.95	0.11	0.03	0.98	15.08	7	27
58	64.50	19.12	0.02	0.03	0.80	15.50	7	50
59	64.46	18.95	0.02	0.03	0.72	15.82	7	20
60	64.40	19.12	0.02	0.03	0.88	15.50	7	30

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