CORRELATION OF VOLCANIC ROCKS IN SANTA CRUZ COUNTY, ARIZONA

by

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TABLES

ABSTRACT

New field work and studies made by previous workers show remarkable similarities in the sequences of volcanic rocks in Santa Cruz County and the Tucson Mountains, Arizona. These sequences consist of Cretaceous (?) andesite and rhyolite; Tertiary andesite, rhyolite, tuff, rhyolite-latite, and andesite; and Quaternary (?) basalt. These sequences also have structural similarities since the Cretaceous (?) rocks are usually badly deformed, the Tertiary rocks are often gently tilted, and the Quaternary (?) rocks are flat-lying. The Tertiary sequence, except for the upper andesites, is dated as ranging from the close of the Cretaceous to early Miocene time by comparing it with the Lower Miocene Mineta beds, the Pantano formation, and the volcanic rocks associated with these sedimentary rocks.

Microscopic studies of the units thought to be correlative show both similarities and dissimilarities in mineralogy. Chemical studies of each volcanic unit consisted of alpha and beta counting to determine the alpha activity and potassium content of each unit as well as emission spectrograph analysis for chromium, copper, magnesium, and

calcium. These chemical studies indicate that although the rocks thought to be correlative have chemical differences, each suite also has chemical similarities. Possible extensions of this volcanic correlation throughout southern Arizona, southwestern New Mexico, and northern Sonora, Mexico are suggested but were not studied.

It is concluded that the chemical studies undertaken in this work are of great value in volcanic petrography. The origin of the volcanic sequence is referred to the relation of structural deformation and fusion of rock at different levels in the crust and mantle.

INTRODUCTION

Location and Extent of Area

This paper comprises a study of the volcanic rocks located in Santa Cruz County, Arizona. This county lies in extreme southern Arizona and is bounded on the south by Mexico (Fig. 1). The area extends approximately 27 miles north from the international border and measures about 64 miles in an east-west direction. Numerous county and private roads make most outcrops readily accessible.

Purpose of Investigation

The purpose of this investigation is to study the volcanic sequences and individual units of the sequences in this area. An attempt was then made to correlate the volcanic rocks on a regional basis from one mountain range to another. Similarities in these volcanic rocks have been noted by several authors but I have no knowledge of any previous attempts at correlation. The volcanic sequence in Santa Cruz County can also be tenatively correlated with other sequences in Arizona and Mexico.

Previous Investigations

Geologic investigations in this area have been

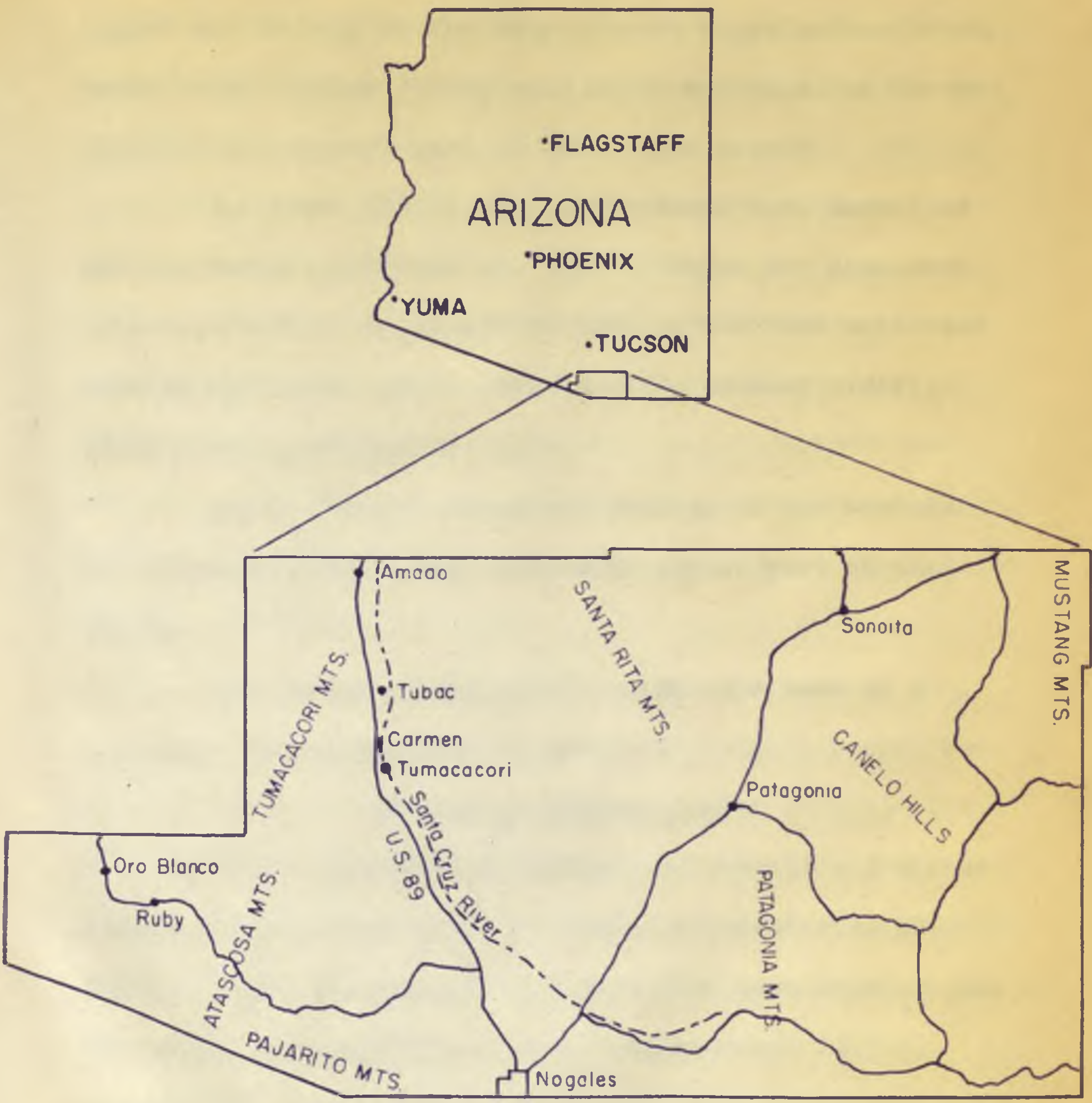

Figure 1. Location and detail of Santa Cruz County.

mostly of the reconnaissance type. Webb and Coryell (1954) mapped the geology of the Ruby area in a preliminary study. Their investigation is the only major work done on the geology of the western part of Santa Cruz County.

Schraeder (1915) mapped the Santa Rita Mountains and the Patagonia Mountains, both of which are prominent volcanic ranges. Localized studies in the same area were made by Kartchner (1944), Feth (1947), Anthony (1951), Smith (1956), and Sulik (1957).

Bryant (1951) mapped the geology of the western Mustang Mountains in the extreme northeast part of the county.

The remaining geologic studies have been of a localized and specialized nature.

Present Investigation

This investigation consists of a field and microscopic study of the volcanic rocks for correlation purposes. Three stratigraphic columns have been constructed, one which represents those units exposed west of U.S. Highway 89, another which represents those units exposed east of this highway, and one which represents the section of the Mustang Mountains. These stratigraphic columns have been compared with the column of volcanic rocks in the

Tucson Mountains which lie just west of Tucson, Arizona about 38 miles north of Santa Cruz County (Pl. 1). The geology of the Tucson Mountains has been mapped by Brown (1939), Kinnison (1958), and others. Comparison with the Tucson Mountains is included because there seems to be a good correlation with Santa Cruz County.

Additional studies were made to determine chemical similarities between the individual units thought to be correlative. These studies consist of radioactive and emission spectrograph analyses of each major volcanic unit.

This investigation was conducted during the fall of 1958 and the spring of 1959.

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I am also grateful to my wife, Clarie, for her contributions toward the preparation and completion of this report.

GENERAL GEOLOGY AND PHYSIOGRAPHY

This portion of Arizona lies in the Basin and Range Province and the prominent geologic features are northerly trending ranges and hills separated by alluvium-filled valleys. The valley of the Santa Cruz River separates this county into an eastern and western series of ranges. These ranges consist almost entirely of volcanic rocks but intrusive and sedimentary rocks are also present.

The relief and topography depend a great deal on the type of rock exposed. The Santa Rita and Patagonia Mountains consist of hard flows, plutonic rocks, and tuffs which reach an elevation of more than 6000 feet above the Santa Cruz Valley to the west. The more gentle Canelo Hills consist of lavas and older sedimentary rocks with a combined relief of 2000 feet. The more rounded outcrops of the Atascosa and Tumacacori Mountains to the west are capped by poorly consolidated tuff and reach an elevation of only about 3000 feet above the surrounding valleys. The Mustang Mountains in the northeast corner of the county have relief of about 1000 feet and consist of rhyolite and older sedimentary rocks.

The age of the volcanic rocks still remains a problem. The scarcity of datable strata associated with the volcanic rocks has forced workers to search for other age indications. Often times the badly folded and faulted strata are assigned to the Cretaceous or older, tilted rocks to the Tertiary, and flat-lying rocks to the Quaternary. These structures as well as the principles of superposition are generally used to assign ages to volcanic units which are not bounded by datable strata. The weaknesses in these suppositions are that badly deformed strata as young as Lower Miocene are known in southern Arizona, Tertiary rocks may be flat-lying, and Quaternary rocks have suffered some faulting.

Webb and Coryell (1954) assigned the coarse rhyolite in the Pajarito Mountains to the Mesozoic on the basis of its badly faulted character and the fact that it is also the oldest volcanic unit to crop out. The relatively undisturbed, thick sequence of volcanic rocks above the Pajarito lavas is assigned to the Tertiary and Quaternary.

Stoyanow (1949) found steeply dipping andesite overlain by Upper Cretaceous sedimentary rocks and decided that these flows in Casa Blanca Canyon of the Santa Rita Mountains were Cretaceous also. He also found thin andesite (?) flows interbedded with the Lower Cretaceous Patagonia group nearby.

Brown (1939) found exactly the same sequence in the Tucson Mountains i.e. andesite flows overlain by Upper Cretaceous (?) sedimentary rocks. These relationships are all shown on Plate 1.

The thick volcanic sequence above the Cretaceous sedimentary rocks and flows is generally regarded as Tertiary by inference. This sequence is usually flat-lying or only slightly tilted and faulted. The lack of structural deformation in this sequence suggests a post-Laramide age as previously mentioned.

A possible clue to the more exact age of the Tertiary sequence can be found east and southeast of Tucson. Here the Lower Miocene Mineta beds and their probable equivalent, the Pantano formation, both either underlie or contain prominent andesite flows. The andesite associated with the Mineta beds was followed by basalt flows (Chew, 1952) and the andesite interbedded with the Pantano formation was preceded by very thick rhyolite and pyroclastics which are younger than Lower Cretaceous (Brennan, 1957). It seems therefore that the post-Lower Miocene andesites here occur at the same place in the section as the upper andesites in Santa Cruz County and the Tucson Mountains. If the upper andesites under study are post-Lower Miocene, then the older Tertiary sequences probably range in age from the close of the Cretaceous to early Miocene. The great thickness of these volcanic rocks tells little about their age since great thicknesses can be accumulated in a very short time.

The basalt flows are regarded as Quaternary since they are more recent than the thick Tertiary sequence and they are interbedded with late Tertiary or Quaternary gravels. They also overlie lake deposits in the Santa Rita and Tucson Mountains. Since lake deposits in this area are thought to be late Pliocene and Pleistocene, and the basalts overlie gravels which overlie the lake deposits, a Quaternary age is reasonable. Lake deposits were not found in the Atascosa or Tumacacori Mountains but no intensive search was made for them. Generally these basalts have not suffered structural deformation like the older rocks (Pl. 3, Fig. 2).

CORRELATION OF VOLCANIC ROCKS

General Statement

Since volcanic rocks are the result of catastrophic events, it is my opinion that correlation can only be attempted on a general basis i.e. the comparison of the results of major catastrophic events. Variance is often noted within flows and tuffs which is indicative of local activity unique to one fissure or vent. In general the thickest units are the most extensive.

It is not my contention that the volcanic rocks in Santa Cruz County and the Tucson Mountains are exactly time equivalent, nor that these rocks were extruded from a small number of fissures. They seem to have been erupted from many vents which are along fissures. Undoubtedly these volcanic rocks were once more extensive but I do not imagine that this portion of Arizona was ever completely covered by them. Instead I propose that the correlative units represent similar types of volcanic activity i.e. explosive ash or lava flows fed by the same parent magma or similar parent magmas. These deposits were probably exhaled from many fissures or vents at approximately the same time. That the regional type of activity changed is shown by the stratigraphic columns on Plate 1. It is true that adjacent vents may erupt different types of rock simultaneously but this phenomenon is comparatively rare.

Most of the flows in this area do not appear to be extensive over long distances, although lavas, especially basic lavas, are known to flow for miles. The fluidity in flowing lava can be retained for a long time if the lava is being constantly recharged by hot gasses (Perret, 1950).

Nuee Ardente explosions which may have formed the welded tuffs are well described by Perret (1950). These explosive, gaseous dust clouds form an expanding disintegrating mass which may reach a height of miles and a velocity of up to 33 meters per second. Thus deposits of this type can be quite extensive whether they are acidic or basic.

Cretaceous (?) Volcanic Rocks

Admittedly there is little evidence for the precise dating of volcanic rocks in this area as Cretaceous except in the Santa Rita Mountains as previously mentioned. There is even some doubt that Cretaceous volcanic rocks exist in the Tucson Mountains since the thickness of the andesite is not known and it is in fault contact with the overlying sedimentary rocks which are believed Upper Cretaceous but may be older. Nevertheless many data suggest a Cretaceous or older age for these units and they will be considered Cretaceous in this study.

The Pajarito lavas in the Pajarito Mountains have a thickness of about 1200 feet and consist mostly of gray rhyolite porphyry with visible phenocrysts of quartz and orthoclase. This badly faulted unit is the major deviation from an otherwise perfect regional correlation as far as rock types are concerned. These mountains have an east-west trend which is in startling contrast with the other ranges which all have northerly trends. Thus this deviation from the other sequences is probably due to a different structural history. The rock contains anhedral phenocrysts of quartz, orthoclase, euhedral sanidine, altered muscovite, altered biotite, and andesine. The feldspar minerals are badly altered to clay and sericite. A few glass shards and magnetite crystals are noted. The matrix is cryptocrystalline to microcrystalline (Pl. 4, Fig. 1).

The andesite in Casa Blanca Canyon of the Santa Rita Mountains varies from a gray porphyry to a brown, coarse volcanic breccia with a thickness of about 100 feet. The texture varies from very fine to very coarse. A few coarse crystals of andesine are noted but most of the plagioclase is fine and very badly altered to clay and sericite. A few large resorbed biotite crystals exist as well as biotite remnants of ferromagnesian minerals. Some of the fragments are aphanitic with anhedral crystals of quartz. Fragmental, strained quartz is also found. Calcite is abundant in the vesicles and euhedral magnetite with iron-stained rims is very common throughout the rock. Some badly altered phenocrysts have the amphibole cleavage but are indistinguishable. There are a few bent, torn masses of muscovite. A few euhedral phenocrysts of orthoclase are noted as well as pseudomorphs after orthoclase (Pl. 4, Fig. 2).

The andesite near the Recreation red beds in the Tucson Mountains consists of fine-grained purple flows and breccias. It contains small phenocrysts of poorly twinned, anhedral andesine and anhedral orthoclase in a glassy matrix of microlites and crystallites. The feldspar minerals show extensive alteration to clay and sericite. A few hematite remnants of biotite (?) are noted as well as numerous zones of hematite. There are a few very small phenocrysts of augite (?) and some anhedral quartz (Pl. 4, Fig. 3).

Tertiary Volcanic Rocks

Lower andesite.—The lower andesites are not very extensive. Only a few exposures of andesite older than the rhyolites were noted in the Santa Rita Mountains; latite is much more extensive but both rocks were sampled for the chemical studies which are covered in a later chapter.

The lower andesite is known as the Ruby Road formation in the Atascosa Mountains. It is a gray andesite which contains abundant white feldspar phenocrysts. It has a maximum thickness of about 250 feet but complex faulting may have caused this thickness and not the original extrusion. It contains many thin local, interbedded tuffs. In thin section the andesite consists of phenocrysts of euhedral orthoclase, labradorite, muscovite, and anhedral quartz in a cryptocrystalline to microcrystalline matrix. The more euhedral minerals always have dark iron-rich growth rims. The feldspar minerals are altered to clay and sericite and there are numerous iron-rich remnants of biotite (Pl. 5, Fig. 1).

The older andesite in the Santa Rita Mountains is at least 100 feet thick. It is a dark gray or green aphanitic flow rock which crops out just southwest of Patagonia, Arizona. It has a fine-grained matrix with larger laths of altered, zoned labradorite with more calcic cores. Unzoned, twinned augite phenocrysts are present and magnetite is abundant throughout the rock. There are a few large inclusions of devitrified glass as well as small irregular glass inclusions. The matrix appears to be in part glassy and in part minute plagioclase crystals. There is some evidence of hydrothermal activity (Pl. 5, Fig. 2).

The latite in the Santa Rita Mountains overlies the andesite and this latite is extensive in Temporal Gulch, Josephine Canyon, and east of Patagonia. The flows are about 100 feet thick and consist of brown to gray porphyrys and volcanic breccias. They contain abundant euhedral to anhedral phenocrysts of altered orthoclase and a few subhedral phenocrysts of andesine which are also badly altered. A few orthoclase overgrowths on andesine are noted. Small calcite overgrowths are present on andesine and orthoclase. Euhedral to anhedral oxidized magnetite is abundant in the matrix. Iron-rich growth rims commonly surround the euhedral feldspar minerals. Anhedral quartz is present but not abundant. The matrix is fine-grained and very impure.

The lower andesite in the Tucson Mountains is a dense purple porphyry which is up to 400 feet thick. This is the unit distinguished by Kinnison (1958) although he was not sure of its exact placement in the sequence of associated rocks. Microscopic studies show the matrix to be cryptocrystalline to microcrystalline. There are large, altered phenocrysts of orthoclase and oligoclase up to 1 cm long. The feldspar minerals are difficult to identify due to this extreme alteration to clay and sericite. Also noted are badly altered, resorbed phenocrysts of biotite and some magnetite (Pl. 5, Fig. 3).

Rhyolites.-The rhyolites are the thickest and most extensive volcanic rocks found in this study. They have little in common when they are compared in the hand specimen. Most of them do have textures which indicate explosive activity but this would be normal due to the high viscosity of acidic magmas. Some of the rhyolites are shown on Plate 2, Figures 1 and 2.

The rhyolite in the Atascosa and Tumacacori

PLATE 2.-RHYOLITES AND TUFF.

Figure 1.-Rhyolite and tuff of Rock Corral Peak, just west of Tumacacori National Monument.

Figure 2.-View looking north toward Golden Gate Mountain, Tucson Mountains. Cat Mountain rhyolite and underlying Amole group dipping gently to the east.

FIGURE I

FIGURE 2

Mountains is known as the Montana Peak formation. It is a red rhyolitic breccia with a thickness of about 800 feet. Although it usually contains abundant fragments, it occasionally occurs as an aphanitic flow rock or porphyry. It contains rounded fragments of the Ruby Road formation, both phenocrysts and fragments of subhedral sanidine, quartz, impure glass, and andesine in a glassy, brecciated matrix. Some might consider this rock to be a coarse tuff. Narrow laths of resorbed biotite are common as well as muscovite which is altering to sericite. Zones of reddish palagonite are noted. There are some euhedral crystals but this rock is generally fragmental with numerous crystallites and microlites (Pl. 6, Fig. 1).

The rhyolite which outcrops in the Santa Rita and Patagonia Mountains has a total thickness of 2100 feet according to Schraeder (1915). This formation varies from leucocratic, aphanitic clean flows to rhyolite flow breccia (Lutton, 1958) and a red porphyry. Most of the outcrops have been badly altered by hydrothermal activity as shown by brilliant red stains and zones of alteration. At times the rock has a eutaxitic texture but not as pronounced as that of the Cat Mountain rhyolite to be mentioned later.

In thin section this type contains impure anhedral quartz which is rimmed, embayed and resorbed in a matrix of glass, devitrified glass, and fine quartz grains. Fumarolic activity is shown by alunite which is abundant in the matrix and in flattened vesicles. A few euhedral phenocrysts of sanidine and altered orthoclase are present as well as magnetite surrounded by oxidized rims of iron (Pl. 6, Fig. 2).

The rhyolite in the Mustang Mountains is a pink to purple fine-grained rock with a thickness of 500 feet. Quartz segregations and flow banding can be seen in the hand specimen. The microscope shows numerous anhedral segregations, veinlets, and microlites of quartz as well as abundant euhedral laths of feldspar which are difficult to identify due to extreme alteration. A few crystals of magnetite exist in the fine matrix (Pl. 6, Fig. 3).

The Cat Mountain rhyolite in the Tucson Mountains was divided into four distinct units by Kinnison (1958) and they have a maximum total thickness of 800 feet. These units actually vary little and have the characteristic eutaxitic texture and vertical joints of welded tuffs. There is a noticeable increase in porosity and decrease in induration toward the upper part of the formation. The groundmass is devitrified glass with phenocrysts of subhedral orthoclase and sanidine. Masses of impure tridymite and volcanic glass contain microlites of altered feldspar. Volcanic glass embayments occur in sanidine phenocrysts and tridymite embayments occur in volcanic glass. Such silica migration is a characteristic of welded tuffs. Some anhedral quartz is present also (Pl. 6, Fig. 4).

Tuffs.-The tuffs are fairly thick and almost as extensive as the rhyolites. They are very extensive in the Atascosa and Tumacacori Mountains where they are the most common rock present. There appears to be two types of tuff in each mountain range: primary tuff which has not been appreciably altered since deposition and hybrid tuff which has been redeposited by water.

The tuff in the Atascosa and Tumacacori Mountains is the lower member of the Atascosa formation. It is a poorly sorted, fragmental, light brown tuff which has a thickness of at least 500 feet. It consists of an argillaceous devitrified glass which contains anhedral to euhedral quartz, orthoclase, acidic plagioclase altering to sericite, magnetite, biotite, glass shards, and pumice fragments zoned with palagonite (Pl. 7, Fig. 1). (See also

PLATE 3.-TUFFS AND BASALT.

Figure 1.-Badly faulted and tilted tuff and agglomerate just northeast of Nogales, Arizona.

Figure 2.-Flat-lying basalt flow unconformably overlying tuff. Two miles east of Lion Mountain, Atascosa Mountains.

FIGURE 1

FIGURE 2

Pl. 2, Fig. 1 and Pl. 3, Fig. 2)

The tuff in the Santa Rita and Patagonia Mountains has a maximum thickness of 500 feet. It consists of fragmental orthoclase, quartz, andesine, spherulitic chalcedony, biotite, and iron-rich remnants of biotite all in a fine brown argillaceous, devitrified glassy matrix. The feldspar minerals are all altered to clay and a few vermicular crystals of kaolin are present (Pl. 7, Fig. 2). (See also Pl. 3, Fig. 1)

The Safford tuff in the Tucson Mountains has a maximum thickness of 500 feet. It consists of numerous fragments of anhedral biotite, quartz, sanidine, impure glass, magnetite, andesine, and spherulitic chalcedony all in a matrix of light brown argillaceous, devitrified glass (Pl. 7, Fig. 3).

Rhyolite and latite.-Fairly extensive outcrops of acidic volcanic rocks are associated with the tuffs in the three principal mountain ranges. The exact age relationships between these acidic rocks and the tuffs are not known but the acidic rocks are probably partly contemporaneous with the tuffs and in part later than the tuffs but still older than the overlying upper andesites.

The clearest relationships can be seen in the Atascosa Mountains where thick spherulitic rhyolite is interbedded with the tuff in Sycamore Canyon. Flows of a basic andesite also crop out in this canyon but the most prevalent rock type is the rhyolite. Other volcanic rocks in the Atascosa Mountains which are interbedded with the tuffs include local rhyolite flows close to Ruby and biotite vitrophyre east and west of Ramanote Peak. Since the spherulitic rhyolite is the most extensive unit, it was considered as a possible equivalent of the quartz latite porphyry in the Santa Rita Mountains and the biotite rhyolite in the Tucson Mountains. The spherulitic rhyolite is 600 feet thick and it is a fine-grained light brown rock which usually contains stained blotches in the hand specimen. In thin section it appears that these black spots are spherulitic growths of feldspar which are stained by hisingerite. Also noted are very badly altered phenocrysts of orthoclase, euhedral quartz, and euhedral oligoclase. The matrix is very fine and without flow structure (Pl. 8, Fig. 1).

The quartz latite porphyry in the Santa Rita

Mountains is dominantly intrusive but extrusive equivalents of the rock crop out in the southwestern part of the range. The exact relation of this rock to the other volcanic rocks in the Santa Rita Mountains was not known by Schraeder (1915) but a few of the relations can be seen in Josephine Canyon. Here the quartz latite porphyry clearly overlies the rhyolite and underlies an extensive andesite flow. Thus the quartz latite porphyry may be contemporaneous with the tuff but no contact of the two could be found. The quartz latite porphyry is a coarse green to pink rock which is dominantly intrusive as previously mentioned. It is fairly extensive on the western side of the Santa Rita range. It contains badly sericitized and clay-altered anhedral orthoclase phenocrysts, anhedral quartz, large altered oligoclase phenocrysts, masses of impure epidote, calcite, magnetite, shreds of muscovite, and microcline. A faint flow structure is visible in the badly altered matrix (Pl. 8, Fig. 2).

The biotite rhyolite in the Tucson Mountains also has many intrusive aspects. It is a brown to pink rock with very abundant flakes of biotite. This rock was reclassified as quartz latite by Kinnison (1958). It contains large phenocrysts of subhedral to euhedral quartz, euhedral sanidine, and subhedral biotite in a fine groundmass of crystallites and microlites in poor flow structure. The groundmass occasionally has the appearance of a devitrified impure glass. There are narrow crystallite overgrowths on glass fragments and pseudomorphs of glass and other minerals after orthoclase (?). Some magnetite and hematite are also present (Pl. 8, Fig. 3).

<u>Upper andesites</u>.-The tuffs, associated rhyolites, and latites are everywhere overlain by andesite. These andesites are the least extensive in the Atascosa Mountains and the most extensive in the Santa Rita and Patagonia Mountains. They also vary considerably in thickness from one range to another.

The upper andesite from Atascosa Peak of the Atascosa Mountains is 100 feet thick and not very extensive. Some rhyolite also caps the peaks but the prominent rock is a gray andesite porphyry with white phenocrysts and iron stains. It contains coarse subhedral, altered phenocrysts of zoned andesine. Anhedral rimmed quartz is present in small amounts. Flakes of altered biotite and phenocrysts of augite are often rimmed with iron alteration zones. A little flow structure is noted in the matrix which contains altered laths of plagioclase and magnetite (Pl. 9, Fig. 1).

The upper andesite in the Santa Rita and Patagonia Mountains is 2000 feet thick (Schraeder, 1915) and widespread. It is generally a green to gray porphyry with white phenocrysts. It seems to always have a much coarser texture than the lower andesite in the same areas. The upper andesite contains zoned euhedral phenocrysts of andesine and anhedral quartz in an altered matrix which consists mostly of plagioclase. Small flakes of biotite are abundant throughout the rock as well as magnetite. There are remnant, resorbed phenocrysts of augite (?) and biotite pseudomorphs after amphibole. A faint flow structure is perceptible in the matrix (Pl. 9, Fig. 2).

The Short's Ranch andesite in the Tucson Mountains is a gray fine-grained rock which is 400 feet thick. It generally has abundant small phenocrysts of feldspar. In thin section the rock contains abundant laths of andesine and orthoclase both altering to clay and sericite. Muscovite is abundant and magnetite, fragments of glass, and calcite are present. The Matrix appears to be a mesh of altered feldspar (Pl. 9, Fig. 3).

Quaternary Volcanic Rocks

Interbedded with the upper gravels and conglomerates are thin local flows of olivine basalt. A thick sequence of basalt flows was described by Tolman (1909) at Tumamoc Hill in the Tucson Mountains but only the most recent flows contain olivine phenocrysts like the flows in Santa Cruz County. These basalt flows can be easily distinguished from all of the older andesites since the basalts have a very different lithology as well as stratigraphic position in the sequences.

The basalt in the Atascosa Mountains has a thickness of 25 feet. There are a few flows just northeast of Pajarito Peak but the majority of the flows occur east of Lion Mountain (Pl. 3, Fig. 2). It is a dark gray, vesicular porphyry with large phenocrysts of plagioclase and abundant cavities filled with goethite. In thin section the fine matrix contains large resorbed labradorite with nondistinct twinning. The plagioclase is not badly altered. There are abundant anhedral phenocrysts of olivine with alteration rims of goethite and some crystals completely altered to goethite. Many vesicles are filled with radiant calcite. In minor quantity are badly strained quartz and small magnetite crystals (Pl. 10, Fig. 1).

The basalt in the Santa Rita Mountains occurs in numerous thin flows which are all very local. They lie just northeast of Nogales, Arizona and also directly east of Nogales on both sides of the international border. The flows are about 40 feet thick and greatly resemble the basalt from the Atascosa Mountains. The black rock contains visible feldspar phenocrysts and numerous small goethite masses. The feldspar is labradorite in coarse laths and fine crystals in the groundmass. A few altered, twinned subhedral phenocrysts of olivine occur but more abundant are goethite pseudomorphs after olivine. A few anhedral masses of quartz are noted in the matrix which contains a little magnetite and has fair flow structure (Pl. 10, Fig. 2).

The basalt in the Tucson Mountains is 700 feet thick and consists of five distinct flows as mapped by Tolman (1909). These flows are all dark brown to black and similar appearing. Thin section studies of the uppermost flow show it to consist of labradorite laths arranged in flow structure and a few badly fractured and altered phenocrysts of olivine which have alteration rims of goethite. Vesicles are filled with volcanic glass, calcite, and quartz

(Pl. 10, Fig. 3).

Intrusive Rocks

Widespread igneous intrusions of the same or similar rock type with approximately equal times of emplacement would add additional strength to the proposed correlations. Only a few good correlations of this type were found, but this may be due to the fact that the geology of Santa Cruz County has not been mapped in detail except in small local areas. Thus intrusive rocks may not crop out or may not have been yet discovered. Also their recognition in localized studies often still leaves doubt as to their time of emplacement.

The oldest intrusive rock recognized in this study is monzonite which appears in two of the columns at the same position, the supposed Cretaceous-Tertiary boundary. Smith (1956) reports early Tertiary (?) monzonite from the Mowry Mine area but the precise age of this intrusive rock is not known.

The next youngest intrusive rock, diorite in the Atascosa Mountains, has no known correlative in the other columns. It does add strength, however, to the argument of Courtright (1958) that in many areas of southern Arizona there are tectonic/sedimentary conglomerates near the Cretaceous-Tertiary boundary which separate two Laramide-type intrusive bodies. In the Atascosa Mountains the Oro Blanco conglomerate clearly separates the older quartz monzonite and the younger diorite.

Intrusive rhyolite was emplaced just before the outpouring of great quantities of extrusive rhyolite in the Santa Rita Mountains, the Mustang Mountains, and the Tucson Mountains. Monzonite was also intruded into the Santa Rita and Tucson Mountains after the outpouring of the upper andesites.

Structural Correlations

Structural trends in southern Arizona have been thoroughly studied by Lutton (1958). He notes that northwest-trending structures are very prominent. They include badly folded, northwest-trending anticlines and synclines in Cretaceous and older rocks. Pre-Laramide structures also include northwest-trending thrust and wrench faults.

Tertiary rocks are generally gently tilted to the east, north, or northeast. The tilting seems to be widespread and extends at least to the vicinity of Tucson and probably farther. Kinnison (1958) commented on the existence of this tilting in many ranges in southern Arizona. Since the Mineta beds and Pantano formation dip east and northeast, and younger deposits do not, the age of the tilting is probably post-Lower Miocene. Since the upper andesites of this study are not tilted, they may be post-Lower Miocene. Lutton (1958) postulated that post-Laramide deformation might be due to fault adjustment along pre-existing faults. Thus this post-Laramide deformation may be a reflection of pre-Laramide deformation.

Webb and Coryell (1954) noted the extreme faulting in Mesozoic (?) rocks in the Atascosa and Pajarito Mountains. The overlying Tertiary volcanic rocks are either tilted to the northeast or flat-lying. The only deviation from these Tertiary structures is a syncline east of Ruby which has folded the tuffs in a small area and some erratic dips which can be seen in the tuffs near Nogales, Arizona (Pl. 3, Fig. 1).

The structures of the Santa Rita Mountains, Patagonia Mountains, and Canelo Hills are very similar to those of western Santa Cruz County. Northwest-trending folds and/or thrust faults were noted in pre-Laramide rocks by Kartchner (1944), Feth (1947), Stoyanow (1949), Anthony

(1951), and Sulik (1957). Both the Santa Rita Mountains and Patagonia Mountains dip gently to the east forming an escarpment on the western side and a dip slope on the eastern side. (Schraeder, 1915). This easterly dip also prevails in the San Cayetano Mountains, just west of the Santa Rita Mountains, and in the Canelo Hills except in the southwestern section (Feth, 1947).

Bryant (1951) mapped northwest-trending thrusts and folds of Laramide age in the Mustang Mountains. The Tertiary (?) rhyolite dips to the northeast at least in part.

Kinnison (1958) suggested that the structure in the Tucson Mountains is a northwest-trending anticlinorium in Cretaceous and older rocks. The Tertiary volcanic rocks are tilted north and east forming an escarpment on the western side of the range and a dip slope on the eastern side (Pl. 2, Fig. 2). This structure therefore seems to be very similar to that of the Santa Rita and Patagonia Mountains.

The predominance of joints trending northeast and northwest was mentioned by Lutton (1958). I concur with his observations since these trends predominate in Santa

Cruz County and the Tucson Mountains. Naturally the cooling joints in volcanic rocks may have any trend but the tectonic joints have the two main trends. These joints may be related to the tilting of the Tertiary rocks.

It appears that these areas of southern Arizona have had similar histories in both volcanic activity and structural deformation.

Radioactivity Studies

Analyses of the alpha activity and potassium content of each volcanic unit were made and the results are shown on Table 1. The figures for alpha ray activity, measured in units of alphas/mg/hr, are proportional to the uranium and thorium content of the rock; separate uranium and thorium analyses were not made in this study. Uranium and thorium should tend to be enriched in acidic rocks and thus increase with the potassium content.

The measurement of the alpha activity of a rock by alpha-counting is probably not as accurate as potassium determination by beta-counting. This is because while potassium is more essential and more abundant, uranium and thorium are trace elements and may be very erratically distributed in the rock. Part of the difficulty is overcome by measuring the alpha activity from a larger sample area than the sample area used in beta-counting. A graphic plot of alpha activity versus potassium content for each unit is shown on Figure 2. A fairly linear relation between the two coordinates is noted except in the very acidic rocks. Some of these rocks have a very high potassium feldspar content which is not accompanied by a high alpha activity since uranium and thorium although enriched in acidic rocks, are not concentrated in potassium feldspar. Other acidic rocks which deviate from the linear relation have very high alpha activities and moderately high potassium contents.

Six samples were collected from the thin basalt flow in the Atascosa Mountains which is shown on Plate 3, Figure 2. Three samples were collected from the bottom of this flow and three other samples were collected from near the top of the flow. Sample 1 Top was collected directly above sample 1 Bottom etc. The similarities of the alpha activities and potassium contents of each sample show that this flow is quite uniform chemically. That the flow is also uniformly differentiated is suggested by the fact that each slight increase or decrease in alpha activity is accompanied by a corresponding increase or decrease in po-

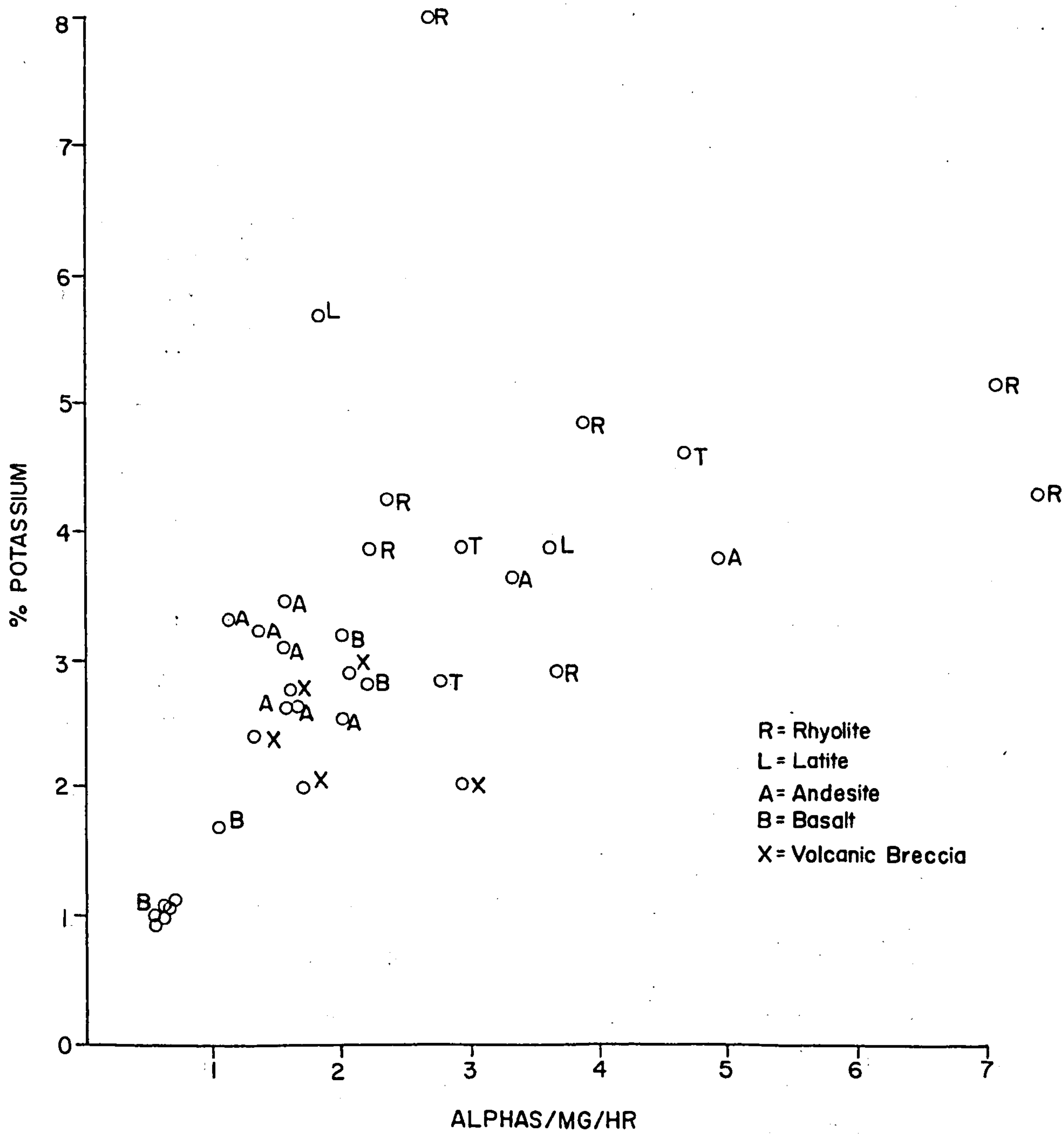

Figure 2. Potassium content versus alpha activity for all samples.

tassium content. These figures also attest to the good accuracy which can be obtained by counting methods even in samples of low alpha and beta activity.

The basalt from the Santa Rita Mountains appears more acidic than the basalt from the Atascosa Mountains judging by its higher alpha activity and potassium content. This is surprising since the two basalts appeared very similar in the hand specimen, thin section, and occurrence in the volcanic section. The basalt from Tumamoc Hill in the Tucson Mountains is the most acidic basalt of all according to the alpha activity and potassium content. The alpha activity figures indicate that the top flow is more basic than the composite sample but the potassium contents give the opposite conclusion. A graphic plot of alpha activity versus potassium content for basalts only is shown on Figure 3. The surprising linearity of basalt sample coordinates is obvious on Figure 3 except for the one sample of Tucson Mountains basalt Composite which is the only deviation. Apparently this one sample represents a more acidic rock such as the erratic acidic samples shown on Figure 2. This one sample may not be a true basalt but an andesite or possibly a basalt which has been effected by

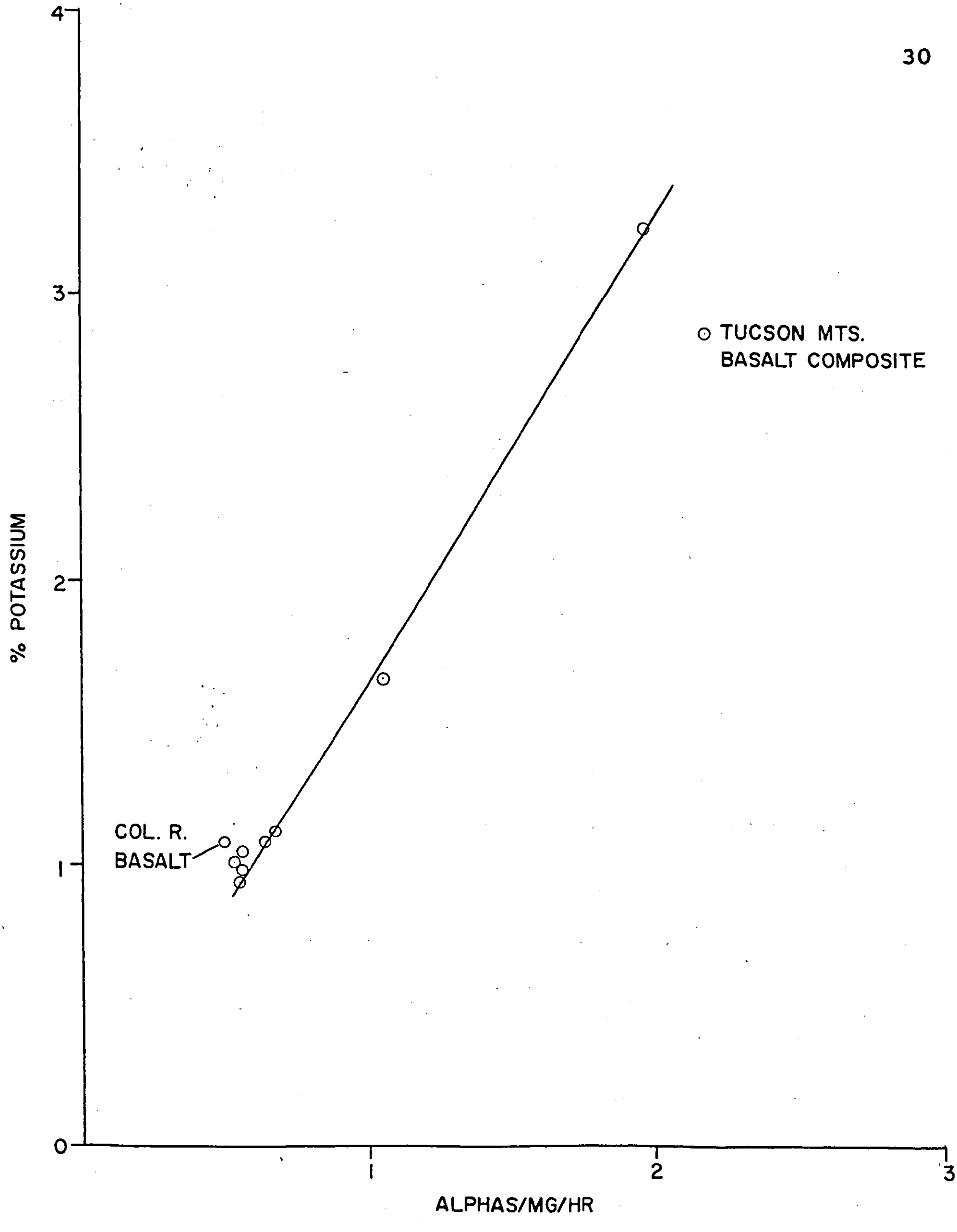

Figure 3. Potassium content versus alpha activity for basalts.

syntexis or some other process. This problem will be discussed further under emission spectrograph studies.

The upper andesites have no great similarities in alpha activity and potassium content in spite of their mineralogical similarities. The Sycamore andesite is not nearly as basic as it appears in the field. Also a thin section of this rock showed small phenocrysts of oxyhornblende. Either the matrix is much more acidic than the phenocrysts or else the rock is very heterogeneous.

In the rhyolites and latites the acidity of the Sycamore spherulitic rhyolite is obvious from the data. The similarity in potassium contents of the quartz latite porphyry and biotite rhyolite is not accompanied by similar alpha activities in these two rocks. In all three rocks the alpha activity appears more sensitive to acidity than the potassium content.

The alpha activities and potassium contents of the tuffs agree as indices of acidity. The tuff from the Santa Rita Mountains and the Safford tuff have similar appearances in the field as well as similar alpha activities. The more acidic tuff from the Atascosa Mountains has a fresher appearance and is not so badly weathered. However, the possibility of oxidation of the uranium and its subsequent leaching is precluded by the agreement of the alpha activities and potassium contents except possibly in the tuff from the Santa Rita Mountains to a small degree.

An intraformational study was also made on the Montana Peak formation. Six samples of this formation were analyzed, three from the bottom of the formation and three from the top but the top samples were not collected directly above similarly numbered bottom samples as in the basalt from the Atascosa Mountains. Although classified as a rhyolite, this formation is basic, for the most part, as can be seen from the low alpha activities and potassium contents. The variations and low figures are undoubtedly due to the inclusion of basic fragments, some of which must be more basic than the included fragments of the Ruby Road formation which were noticed in the field. One sample which was noticeably pure, 2 Top, has a much higher alpha activity and potassium content and the true rhyolitic character of the rock can be seen. In the other xenolithic samples an increase or decrease in alpha activity is well accompanied by a corresponding increase or decrease in potassium content. This sorting of trace elements and essential constituents is surprising for this chaotic rock. Figure 2 shows, however, that the linearity of the plots of coordinates is much higher for the true basalts than for the volcanic breccia.

Comparison of the most acidic sample of the Montana Peak formation, 2 Top, with the other rhyolites shows few similarities except for the nearly equal alpha activities of the rhyolite from the Mustang Mountains and the Cat Mountain rhyolite from the Tucson Mountains. There are many mineralogical and textural differences in these rhyolites as can be seen on Plate 6.

The great similarities in alpha activities of the older andesites are not substantiated by similar potassium contents. Both figures indicate the relative acidity of the older latite from the Santa Rita Mountains which was apparent from thin section studies. The abundance of orthoclase in this rock makes it appear more acidic than a rhyolite even though the plagioclase is andesine. Its alpha activity is lower than all of the younger rhyolites, however.

In the Cretaceous (?) volcanic rocks, no similarities are noted. The Cretaceous andesite from the Santa Rita Mountains has an alpha activity and potassium content very similar to the Tertiary older andesite from the same range. Also the Cretaceous (?) andesite from the Tucson Mountains has a very similar potassium content to that of the Tertiary lower andesite from the Tucson Mountains.

Emission Spectrograph Studies

A sample of each major volcanic unit was arced in an emission spectrograph to search for trace elements which might add strength to the proposed correlations. A sample of the Columbia River basalt was also analyzed for comparison with the basalts in this study.

Unfortunately the emission spectrographic data obtained is at best semi-quantitative. There is a direct relation between the readings obtained and the quantity of the element present but it is not necessarily a linear relation. Also the sensitivity varies for each element and each different line of the same element. The numbers shown on Table 1 represent readings on a photometric density scale which have been multiplied by 100. The most sensitive line for each element was read.

The four elements for which data are given; chromium, copper, magnesium, and calcium; should all tend to be enriched in basic rather than acidic rocks. Thus while an increasing alpha and beta count is an indication of increasing acidity, increasing amounts of these four elements indicate increasing basicity.

A possible weakness in this method is that a very small sample is used and it may not be representative of the entire formation. The data obtained seem reasonable, however.

Since only the basalts showed a trace of chromium, it is most likely present in the mineral olivine. Chromium is known to be abundant in some magnetites but none of the more acid rocks (some of which appear to contain as much magnetite as the basalts) gave a reading for chromium. The parallelism of the readings for chromium and magnesium substantiate present thought that chromium either replaces Mg^{2+} (and probably Fe^{2+}) in olivine or is present as chromite in the olivine.

The basalt from the Santa Rita Mountains appears to be the most basic basalt of all. Although it contains smaller phenocrysts of olivine than the basalt from the Atascosa Mountains, the phenocrysts may be much more abundant.

The most recent flow of basalt in the Tucson Mountains has a great resemblance to the basalt from the

Atascosa Mountains. The most recent flow also seems much more basic than the composite sample of the section of basalt in the Tucson Mountains. Thus although the alpha activity and potassium analysis show confusing differences between the two samples, the most recent flow contains more chromium, copper, and magnesium. The higher reading for calcium suggests that the plagioclase may be more basic also. It appears that the very basic basalts encountered in this study occur only in thin flows.

The sample of the Columbia River basalt seems more basic than all of the basalts in this study except for its lower chromium content.

The upper andesites as well as the andesite in Sycamore Canyon of the Atascosa Mountains have similar copper contents but other differences. The upper andesites from the Atascosa Mountains and Santa Rita Mountains both contain augite, biotite, and andesine. They also have similar magnesium and calcium contents. Short's Ranch andesite, lacking augite and biotite (?) has a lower magnesium and calcium content. The andesite in Sycamore Canyon appears still more acidic so it must contain oxyhornblende only in small amounts.

The rhyolites and latites have similar magnesium and calcium contents but differences in copper content. Since they contain very different minerals, the similarities are not apparent from thin-section studies. The quartz latite porphyry and biotite rhyolite have many similarities as well as similar potassium contents as previously mentioned. The high alpha activity and low copper content of the Sycamore spherulitic rhyolite suggest that the trace elements in this rock indicate higher acidity than major constituents.

Both counting data and emission spectrographic work show the tuffs are listed in order of decreasing acidity on Table 1. The fact that there are any similarities at all such as the copper and magnesium contents of the tuffs from the Santa Rita Mountains and the Safford tuff is surprising in explosive fragmental rocks. However, in each case an orderly decrease in alpha activity and potassium content is accompanied by an orderly increase in copper, magnesium, and calcium so these tuffs may not be as chaotic as they appear.

The rhyolites show similarities in magnesium and calcium content except for the Montana Peak formation which is more acidic. The erratic copper values suggest that this trace element was not well differentiated in these explosive acidic rocks.

The older andesites and latite mostly show contents which do not follow the similar alpha activities or potassium content variations. A possible exception is the copper which is similar in the andesites and drops off in the more acidic latite. However, the magnesium and calcium do not follow the trends of the radioactive studies. This may be due to the fact that these rocks have different accessory minerals as well as differences in the matrix plagioclase.

In the Cretaceous (?) volcanic rocks the relative acidity of the Pajarito lavas is apparent. Few similarities are noted in the andesites except that the magnesium and calcium are richer in the andesite with the lower potassium content. The higher calcium of the andesite in the Santa Rita Mountains is probably due to the presence of calcite. In the andesites the erratic alpha activity and copper content do not follow each other nor the basicity indicated by magnesium and calcium. Important differences in the copper, magnesium, and calcium contents are noted between the Cretaceous (?) andesite and Tertiary older andesite in the Santa Rita Mountains in spite of similarities in alpha activities and potassium contents.

Extension of Correlation to Other Areas

The volcanic sequence in Santa Cruz County and the Tucson Mountains can be extended tenatively to other areas of Arizona and northern Mexico.

Brown (1939) mentions the similarity of the Cretaceous (?) andesite in the Tucson Mountains with the Cretaceous andesite at Aravaipa, 67 miles northeast of Tucson. At Aravaipa the andesite is overlain by Tertiary rhyolite according to Ross (1925).

In the Huachuca Mountains, which lie directly southeast of the Mustang Mountains, Alexis (1949) mapped thick Cretaceous andesite with some latite and dacite. These flows are overlain by thick Tertiary rhyolite porphyry.

An excellent correlation with Santa Cruz County can be found in central Cochise County as mapped by Gilully (1956). He assigned the oldest volcanic rocks to the Cretaceous but stated they might be Triassic or Jurassic. The Cretaceous (?) andesite and overlying sequence appear to correlate well with the sequences of Santa Cruz County.

The section in the Chiricahua and Dos Cabezas

Mountains as described by Enlows (1955) and Sabins (1957) shows late Cretaceous or Tertiary andesite and conglomerate of volcanic rocks, both overlain by thick rhyolite flows and rhyolitic welded tuffs. Their description indicates a remarkable similarity in the welded tuffs of the Chiricahua Mountains and those of the Tucson Mountains.

Stoyanow (1949) noted great similarity between the Upper Cretaceous Sonoita group near Sonoita, Arizona and the Cabullona group of the same age which occurs 25 miles southwest of Douglas, Arizona in northeastern Sonora, Mexico. This area was mapped by Taliaferro (1933) who found the Upper Cretaceous sedimentary rocks overlain by 800 feet of fragmental rhyolitic tuff. The tuff was assigned to the late Cretaceous because of its apparently conformable relation with the underlying sedimentary rocks. A correlation with the Tertiary rhyolitic tuffs of Santa Cruz County is possible.

Since most of the northly trending ranges of Santa Cruz County are continuous to the south, a correlative sequence may exist in northern Sonora, Mexico. Rocks very similar to the Pajarito lavas, Montana Peak formation, and Atascosa tuff crop out just east of Nogales, Arizona and they appear to be the northern tip of ranges in Sonora.

West of Santa Cruz County lie the Baboquivari Mountains and the Cerro Colorado Mountains. These ranges are both volcanic in part but since the regional geology is not yet well deciphered, a correlation will not be suggested. Fowler (1938) comments on the wide extension of the Oro Blanco conglomerate and suggests that it can be traced from west of the Baboquivari Mountains to the Santa Rita Mountains.

The volcanic sequences studied in Santa Cruz County show great similarity with a sequence reported in southwestern New Mexico by Wargo (1959). This study may well represent an extension of the sequences in New Mexico.

Any future extensions of the proposed volcanic sequence should consider the sequences and not mere lithology of one volcanic unit. It is noteworthy that the best correlations are obtained in areas in which thorough regional mapping has been done. Small outcrops and ranges seem to be correlative only in part.

CONCLUSIONS

The volcanic sequences under study have many structural and sequential similarities which suggest quasi-contemporaneous eruption. Correlation of major intrusive bodies and the mineralogy of similar volcanic rock types show both similarities and dissimilarities.

Geochemical studies indicated the following correlations: the basalts all have similar copper contents; the upper andesites also have similar copper contents; in the rhyolite and latite group two of the units have similar potassium, copper, and magnesium contents; two of the tuffs have similar alpha activities, magnesium, and copper contents; the rhyolites have similar magnesium and calcium contents except for one more acidic rhyolite; the older andesites have almost identical alpha activities; and the Cretaceous (?) andesites have very few similarities.

The analysis of the alpha and beta activity of a rock should prove to be an effective aid to petrography. The methods used in this study are very simple yet they give good estimates of the potassium content and alpha activity of the entire rock. Since both alpha and beta analysis indicate acidity, they provide independent substantiation for true acidity by pointing out anomalous uranium-thorium and potassium contents. For instance the older latite from the Santa Rita Mountains has such a high potassium content that it appears to be a rhyolite. Its alpha activity is lower than the other rhyolites though so it can be classified as a latite with an anomalously high potassium content. Beta counting is also valuable in distinguishing badly altered potassium feldspar from badly altered plagioclase. For instance in the rhyolite from the Mustang Mountains, the very high potassium content of the rock indicates that the altered feldspar must be potassium feldspar.

These methods are particularly applicable to the study of volcanic rocks since volcanic rocks are often porphyrys or aphanites. The microscopic study of a porphyry often only indicates the composition of the phenocrysts since the matrix of these rocks is often microcrystalline or cryptocrystalline. This is not a good analysis since the bulk of the rock is in the matrix and not the phenocrysts. The matrix is invariably more acidic than the phenocrysts due to its later crystallization time. Some rocks in which orthoclase phenocrysts could be seen in the microscope had lower potassium contents than rocks in which no potassium feldspar was visible. Figure 4 shows that some of the rocks should probably be reclassified to more acidic rock types judging by their potassium contents although mineralogically they are correctly classified. However, none of the potassium contents indicate that the rock is really more basic than the microscopic classification.

The emission spectrograph studies also point out weaknesses in ordinary microscopic classification. Some of the rocks studied which contain very basic plagioclase gave lower readings for calcium than rocks with more acidic plagioclase. Also many times in a suite of similar rocks, an increase in potassium content and or alpha activity is not accompanied by a decrease in copper, magnesium, and calcium as should be the case. Thus very few petrographic generalizations can be made for the rocks in this study.

It is obvious that previous attempts to correlate volcanic rocks by lithology or microscopic studies alone may have been unsucessful because of incomplete analysis. Also as noted in this study, rocks which are very different mineralogically may have many chemical similarities. If these rocks have had similar origins, then they must have

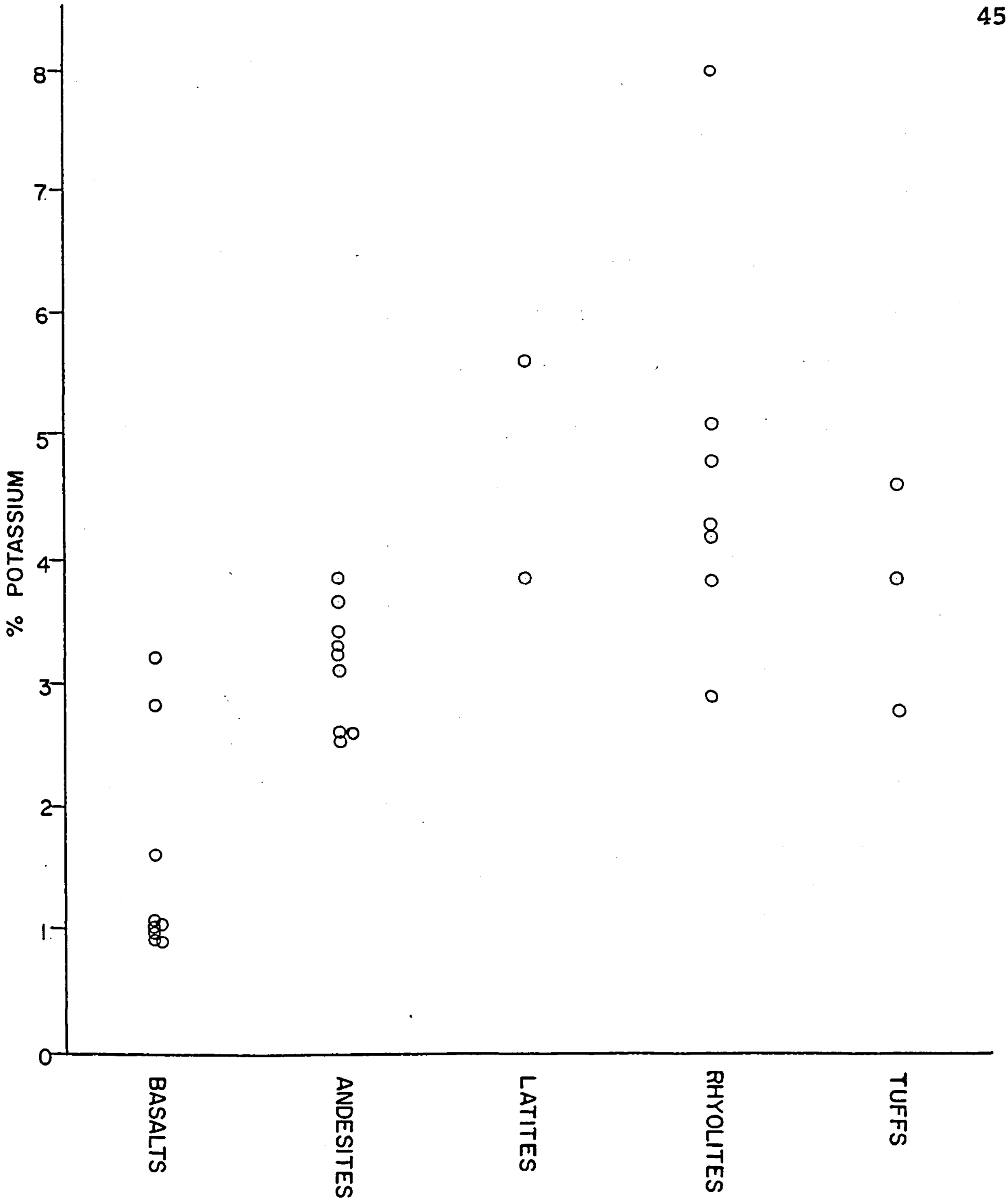

Figure 4. Comparison of potassium contents by rock type.

had very different crystallization histories.

Although dissimilarities exist when the volcanic units are compared, the almost constant sequences suggest that they are not unrelated or fortuitous. The origin of such a sequence can be related to either magmatic differentiation from a magmatic chamber or fusion and extrusion of existing solid rock in the crust and mantle.

If magmatic differentiation alone is considered, it is doubtful that even similar parent magmas could each produce the same sequence of erupted rocks. The complexity of magmatic differentiation and its dependency upon physico-chemical conditions have been emphasized by many writers. Each magma and its differentiation are probably unique and few generalizations can be made. Therefore if differentiation is the cause of the sequence it must have occurred in one parent magma. Also this parent magma would likely be noticeably acidic in order to account for the great predominance of acidic rocks.

Since the sequences show the greatest similarities from the Tertiary rhyolites to the basalts, these sequences of thick acidic rocks followed by increasingly more basic and thinner rocks may have been differentiated from one parent magma. The andesites older than this main sequence are thin and intermittent and the thick Pajarito lavas appear to be completely unrelated as previously mentioned.

If this sequence is very widespread then perhaps it is not mainly the result of magmatic differentiation but the result of deformation and fusion within the crust (and perhaps the mantle) at progressively deeper levels. Wahlstrom (1950) notes that in areas where a series of volcanic rocks are clearly related differentiation products, basalt is commonly the first rock type to be extruded. This is not the case in the sequences under study.

A logical explanation for the origin of volcanic rocks has been suggested by Bullard (1954). Since the thermal gradient in the mantle is low and neither crustal radioactive disintegrations nor chemical action explain the origin of volcanic heat, it is obvious that volcanic activity is indeed a rare phenomenon which must require very special conditions. Bullard (1954) relates these conditions to seismic activity. Most earthquakes occur shallower than 60 km which approximates the zone from which volcanic rocks are thought to flow. The heat required to melt existing solid rock could result from the conversion of elastic energy within the earth to mechanical energy (faulting and folding) and then to thermal energy thus melting the rocks either completely or by partial fusion. Also the faulting would allow great pressure releases and negligible heat loss. The drop in pressure would lower the fusion point of the rocks according to the relations given by the Clausius-Clapeyron equation. The faults also might provide the vents for the eventual extrusion of the magma.

This association of structural deformation and volcanic activity is widely accepted. In the Precambrian of Arizona there was notable orogeny and volcanic activity. In the Paleozoic, structural deformation is negligible and volcanic activity is unknown. Again in the Mesozoic and Cenozoic, deformation and volcanic activity occurred and are undoubtedly related.

According to this hypothesis, structural deformation should always precede volcanism. Thus in the area under study, the Cretaceous volcanic rocks were preceded by structural uplift in southern Arizona in early Mesozoic time. The thick Tertiary sequence was preceded by Laramide deformation noted in Cretaceous and older rocks. The thin Quaternary volcanic rocks were preceded by Tertiary deformation which was mainly tilting. This well explains the occurrence of volcanism as related to structural deformation. Also the periods of extreme deformation are followed by extreme volcanism and periods of minor deformation are followed by minor volcanism.

The fusion of existing solid rock in the crust and mantle could have been at various depths or at one principal depth. If the fusion occurred at various depths then the acidic rocks are probably from a more shallow source than the basic rocks. If fusion occurred at one principal depth then the acidic rocks are the first products of the selective fusion of more basic rocks. The outpouring of the acidic rocks may have been inhibited until the culmination of activity on account of the high viscosity of acidic melts. This viscosity would not be so high, however, if the magma contained great quantities of water and volatiles which lowered polymerization in the magma. The predominance of basalt outpourings today is probably due to the fact that basalt in the crust or mantle lies more closely to the depth-temperature curve than any shallower rock and its high fluidity fascilitates its extrusion. A study of trace elements in these rocks would not likely distinguish fusion products from differentiation products. Fusion from various depths as previously mentioned may be from rocks originally emplaced by the primary differentiation of the earth. Also selective fusion which is really reverse magmatic differentiation greatly resembles normal magmatic differentiation and the sorting of magmatic constituents would be similar.

EXPERIMENTAL DATA

For the purpose of making chemical tests on the volcanic units under study, each unit was sampled. The samples were then ground to -65 mesh, washed in distilled water, and dried.

Alpha activity was analyzed on a 5-inch low level scintillation alpha detector. This detector is one of those described by Kulp, Holland, and Volchok (1952) which does not employ a lucite cone. The sample planchets had a surface area of 118.9 cm^2 and the samples were alternated with dunite samples for the background.

The alpha activity is given for each sample in alphas/mg/hr. This figure was computed from the formula

$$N = \frac{4n}{RudA \times 10^3}$$

where N = alphas/mg/hr emitted from a thick source, n = alphas/hr emitted from the source, R = mean range of alphas in air, u = range in substance/range in air, d = density of material in gm/cc, and A = area of sample in cm^2. Possible sources of error are: (1) Errors in counting, the standard deviation of n. This deviation results from the fact that the emission of alpha particles and beta rays from a sample is a random process in which statistical laws must be employed. The standard deviation of counting decreases as a sample is counted for an increasing period of time. This deviation can be computed from the formula sd = the square root of the number of counts/the time counted. This same formula is used to compute the standard deviation of the background count after the addition of the counts and times of the background immediately before and after the sample count. (2) Variations in R. The factor R, the mean range of alphas in air, varies with each radioactive series. It is known to be lower for the U^{238} series than for the Th^{232} series. For this study the factor R was computed for the Columbia River basalt from the known uranium and thorium content (0.88$\pm$.06 ppm U and 1.9$\pm$.4 ppm Th) and from the equations 1 ppm U = 0.3674 alphas/mg/hr and 1 ppm Th = 0.08858 alphas/mg/hr. In this manner a value for R is found which is dependent upon the decay of both uranium and thorium and a Th/U ratio of 2.16. Although this ratio would be slightly higher in the average igneous rock, the computed value of R is intermediate between the two extreme values for uranium and thorium. Therefore the computed value of R is a possible source of error in rocks which have an abnormal thorium or uranium content. This error would have a maximum value of ± 10% but it cannot be estimated since the alpha activity of a rock gives no indication of the Th/U ratio. (3) Errors in ud. The value used in this study was 1.53×10^{-3} gm/cm^3. This factor is known to vary for each mineral type but its variation is insignificant for most silicate rocks. Consider for example the values of ud computed below for an average rhyolite and an average basalt, the two extreme rock types encountered in this study.

Rhyolite

Mineral	%		ud x 10^{-3} gm/cm^3
Orthoclase	48	x	1.54
Oligoclase	13	x	1.49
Quartz	35	x	1.48
Biotite	3	x	1.69
Magnetite	1	x	2.08

ud Rhyolite = 1.523×10^{-3} gm/cm^3

Basalt

Mineral	%		ud x 10^{-3} gm/cm^3
Labradorite	92	x	1.52
Olivine	5	x	1.88
Quartz	2	x	1.48
Magnetite	1	x	2.08

ud Basalt = 1.544×10^{-3} gm/cm^3

Thus it can be seen that the possible source of error in the factor ud is insignificant for this study.

Alpha counting of the following samples from the National Bureau of Standards gave the results listed:

Sample	Alphas/mg/hr	%sd
Milford granite	1.74	6.18
Graniteville granite	8.25	5.80
Chelmsford granite	5.68	6.22
Gabbro-Diorite	0.345	10.15
Triassic diabase	0.438	8.35

Measurement of the beta activity of a sample is a measure of the decay of the K^{40} isotope. This isotope decays to A^{40} by electron capture and also to Ca^{40} by beta emission. Since the isotopic abundance of K^{40} is believed constant, a measure of the beta activity gives an estimate of the total potassium content.

The beta activity was analyzed on a low level anti-coincidence beta counter which was lead-shielded. The sample planchets had a surface area of 2.99 cm^2 and the samples were alternated with dunite for the background. All samples were compared with a standard sample of potassium dichromate for calibration.

The beta activities obtained (betas/min.) were corrected for beta activity due to uranium and thorium decay but no correction was made for beta activity due to rubidium in igneous rocks. The correction factor used in this study for U and Th decay was 0.005 %K/alpha/hr which was subtracted from the computed, uncorrected values of potassium.

The standard deviation of beta counting was computed exactly the same as for alpha counting as previously described. The computation of the standard deviation of the computed uncorrected value of potassium involves the standard deviations of beta counting of both the sample and the potassium dichromate. Since these two standard deviations are divided, the per cent standard deviation of the computed uncorrected value of potassium is equal to 100 times the square root of

$$\left(\frac{sd_1}{n_1}\right)^2 + \left(\frac{sd_2}{n_2}\right)^2$$

After subtraction of the correction factor, the final standard deviation is equal to the square root of the sum of the squares of the standard deviations of the correction factor and the computed uncorrected value of potassium.

Two of the samples were analyzed for potassium by Mr. Carl Hedge using flame photometry. These values are shown on Table 1 and they agree well with the values obtained by counting. Beta and alpha counting and computation of the potassium content of the standard samples gave the following results:

Sample	%K	%s.d.	Natl. Bur. of Stds.
Milford granite	3.41	3.02	3.32
Graniteville granite	4.36	3.51	3.81
Chelmsford granite	4.61	5.85	4.61
Gabbro-Diorite	1.58	5.97	1.30
Triassic diabase	0.455	13.5	0.482
Columbia River basalt	1.07	5.94	0.819

Better agreement is obtained with the acidic samples than with the basic samples, but this is to be expected. The potassium analyses given by the National Bureau of Standards are undoubtedly less accurate for samples of low potassium content. The accuracy of potassium determination by beta counting is also lower for basic samples when all samples are counted for the same number of counts as they were in this study. Also, in samples of low beta-activity, background fluctuations become significant.

Each sample was prepared for analysis in the emission spectrograph by mixing it with ground carbon in a 1:1 ratio. This mixing was performed for added sensitivity at the suggestion of Mr. Bruno Sabels. Each sample was first arced at 7 amperes for 30 sec. followed by a final arc at 14 amperes for 30 sec. The following lines were analyzed:

Chromium	4254.346
Copper	3247.540
Magnesium	2852.129
Calcium	4226.728

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APPENDIX

PLATE 4.-PHOTOMICROGRAPHS OF CRETACEOUS (?) VOLCANIC ROCKS.

Figure 1.-Pajarito lavas from Pajarito Mountains. Subhedral sanidine (s), sericitized orthoclase (o), and quartz (q) in a fine-grained matrix. Crossed nicols, 25X.

Figure 2.-Cretaceous andesitic breccia from Santa Rita Mountains. Fragments and crystals of coarse biotite, altered orthoclase, and stained magnetite. Nicols not crossed, 25X.

Figure 3.-Cretaceous (?) andesite from Tucson Mountains. Coarse anhedral phenocrysts of andesine (a) and fragments of biotite in a fine matrix. Crossed nicols, 80X.

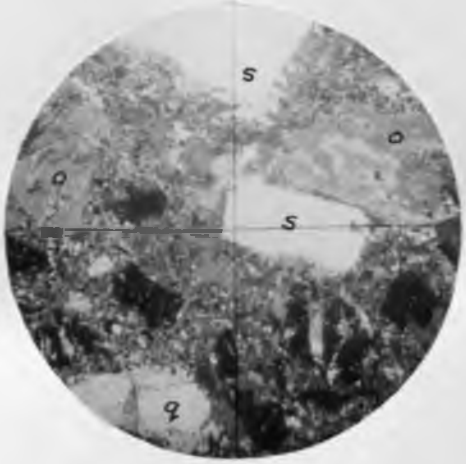
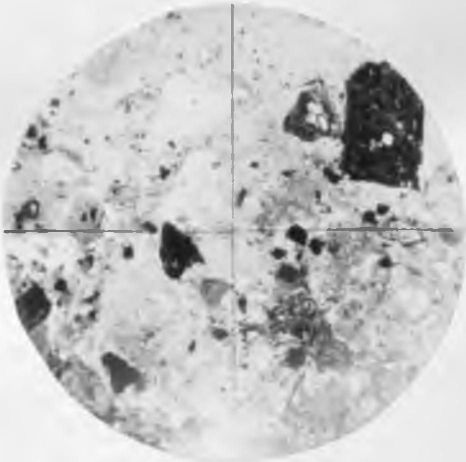


FIGURE 1



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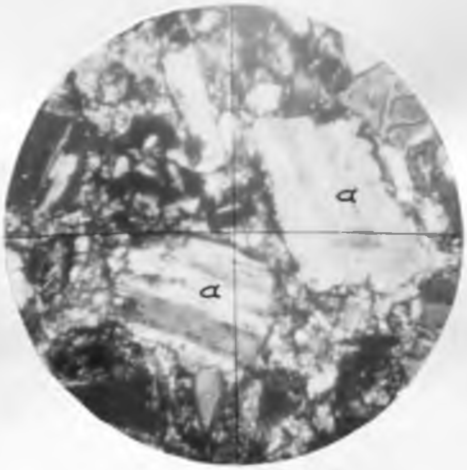


FIGURE 3

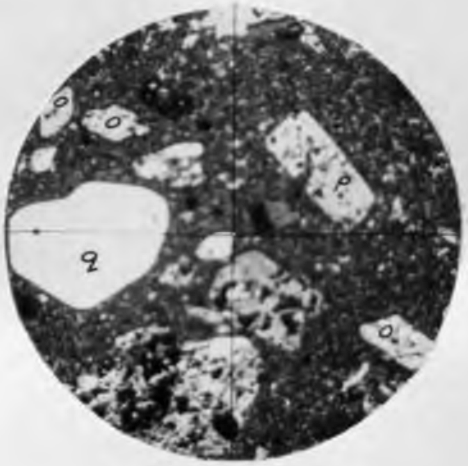
PLATE 5.-PHOTOMICROGRAPHS OF LOWER ANDESITES

Figure 1.-Ruby Road formation from Atascosa Mountains. Rimmed euhedral orthoclase (o), subhedral plagioclase (p) and anhedral quartz (q) in an aphanitic matrix. Crossed nicols, 25X.

Figure 2.-Lower andesite from Santa Rita Mountains. Coarse, twinned, euhedral crystal of augite (a) in matrix of altered, zoned labradorite. No flow texture. Crossed nicols, 80X.

Figure 3.-Lower andesite from Tucson Mountains. Biotite pseudomorphs after pyroxene and amphibole in matrix of altered plagioclase. Nicols not crossed, 25X.

PL. 5



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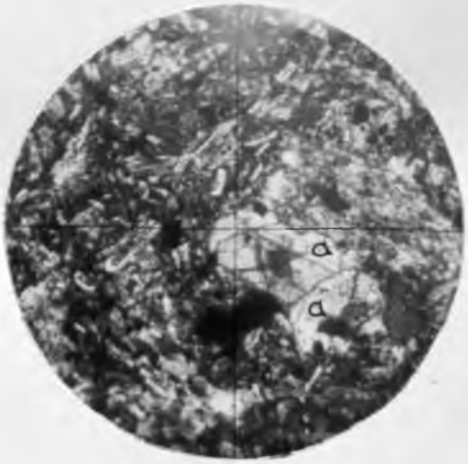

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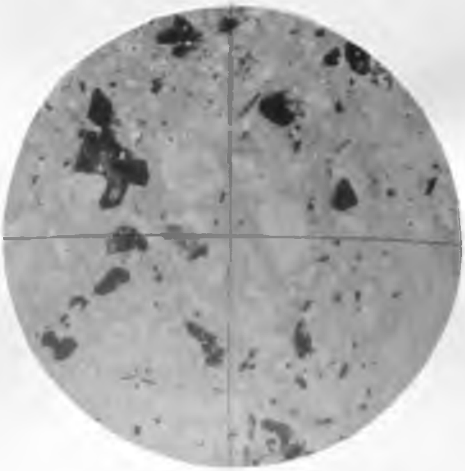


FIGURE 3

PLATE 6.-PHOTOMICROGRAPHS OF RHYOLITES

Figure 1.-Rhyolite breccia from Tumacacori and Atascosa Mountains. Chaotic arrangement of volcanic glass, plagioclase, quartz, and calcite. Crossed nicols, 25X.

Figure 2.-Rhyolite from Santa Rita Mountains. Flattened cavity filled with alunite crystals which are also disseminated in the glassy matrix. Nicols not crossed, 80X.

Figure 3.-Rhyolite from Mustang Mountains. Dark altered crystals of orthoclase intergrown with quartz. Nicols not crossed, 80X.

Figure 4.-Cat Mountain ignimbrite from Tucson Mountains. Glassy eutaxitic texture between impure glass fragments with aligned plagioclase crystals (p) and embayment of tridymite (t). Nicols not crossed, 80X.

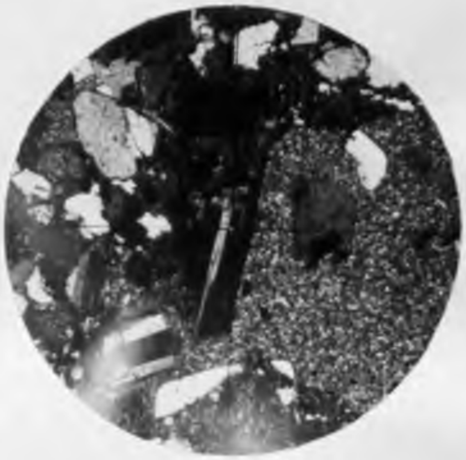


FIGURE 1

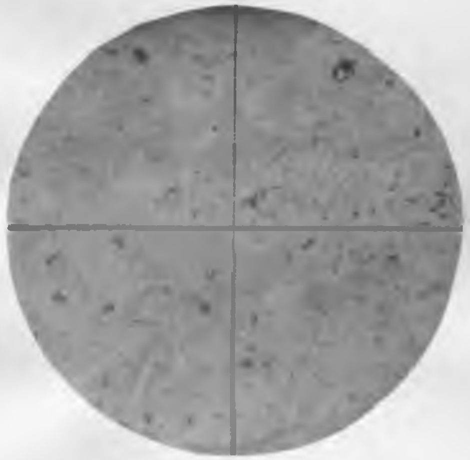


FIGURE 2

FIGURE 3

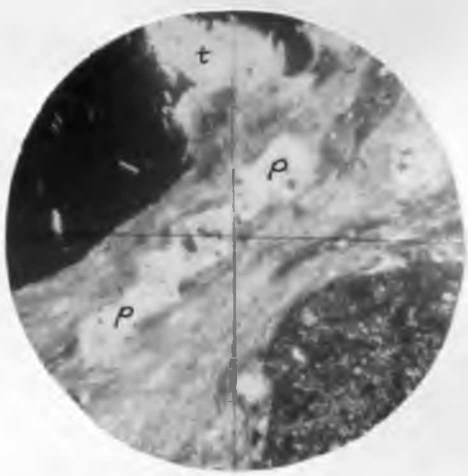


FIGURE 4

PLATE 7.-PHOTOMICROGRAPHS OF TUFFS

Figure 1.-Tuff from Atascosa Mountains. Fragments of impure glass (g), euhedral plagioclase, glass shards, and quartz in matrix of argillaceous, devitrified glass. Nicols not crossed, 25X.

Figure 2.-Tuff from Santa Rita Mountains. Fragments of orthoclase, quartz, plagioclase, biotite, and crystals in matrix of argillaceous, devitrified glass. Nicols not crossed, 25X.

Figure 3.-Safford tuff from Tucson Mountains. Unsorted, angular fragments of feldspar, glass (g), biotite (b) with numerous voids in matrix of argillaceous, devitrified glass. Nicols not crossed, 25X.

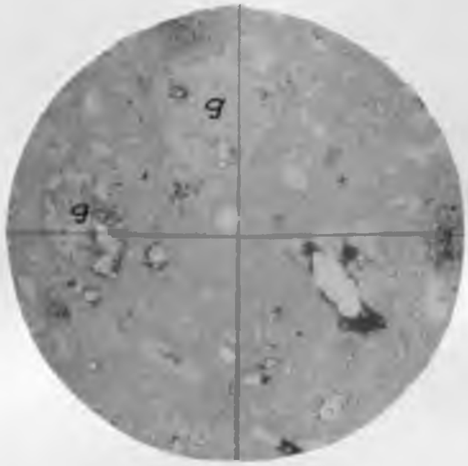


FIGURE 1

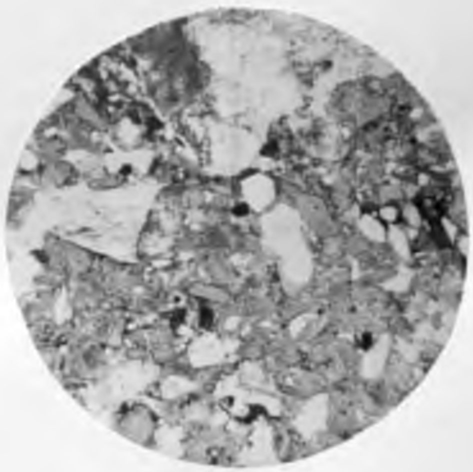


FIGURE 2

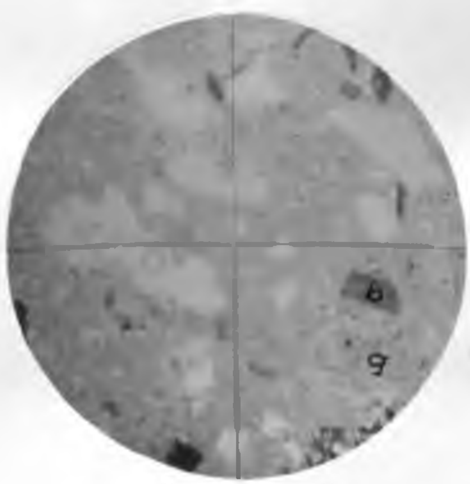


FIGURE 3

PLATE 8.-PHOTOMICROGRAPHS OF RHYOLITE AND LATITE

Figure 1.-Spherulitic rhyolite from Sycamore Canyon in the Atascosa Mountains. Spherulitic feldspar stained by dark hisingerite, altered phenocrysts of orthoclase (o). Nicols not crossed, 25X.

Figure 2.-Quartz latite porphyry from Santa Rita Mountains. Phenocryst of altered orthoclase (o) and masses of epidote (e) in a matrix consisting mostly of altered orthoclase. Nicols not crossed, 25X.

Figure 3.-Biotite rhyolite from Tucson Mountains. Euhedral to anhedral quartz (q), flakes of biotite (dark minerals), and fractured impure glass pseudomorph (g) in fine-grained matrix. Nicols not crossed, 25X.

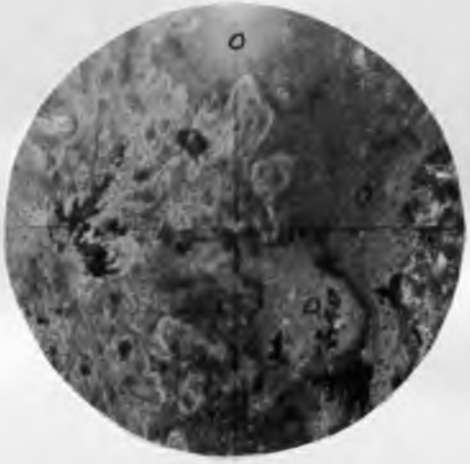


FIGURE 1

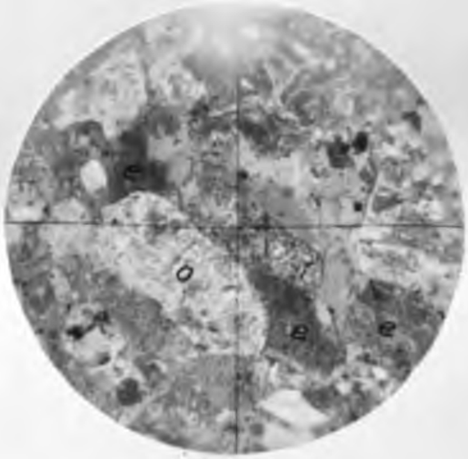


FIGURE 2

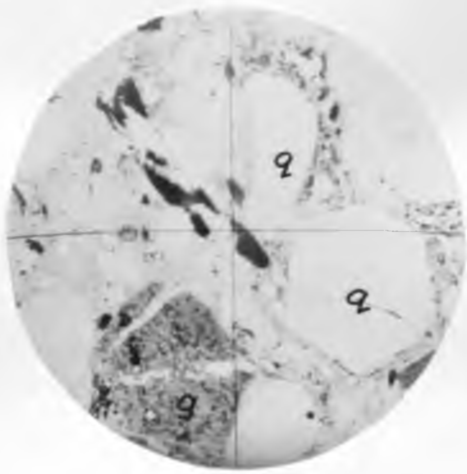


FIGURE 3

PLATE 9.-PHOTOMICROGRAPHS OF UPPER ANDESITES

Figure 1.-Andesite from Atascosa Mountains. Coarse phenocrysts of augite (a) and plagioclase (p) in fine impure matrix. Nicols not crossed, 80X.

Figure 2.-Andesite from Santa Rita Mountains. Euhedral and anhedral phenocrysts of andesine (a) and anhedral quartz in glassy matrix. Crossed nicols, 25X.

Figure 3.-Short's Ranch andesite from Tucson Mountains. Coarse euhedral crystals of orthoclase (o) and coarse anhedral crystals of plagioclase (p) in badly altered matrix. Crossed nicols, 80X.

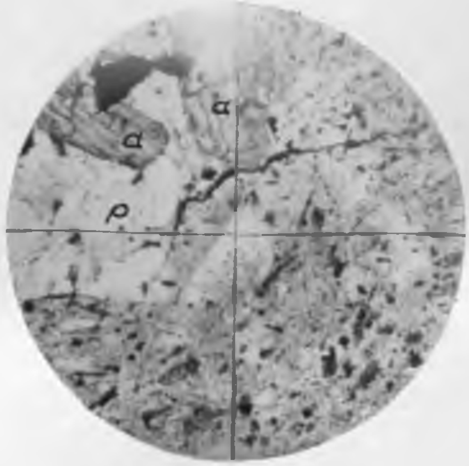


FIGURE 1

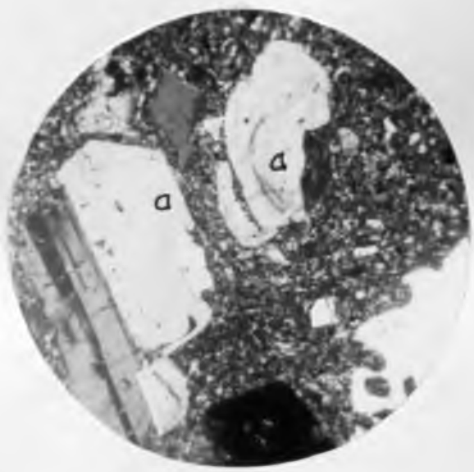


FIGURE 2

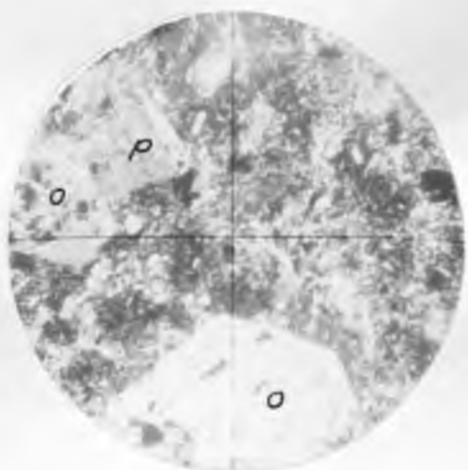


FIGURE 3

PLATE 10.-PHOTOMICROGRAPHS OF BASALTS

Figure 1.-Basalt from Tumacacori Mountains. Coarse labradorite crystals and zoned goethite alteration remnants of olivine, all in a fine matrix. Crossed nicols, 25X.

Figure 2.-Basalt from Santa Rita Mountains. Anhedral Quartz (q) in matrix of labradorite and goethite which shows a little flow structure. Crossed nicols, 25X.

Figure 3.-Basalt from Tucson Mountains. Euhedral phenocrysts of olivine (o) with alteration rims of goethite, all in a felted mass of labradorite in flow structure. Nicols not crossed, 80X.

PL. 10

FIGURE 1

FIGURE 2

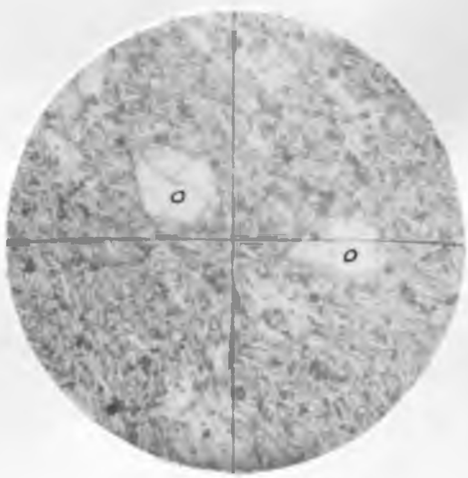
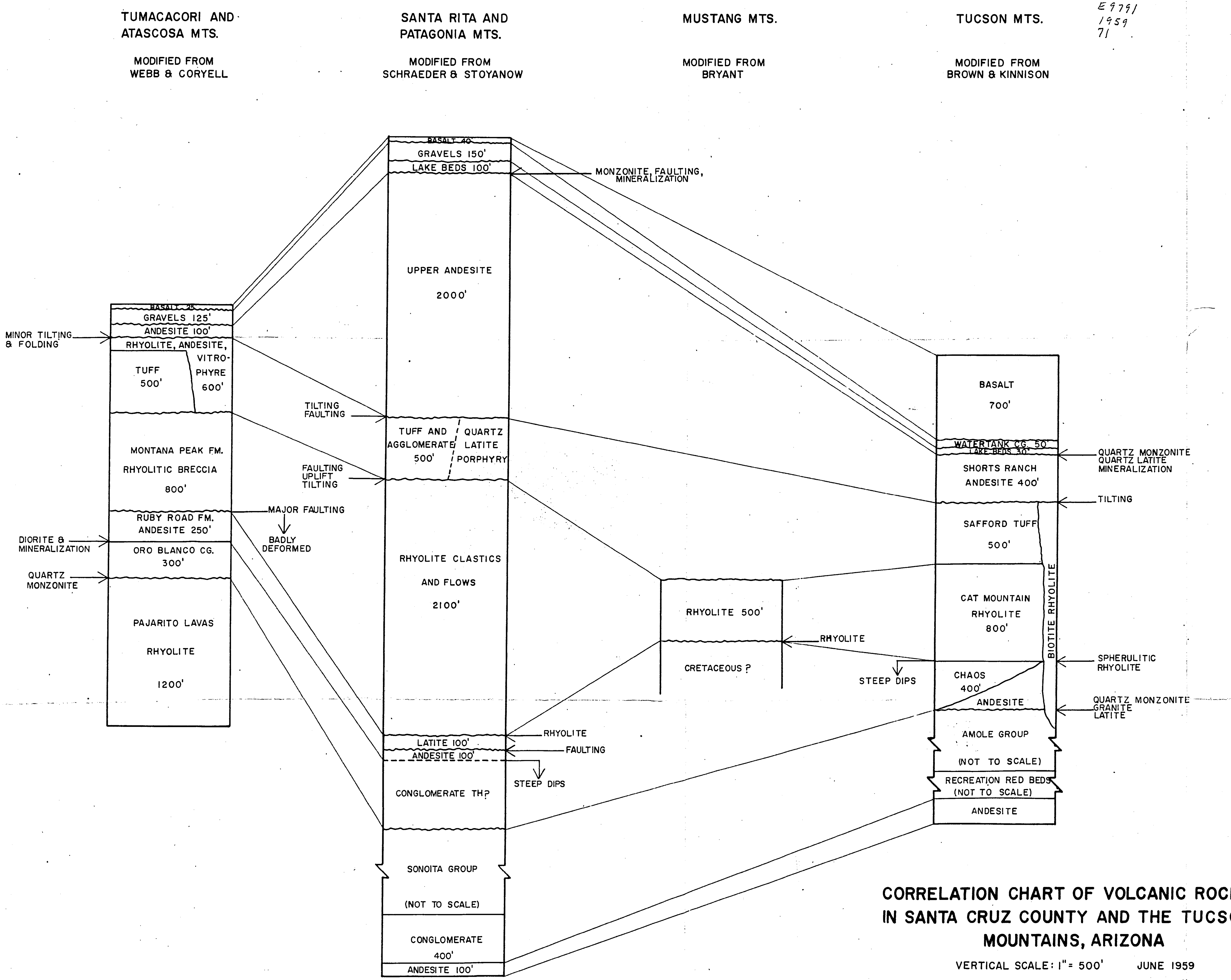


FIGURE 3

PLATE ONE



CORRELATION CHART OF VOLCANIC ROCKS IN SANTA CRUZ COUNTY AND THE TUCSON MOUNTAINS, ARIZONA

VERTICAL SCALE: 1" = 500' JUNE 1959

COMPILED BY O. J. TAYLOR

O.J. TAYLOR

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TABLE 1.-ALPHA COUNT, POTASSIUM CONTENT, AND EMISSION SPECTROGRAPH DATA OF VOLCANIC UNITS.

Sample	ALPHAS/mg/hr	%sd	%K	%sd	Cr	Cu	Mg	Ca
Atascosa Mts. basalt 1 Bottom	0.559	7.86	1.04[1]	7.10	28	40	62	64
Atascosa Mts. basalt 2 Bottom	0.558	7.99	0.963	6.46				
Atascosa Mts. basalt 3 Bottom	0.668	7.40	1.11	6.40				
Atascosa Mts. basalt 1 Top	0.530	8.36	1.00	6.28				
Atascosa Mts. basalt 2 Top	0.633	7.76	1.07	4.99				
Atascosa Mts. basalt 3 Top	0.547	8.38	0.917	6.63				
Santa Rita Mts. basalt	1.05	6.75	1.66	5.53	48	44	72	63
Tucson Mts. basalt Composite	2.18	5.74	2.85	3.52	13	37	46	52
Tucson Mts. basalt Top	1.97	6.50	3.22	3.03	27	38	64	67
Atascosa Mts. upper andesite	3.29	5.64	3.68	4.98	00	35	66	70
Sycamore andesite	4.88	6.24	3.87	4.46	00	36	45	46
Santa Rita Mts. upper andesite	2.00	5.88	2.54	4.74	00	41	66	64
Short's Ranch andesite	1.34	6.07	3.26	5.02	00	37	57	60
Sycamore spherulitic rhyolite	7.40	5.77	4.32	5.80	00	12	45	50
Quartz latite porphyry	3.57	5.60	3.91	4.48	00	21	49	52
Biotite rhyolite	2.22	6.36	3.89	2.76	00	18	49	56
Atascosa Mts. tuff	4.64	6.32	4.64	5.42	00	24	56	55
Santa Rita Mts. tuff	2.90	6.41	3.90	5.35	00	32	60	59
Safford tuff	2.76	6.50	2.84	6.13	00	34	61	64
Montana Pk. fm. 1 Bottom	2.02	6.35	2.92	4.94				
Montana Pk. fm. 2 Bottom	1.70	6.34	2.00	4.02				
Montana Pk. fm. 3 Bottom	1.31	6.19	2.40	5.94				
Montana Pk. fm. 1 Top	1.58	6.70	2.77	5.06				
Montana Pk. fm. 2 Top	7.06	6.20	5.14	5.92	00	26	42	41
Montana Pk. fm. 3 Top	2.92	6.08	2.01	6.45				
Santa Rita Mts. rhyolite	3.66	6.10	2.97	3.65	00	35	56	52
Mustang Mts. rhyolite	2.66	6.50	8.02	1.78	00	10	53	51
Cat Mountain rhyolite	2.33	5.65	4.24[2]	5.07	00	22	54	51
Ruby Road fm.	1.52	6.64	3.12	4.31	00	32	57	58
Santa Rita Mts. older andesite	1.55	6.19	2.62	3.26	00	28	48	44
Santa Rita Mts. older latite	1.81	6.68	5.68	1.81	00	10	66	67
Tucson Mts. older andesite	1.52	6.56	3.43	4.24	00	37	57	66
Pajarito lavas	3.84	6.38	4.84	3.27	00	05	50	57
Santa Rita Mts. Cret. andesite	1.59	6.54	2.62	6.14	00	45	69	79
Tucson Mts. Cret. andesite	1.09	7.19	3.29	3.58	00	13	61	73
Columbia River basalt	0.4916	?	1.07	5.94	10	48	80	82

1. 0.98% by flame photometry
2. 4.41% by flame photometry