GEOCHEMICAL INVESTIGATION OF THE DEL BAC HILLS VOLCANICS, PIMA COUNTY, ARIZONA

by

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ABSTRACT

The Del Bac Hills are a northeast-trending chain composed of mid-Tertiary Turkey Track porphyry dikes and flows, overlain by potassic basaltic andesites intercalated with sediments. These hills are considered the southernmost extension of the Tucson Mountains and lie along a northeast-trending basement scarp which extends across the Tucson Basin. Turkey Track porphyry intrudes the San Xavier conglomerate as two parallel dikes, closely associated in time but with different magnetic orientations. Potassium-argon dating of a flow associated with the older dike yielded a mean of 26.8 m.y. for plagioclase phenocrysts and groundmass. Plagioclase of the younger dike sampled 50 feet from the contact with the San Xavier conglomerate and at a depth of approximately 200 feet yielded an anomalous age of 46.4 m.y., representing 0.29 x 10^{-10} moles per gram excess Ar^{40} in comparison with the extrusive. The 21 basaltic andesite flows are essentially contemporaneous at 24-25 m.y. Tight grouping of K/Rb and Rb/Sr for the basaltic andesites confirms the field inference of two separate sources. Specific gravity and initial Sr^{87}/Sr^{86}

determinations for the porphyry and basaltic andesites do not preclude a comagmatic origin for the two rock types. Post-extrusive faulting along three principal directions has established the present configuration of the hills.

INTRODUCTION

The Del Bac Hills, located on the San Xavier Indian Reservation approximately 10 miles southwest of Tucson, are of interest as an example of mid-Tertiary volcanic rocks common in southeastern Arizona. These hills are regarded geologically as the southernmost extension of the Tucson Mountains but structurally appear to form a portion of a northeast trend which segments the Tucson Basin and separates the Tucson and Sierrita Mountains. Lithologies of the area are similar to those in the upper part of the Tertiary sequence exposed in the Sentinel Peak ("A" Mountain)-Tumamoc Hill area.

REGIONAL SETTING

The Del Bac Hills form a physiographic unit approximately 7 miles long and were recognized by Ganus (1965) as part of a regional northeast structural trend. Ganus based the definition of this trend on the interpretation of water table contour maps and on the structurally high occurrence of sediments of probable Pantano age in deep wells south of Tucson along the belt formed by the Del Bac Hills, Twin Hills, and Redington Pass between the Santa Catalina and Rincon Mountains. Turkey Track porphyry is exposed both in the Del Bac and Twin Hills. Gravity and magnetic surveys (Sumner, 1965; Davis, 1967) have revealed that this trend marks a probable basement scarp extending from the Avra Valley to Twin Hills. North of this trend alluvial deposits are approximately 3,000 feet thick and south of it the same deposits exceed 5,000 feet in thickness. Basin sediments encountered in wells of the central basin south of the trend are much finer than similar sediments north of the trend (Davis, 1967).

Sherman and Hatheway (1964) observed "linears," trending N 50° W and N 10° W, on aerial photographs of the

Tucson Basin and suggested that these features were caused by faulting or differential compaction of upper aquifer sediments. Davis (1967) pointed out that the linears overlie the basement scarp as defined by geophysical investigation. Similar prominent features trending N 45-60° W are seen on aerial photographs of the area immediately southeast of Black Mountain in the Del Bac Hills, cross-cutting primarily northeast drainage, and can be correlated with structural features in the area (Figure 1).

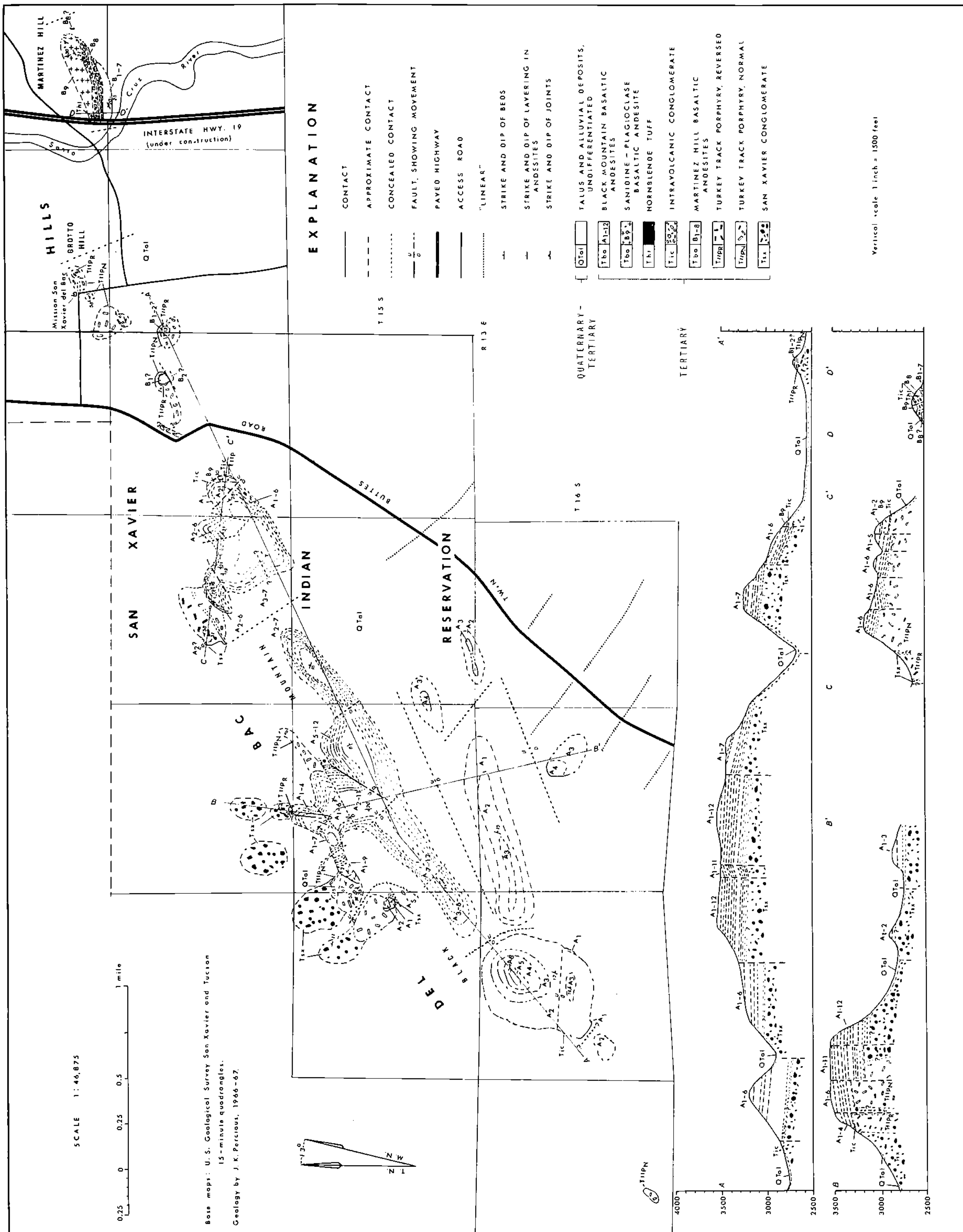

Figure 1. Geologic map and cross sections of the
Del Bac Hills, Pima County, Arizona

ROCK UNITS

Rocks cropping out in the Del Bac Hills were described by Heindl (1959) as consisting of basalt and andesite, andesite porphyry, speckled rhyolite, and conglomerate, probably a Pantano equivalent, which he termed the San Xavier conglomerate. The conglomerate will not be described here. Volcanic rocks of the Del Bac Hills are of two principal types, Turkey Track porphyry (Cooper, 1961) and potassic basaltic andesites (Halva, 1961), both chemically unusual rocks which are widespread in southeastern Arizona. The limits of the area in which rocks of this age and type are found have not been established and they may prove to be quite extensive. On a regional scale, Turkey Track porphyry forms the base of a sequence of basaltic andesites when the two rock types are found in juxtaposition (Halva, 1961). This association lead Mielke (1964) to postulate that the two rock types may be products of gravitational differentiation within a magmatic source.

The units studied in this investigation are shown in Figures 1 and 2.

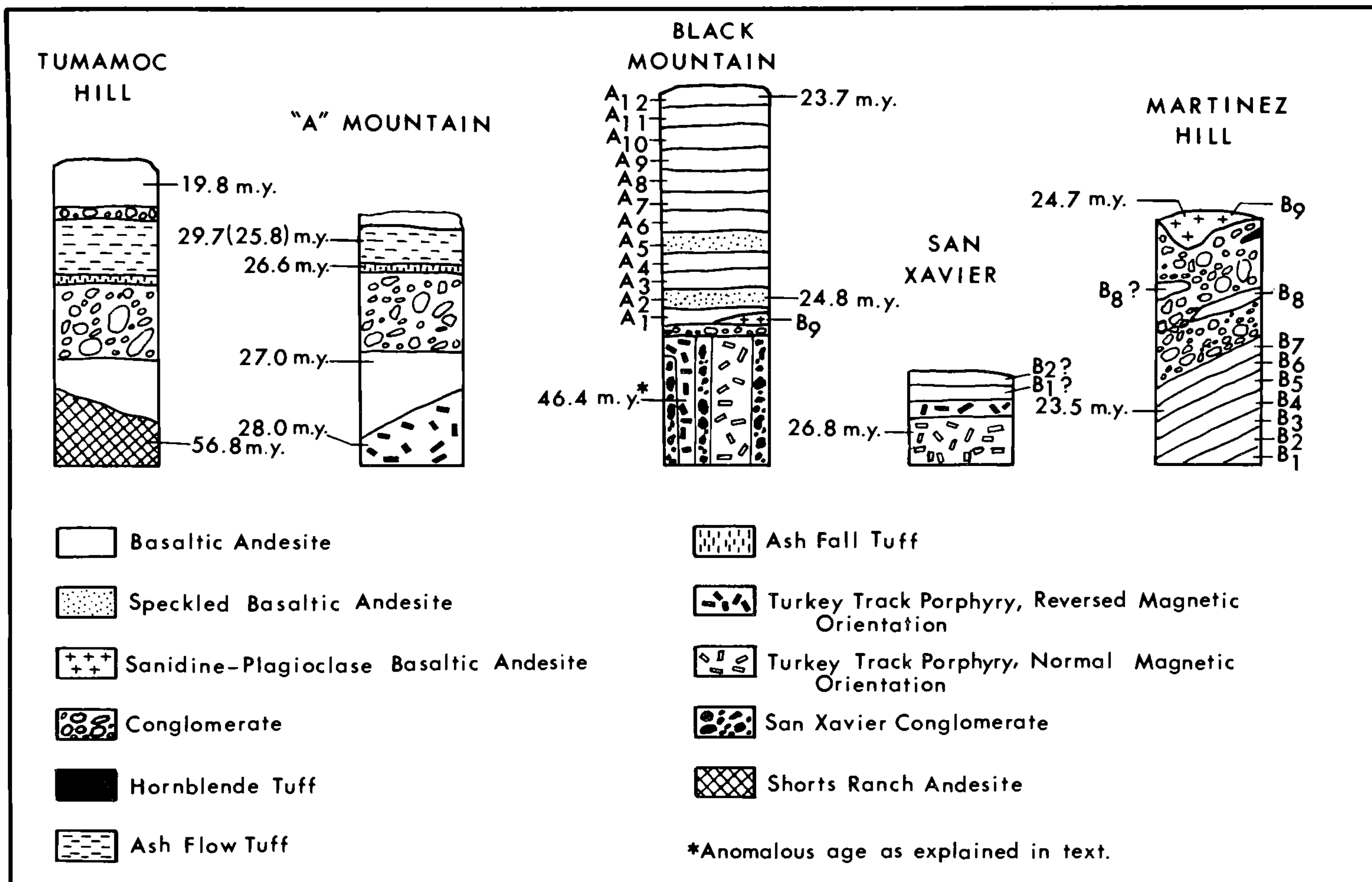

Figure 2. Schematic northwest-southeast stratigraphic sections of the Del Bac Hills and "A" Mountain-Tumamoc Hill area, with apparent ages as determined by potassium-argon dating

Turkey Track Porphyry

At least two approximately parallel dikes of Turkey Track porphyry are present in the Del Bac Hills. These dikes appear as scattered outcrops which probably were originally continuous. The south dike seems to be the older of the two and has normal magnetic orientation. Its outcrop is approximately 1/3 mile wide and 4 miles long. The north dike has reversed magnetic orientation and is approximately 400 feet wide and 1½ miles long. Near San Xavier Mission a Turkey Track porphyry flow of reversed magnetic orientation overlies the porphyry of normal magnetic orientation. Both dikes entered along the strike of the San Xavier conglomerate, probably a Pantano equivalent, which dips 15-35° NW. The south dike is highly weathered and iron-stained, giving it a characteristic yellow to red-brown appearance. The north dike is in general a much fresher appearing rock but also contains strongly weathered areas. Phenocrysts of plagioclase up to 1½ inches in length and of pyroxene ¼ inch in length are typical of both intrusive and extrusive phases. Joints trending parallel to the lengths of the dikes, roughly N 65° E, and dipping predominantly 60-70° SE are well developed in both dikes; joints of this strike dipping 50-60° NW are less well developed. Northwest-trending joints dipping steeply to the northeast and southwest are also common. Joints trending north-south and approximately east-west are present. Small quartz crystals commonly coat joints of the porphyry.

Structural adjustment along the south contact of the north dike is suggested by the stressed nature of a 2- to 8-inch wide zone of brown glass rimmed by calcite crystals, exposed in the NE¼, SW¼ of Sec. 29, T. 15 S, R. 13 E. The south dike also shows evidence of deformation in its southeastern half. Strongly sheared feldspars and needles of ferruginous material forming irregularly shaped zones several feet in diameter are interspersed in the dike with pods of normally porphyritic Turkey Track of similar dimensions. In some exposures the sheared material forms the matrix of the porphyry. The shearing is tentatively considered to be autoclastic in origin because well-defined zones of movement are absent. The pods of porphyritic rock may represent post-intrusion settling of stray phenocrysts from the overlying liquid.

Petrographically the dikes and associated flows vary somewhat in mineralogy but considerably in texture. Phenocrysts of plagioclase, orthopyroxene, and clinopyroxene occur in a groundmass of plagioclase and pyroxene; olivine is major to accessory; small crystals of magnetite are abundant; quartz is minor. A vesicular, strongly oxidized flow associated with the south dike, exposed on the two small hills southwest of San Xavier Mission in Sec. 27 and 28 of T. 15 S, R. 13 E, exhibits unzoned plagioclase phenocrysts 1/2 to 3/4 inches in length in a matrix of pyroxene and plagioclase microlites. Phenocrysts and prismatic minerals of the groundmass are strongly oriented N 12-20° W, perpendicularly to the dike trend. The interior of the south dike contains up to 90 modal percent plagioclase phenocrysts, commonly zoned. Within a few feet of the dike walls these phenocrysts are smaller and less abundant, about 20 percent, and are fairly well oriented parallel to the trend of the dike. The orientation suggests that the fissure along which the dike was emplaced was not opened by NW-SE tensional forces but by movement along the N 60-70° E trend, as indicated by Heindl (1959). The lower unit of Grotto Hill is not clearly extrusive, but is gradational with the south dike; its phenocrysts are oriented both parallel to the dike walls and N 30-40° W. The groundmass of this unit consists largely of small, untwinned subhedral equigranular plagioclase with some laths.

The north dike contains a lower percentage of phenocrysts than the south dike, approximately 50 percent, and in it plagioclase phenocrysts are oriented N 30° E and N 10° E, oblique to the dike walls. Within a distance of a few feet from the dike walls the phenocrysts are smaller and less abundant and are fairly well oriented parallel to the dike walls. The upper porphyry unit of Grotto Hill contains phenocrysts of plagioclase with preferred orientation in the N 30° E and N 10° W directions. A flow or sill which is continuous with the north dike and which caps the San Xavier conglomerate on the north end of Black Mountain contains phenocrysts oriented principally N 40-50° W, roughly perpendicularly to the N 30° E trend of plagioclase phenocrysts in the dike. This flow and the upper unit of Grotto Hill both contain phenocrysts showing reaction with the groundmass; the phenocrysts occur in a matrix of predominantly subhedral equigranular plagioclase grains but with some laths. The deviation from parallelism of prismatic grains with the dike walls may have been the result of shearing stresses operating at the time of emplacement or may reflect disorder resulting from flow concentration of phenocrysts as described by Simkin (1967). Planar orientation of mineral grains is not well developed in the porphyry.

There is good correlation of the degree of preferred orientation of plagioclase phenocrysts with the apparent fluidity of the magma as determined petrographically. Slow cooling and minimal departure from equilibrium with the magma are implied by the size and homogeneity of phenocrysts in the extrusive phases of the porphyry. The flow associated with the south dike was probably rather viscous, whereas the flow or sill associated with the north dike seems to have been relatively fluid. The small outcrop of Turkey Track porphyry in Sec. 2, T. 16 S, R. 12 E appears to be very shallow or extrusive and associated with the south dike.

As first suggested by Tolman (1909) there is cogent evidence that the Turkey Track porphyry formed in two stages, first developing large plagioclase crystals in a closed reservoir and later extruding as a porphyritic lava. The most compelling support for this premise is the occurrence of plagioclase phenocrysts 1/4 inch or more in length at the contacts of the dikes with the San Xavier conglomerate. The presence of fractured plagioclase phenocrysts with groundmass in the fractures also supports the theory. Ferromagnesian minerals rarely exhibit this relationship to the groundmass. Olivine is generally more abundant in the extrusive phases than in the dikes; a comparison of the proportions of ortho- and clinopyroxenes in the various bodies will require additional investigation.

The apparent ages of rocks dated by the potassium-argon method in this study are shown in Table 1. JKP-1-67 is a sample of the north dike taken approximately 30 feet from the south wall of the dike. It is not possible to specify the depth in the dike at which this sample was taken but it is reasonable to assume that it represents a depth of approximately 200 feet. JKP-9-67 is a sample of the most typically extrusive phase of the porphyry and is associated with the south dike. The nature of the contact between older and younger porphyry units suggests that little time elapsed between their extrusion. Assuming that the two units were emplaced approximately contemporaneously, the anomalous 46.4 m.y. date for the north dike is explained if the plagioclase of this sample contains about 0.29×10^{-10} moles per gram of excess Ar^{40}. The phenomenon of excess radiogenic argon is well known and has been observed in low-potassium minerals of most igneous and metamorphic environments. Livingston _et al_. (1967) obtained values of 0.14×10^{-10} to 0.35×10^{-10} moles per gram excess Ar^{40} in plutonic, pegmatitic, and metamorphic plagioclases of Paleozoic and Tertiary ages. Damon, Laughlin, and Percious (1967) detected

TABLE 1. Potassium-Argon Ages of Volcanic Rocks of the Del Bac Hills

Sample No.	Mineral or Rock	Radiogenic Ar^{40} x 10^{-10} m/g	Atmospheric Ar^{40}, %	K, %	Apparent Age, m.y.
JKP-1-67	Turkey Track, north dike, plagioclase	0.669	47.7	0.802	46.4 $\pm$ 1.4
JKP-9-67	Turkey Track, flow, plagioclase	0.360	33.8	0.765	26.3 $\pm$ 0.8
JKP-9-67	Turkey Track, flow, plagioclase, HF leached and insonated	0.374	33.5	0.765	27.3 $\pm$ 0.8
JKP-9-67	Groundmass, magnetic fraction removed	1.60	26.8	3.86	26.9 $\pm$ 0.8
JKP-10-67	Basaltic andesite (B_6), Martinez Hill, whole rock	0.837	39.2	1.99	23.5 $\pm$ 0.7
JKP-68-66	Sanidine-plagioclase, basaltic andesite (B_9), whole rock, no phenocrysts	0.876	38.7	1.99	24.7 $\pm$ 0.7
JKP-49-66	Basaltic andesite, speckled (A_2), whole rock	0.892	32.8	2.01	24.8 $\pm$ 0.7
JKP-50-66	Basaltic andesite (A_{12}), whole rock	1.05	58.6	2.48	23.7 $\pm$ 1.0

1.2 x 10^{-12} moles per gram excess radiogenic argon in plagioclase phenocrysts of a small Pliocene camptonite dike, and 2.5 x 10^{-12} moles per gram excess Ar^{40} in plagioclase phenocrysts of a porphyritic Pliocene basalt. Laughlin (1966) reported 0.19 x 10^{-10} to 0.57 x 10^{-10} moles per gram excess Ar^{40} in albites from the Amelia, Virginia, pegmatites. The value of 0.29 x 10^{-10} moles per gram excess Ar^{40} obtained in the present study is thus typical of plutonic plagioclase and suggests that the phenocrysts of the dike cooled under closed system conditions which prevented diffusional degassing. No Ar^{40} excess was detected in plagioclase phenocrysts of the extrusive phase if the groundmass age is taken as a minimum, i.e., the Ar^{40} excess is less than 0.21 x 10^{-11} moles per gram, based on the error in determination of 0.8 m.y. and a 2-sigma criterion.

Tolman (1909) suggested that the source of the Turkey Track porphyry flow at "A" Mountain, dated at 28.0 ± 2.6 m.y. (Bikerman and Damon, 1966), appeared to be to the south. As the upper Turkey Track porphyry flow and north dike at San Xavier have the same magnetic orientation as the flow at "A" Mountain, and statistically the potassium-argon dates permit the correlation, the possibility that the "A" Mountain Turkey Track porphyry originated as far as 7 miles to the south cannot be excluded. The upper porphyry flow at San Xavier thins southward, implying a source north of the mission and Grotto Hill, which would be fulfilled by the northeast extension of the north dike at Black Mountain.

Basaltic Andesites

Rocks which have the general appearance of basalts but which have relatively high alkali metal and silica contents were described by Halva (1961) as occurring in many localities in southeastern Arizona, including the Del Bac Hills. These rocks cap the upper flow of Turkey Track porphyry near San Xavier Mission; at Black Mountain they overlie a thin colluvial deposit formed on top of the Turkey Track porphyry; at Martinez Hill they are intercalated with similar colluvium containing abundant Turkey Track porphyry fragments, some units having flowed into channels of the conglomerate. The stratigraphic sections of these areas and of the "A" Mountain-Tumamoc Hill area are shown schematically in northwest-southeast section in Figure 2.

The petrologic and chemical similarity of these basaltic andesite flows hinders correlation and mapping of individual flows. Halva (1961) noted the chemical variability within a single flow of basaltic andesite at Tumamoc

Hill; in view of the chemical similarity of different flows within a series, a geochemical "fingerprinting" of individual flows may not be possible.

In general flows of basaltic andesite cropping out in the Del Bac Hills are thin, less than 20 feet, but locally thicknesses of 75 to 100 feet are encountered. Three units, A2, A5, and B9, have distinctive appearances in the hand specimen. Flows A2 and A5 are lighter colored than the average basaltic andesite and have a speckled appearance produced by small dots of opaque minerals in a matrix of feldspar laths. The lighter color owes its origin to the fact that the average size of feldspar laths is two to three times that of the typical basaltic andesite. Flow A5 is in general somewhat lighter in color than A2. Flow B9 is a porphyritic basaltic andesite with plagioclase, sanidine and quartz phenocrysts which crops out both at the top of Martinez Hill and at the northeast end of Black Mountain. The plagioclase phenocrysts are deeply corroded and rimmed by pyroxene; the sanidine phenocrysts are strongly resorbed and may have rounded, rectangular, or pseudohexagonal outlines as well as the normal crystal morphology. The phenocrysts typically contain one or two large dark inclusions of glass or pyroxene. Phenocryst abundance increases upward in the

Martinez Hill outcrop. Chemically, the rock is indistinguishable from other basaltic andesites of the Martinez Hill (B) series. This porphyritic unit is presumably the rock described by Guild (1905) as a "rare quartz basalt." Flows A_3 and A_4 appear minutely porphyritic in the hand specimen and are useful in correlation when exposed in contact with either of the speckled basaltic andesites.

Age relations deduced from field relations have in general been borne out by radiometric dating (Table 1). Extrusion of these flows was essentially isochronous, and the standard deviation of the basaltic andesite dates in Table 1 is approximately equivalent to the analytical error.

The older basaltic andesites (B series) are characterized by K/Rb values of approximately 350 and Rb/Sr values of approximately 0.08, while flows of the Black Mountain (A) series have typical K/Rb values of about 260 and typical Rb/Sr values of about 0.15 (Table 2). This chemical grouping as well as geologic evidence implies separate sources for the two series. Based on their K/Rb and Rb/Sr values, the two basaltic andesite flows exposed on the small hills southwest of San Xavier Mission belong to the B series. These two flows are similar in texture to the two stratigraphically lowest flows (B_1 and B_2) exposed at Martinez Hill and are tentatively correlated with them.

No evidence was obtained for vents under the present outcrops. Gradations in thickness suggest a source south or southeast of Black Mountain and one south or east of Martinez Hill. A very small outcrop of hornblende tuff within the sediments at Martinez Hill thins and disappears northward; clearly its source was southward.

Flows of the Black Mountain series strike northwest and dip 5-20° northeast. At San Xavier, the two basaltic andesite flows strike northeast and dip 13° northward. At Martinez Hill the intravolcanic sediments dip 12° N on the north side of a northeast-trending fault, while south of the fault sediments and flows strike N 50-60° E and dip 20-25° NW. Very similar sediments intercalated with basaltic andesites at "A" Mountain dip gently northward.

TABLE 2. K/Rb and Rb/Sr Values for Del Bac Hills Volcanics

Sample No.	Rock or Mineral	K, %	Rb, PPM	Sr, PPM	K/Rb	Rb/Sr
JKP-1-67	Turkey Track, north dike, plagioclase	0.802	7.9	1062.9	1015	.007
JKP-1-67	Turkey Track, north dike, whole rock	2.57	148.1	531.1	174	.279
JKP-74-66	Basaltic andesite B_1 (?)	2.00	62.0	685.0	323	.090
JKP-5-67	B_7	2.18	59.1	655.1	369	.090
JKP-68-66	B_9, no phenocrysts	1.99	53.3	788.1	373	.068
JKP-65-66	B_9, porphyritic	2.35	66.1	674.4	356	.098
JKP-49-66	A_2	2.01	71.8	618.9	284	.116
JKP-26-66	A6	2.32	99.1	558.8	234	.177
JKP-50-66	A_{12}	2.48	92.7	567.8	268	.163

PETROGENESIS

The theory of Mielke (1964) that the Turkey Track porphyry and basaltic andesites may be genetically related, i.e., may have formed within a single magma chamber by means of gravitational separation, is at least not disproved by several sources of information. First, all determinations of initial Sr^{87}/Sr^{86} for the two rock types performed in this laboratory prior to the present study have yielded values near 0.710 (Bikerman, 1965; Damon et al., 1965). The values of initial Sr^{87}/Sr^{86} determined in the present investigation are listed in Table 3. The similarity of these values for the Turkey Track plagioclase and whole rock Turkey Track porphyry suggest that the plagioclase phenocrysts crystallized in approximate isotopic equilibrium with the magma. The four values given in Table 3 are grossly similar but are statistically different. The decrease in initial Sr^{87}/Sr^{86} with decreasing age may imply the progressive evolution of more primitive (less contaminated by crustal material) magma with time, as would be expected if the magma were produced near the base of the crust.

TABLE 3. Strontium Isotopic Data for Del Bac Hills Volcanics

Sample No.	Rock or Mineral	Sr^{87}/Sr^{86} (p)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}(o)
JKP-1-67	Turkey Track, north dike, plagioclase	0.7094	0.022	$.7094 \pm .0001$
JKP-1-67	Turkey Track, north dike, whole rock	0.7094	0.817	$.7091 \pm .0001$
JKP-68-66	Sanidine-plagioclase basaltic andesite (B_9), whole rock, no phenocrysts	0.7078	0.198	$.7077 \pm .0001$
JKP-50-66	Basaltic andesite (A_{12}), whole rock	0.7071	0.478	$.7070 \pm .0001$

The estimate of precision for each value of initial ratio, Sr^{87}/Sr^{86}(o), is based on 0.02 percent standard deviation for the measured ratio, Sr^{87}/Sr^{86} (p); a precision estimate of $\pm$ 3 percent for the K-Ar date; and estimates of $\pm$ 1 percent and $\pm$ 2 percent for the precision of determination of Sr and Rb, respectively, by x-ray fluorescence.

The results of a number of specific gravity determinations on samples of these rocks from the Del Bac Hills suggest that the specific gravity of the Turkey Track porphyry is generally less than or approximately equal to that of the basaltic andesites (Table 4). The density of a molten rock is strongly dependent upon its gas content. Invoking a gravity separation mechanism implicitly excludes strong turbulence and convection, in which case the most highly gas-charged portion of the magma would be located at the top of the magma chamber. Plagioclase phenocrysts formed within such a gas-charged phase would very likely sink. It is curious that we have found no record of extrusives texturally and chronologically intermediate between the porphyry and basaltic andesites, though Halva (1961) demonstrated that the basaltic andesites are composed of low-potassium feldspars in a highly potassic matrix, analogous to the porphyry. If the two rock types formed from a single magma, conditions within the magma chamber must have been drastically altered following extrusion of the porphyry, or else the texture of the porphyry was developed during its migration to the surface, as suggested by Tolman (1909). Possibly heating of the upper crustal rocks as the porphyry crystallized prevented the formation of additional porphyry from the remaining

TABLE 4. Specific Gravity Determinations for Del Bac Hills Volcanics

Sample No.	Rock or Mineral	Sp. G., 22° C.	Mean Sp. G.
JKP-1-67	Turkey Track, north dike, plagioclase	2.669	
JKP-9-67	Turkey Track, flow, plagioclase	2.661	2.665
JKP-1-67	Turkey Track, north dike, whole rock	2.705	---
JKP-9-67	Turkey Track, flow, whole rock	2.706	
		2.709	
		2.719	
		2.715	
		2.714	2.713 ± 0.002
JKP-9-67	Turkey Track, flow, groundmass, magnetic fraction removed	2.688	
		2.698	2.693
JKP-74-66	Basaltic andesite, B_1 (?)	2.702	
		2.683	
		2.666	
		2.698	
		2.689	2.688 ± 0.005
JKP-5-67	B_7	2.766	
JKP-68-66	B_9	2.750	
JKP-49-66	A_2	2.772	
JKP-26-66	A_6	2.698	
JKP-50-66	A_{12}	2.699	
JKP-74-66	B_1 (?)	2.688	2.729 ± 0.014

magma, which was then extruded as basaltic andesite, as suggested by Damon (1967, personal communication). It is also interesting that the only porphyritic basaltic andesite, B_9, was extruded following a hiatus in volcanic activity.

The time variation of K/Rb and Rb/Sr for these volcanic rocks is not unidirectional and thus suggests neither continuous differentiation nor progressive mixing of primitive subcrustal material with the deep crust.

Whatever the genetic relationship between the porphyry and basaltic andesites, the two are closely associated in time and space and are indisputably synorogenic. Although their geotectonic significance is not yet clear, their emplacement would appear to accompany the development of major Basin and Range features in southeastern Arizona. Radiometric dating of these rocks is hampered by the tendency of large phenocrysts to retain excess Ar^{40} and by the tendency of the basaltic andesites to lose Ar^{40} through devitrification of the groundmass and weathering. It is possible that when these problems are completely resolved and more data are available we may find the two rock types even more restricted in time than we now consider them to be.

GEOLOGIC HISTORY AND STRUCTURE

Volcanism in the Del Bac Hills area commenced approximately 27 million years ago as dikes of Turkey Track porphyry broke through the San Xavier conglomerate and spread both as relatively fluid and viscous flows. These flows were soon capped by a sequence of basaltic andesite flows in the area near the present channel of the Santa Cruz River. The Turkey Track porphyry in the west was topographically high and became deeply eroded. A thin conglomerate was deposited on top of the western portion of the porphyry, while a much greater thickness of the same deposit accumulated above the basaltic andesites in the east. Additional volcanism took place in the east during deposition of the conglomerate, culminating in a thick flow of sanidine-quartz-plagioclase basaltic andesite deposited in a stream channel of the conglomerate. This distinctive flow also extended to the extreme northern end of Black Mountain. No record of further volcanism remains in the eastern part of the area. Black Mountain volcanism ensued with the extrusion of cindery material soon after extrusion of the porphyritic basaltic andesite, incorporating fragments of it at the contact at the northeast end of Black Mountain. The composite thickness of basaltic andesites and intercalated sediments in the Del Bac Hills probably exceeds 1,000 feet.

The structural complexity produced by post-extrusive faulting in the Del Bac Hills may be appreciated from a view of the roadcut at the west end of Martinez Hill. No evidence was found for faulting during the emplacement of the volcanic rocks. Following emplacement, faulting occurred along the N 50-60° E, N 35-55° W, and N 10° W - N 10° E directions. The N 60° E trend which established the present configuration of the hills as a narrow chain was probably active first. Faults along this trend have the greatest throw, about 350 feet, and are high-angle normal faults generally downthrown to the south within the outcrops of volcanic rocks. Data from water wells drilled in alluvium adjacent to the hills indicate that the volcanics are present at depths of 200-500 feet. Heindl (1962) discussed ground-water shadows caused by the presence of buried ridges parallel to the trend of the Del Bac Hills and located approximately 2, 5, and 9 miles southeast of the hills. Transverse faults of north trend are approximately vertical and generally have less than 100 feet of throw. Transverse faults in the northwest direction have intermediate throw but some of them appear to have significant heave. The northwest faults seem to be the most recent, apparently offsetting other trends, though this was not demonstrated unequivocally. Transverse faults probably defined the structure upon which the Santa Cruz River is superimposed; the bedrock block present less than 100 feet below the river channel between Grotto Hill and Martinez Hill has been termed the Allison Barrier. Heindl (1962) also described ground-water shadows produced by buried topography near Martinez Hill which can be ascribed to the presence of transverse faults.

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