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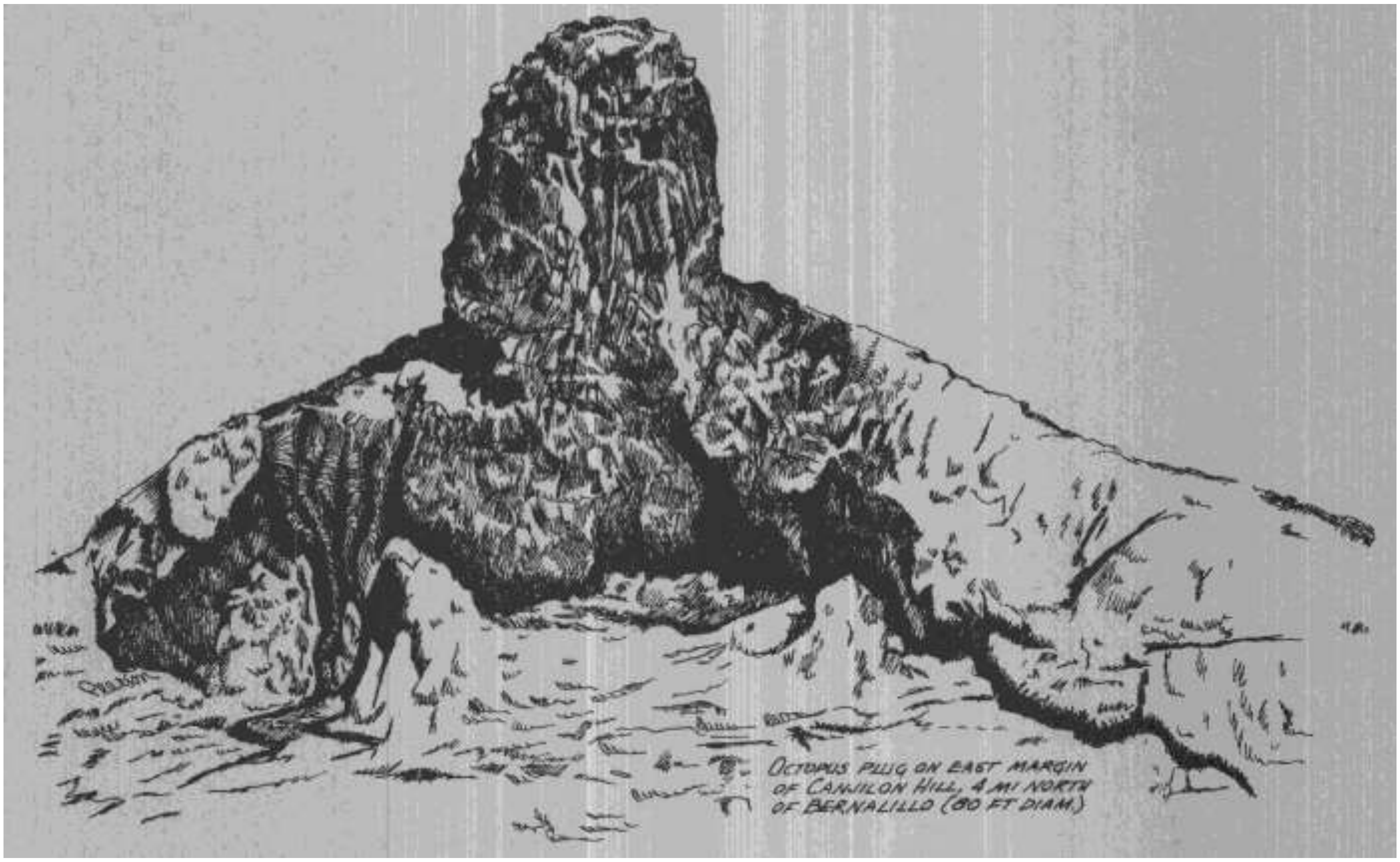

Volcanoes and related basalts of Albuquerque Basin, New Mexico

by V. C. Kelley and A. M. Kudo

New Mexico Bureau of Mines & Mineral Resources

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SOCORRO 1978

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Preface

This paper results from our mutual interest and current work on basalts of the Albuquerque Basin. Much new work is presented on the petrology and chemistry of the rocks (by Kudo) and on field relationships (by Kelley). Kudo's contributions are a part of his study of basalts in New Mexico and other places in the Rockies. Kelley's contribution is an outgrowth of current study of the stratigraphy, structure, and geomorphology of the Albuquerque Basin (Kelley, 1977). Parts of this circular appeared in "Guidebook to Albuquerque Basin of the Rio Grande rift" (Kelley and others, 1976).

We acknowledge the assistance of: 1) John Husler, for chemical analyses of the rocks, 2) James A. Kasten, who mapped Cerro de Los Lunas and Tome Hill for his master's thesis under Kudo's direction, and 3) Jacques R. Renault, for suggestions on improving the manuscript. More detailed studies involving electron microprobe analysis and instrumental neutron activation analysis for trace elements in these volcanic rocks are underway (publication planned) by Kudo and his students. Samples collected for the present investigation are on file in the Department of Geology at the University of New Mexico.

Part of the funding for thin sections and chemical analysis was provided by the New Mexico Energy Resources Board (grant ERB76-264) and U.S. Geological Survey (geothermal grant 14-08-001-G255). Kelley also received support from the University of New Mexico Research Allocations Committee and the New Mexico Bureau of Mines and Mineral Resources.

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Albuquerque
March 15, 1978

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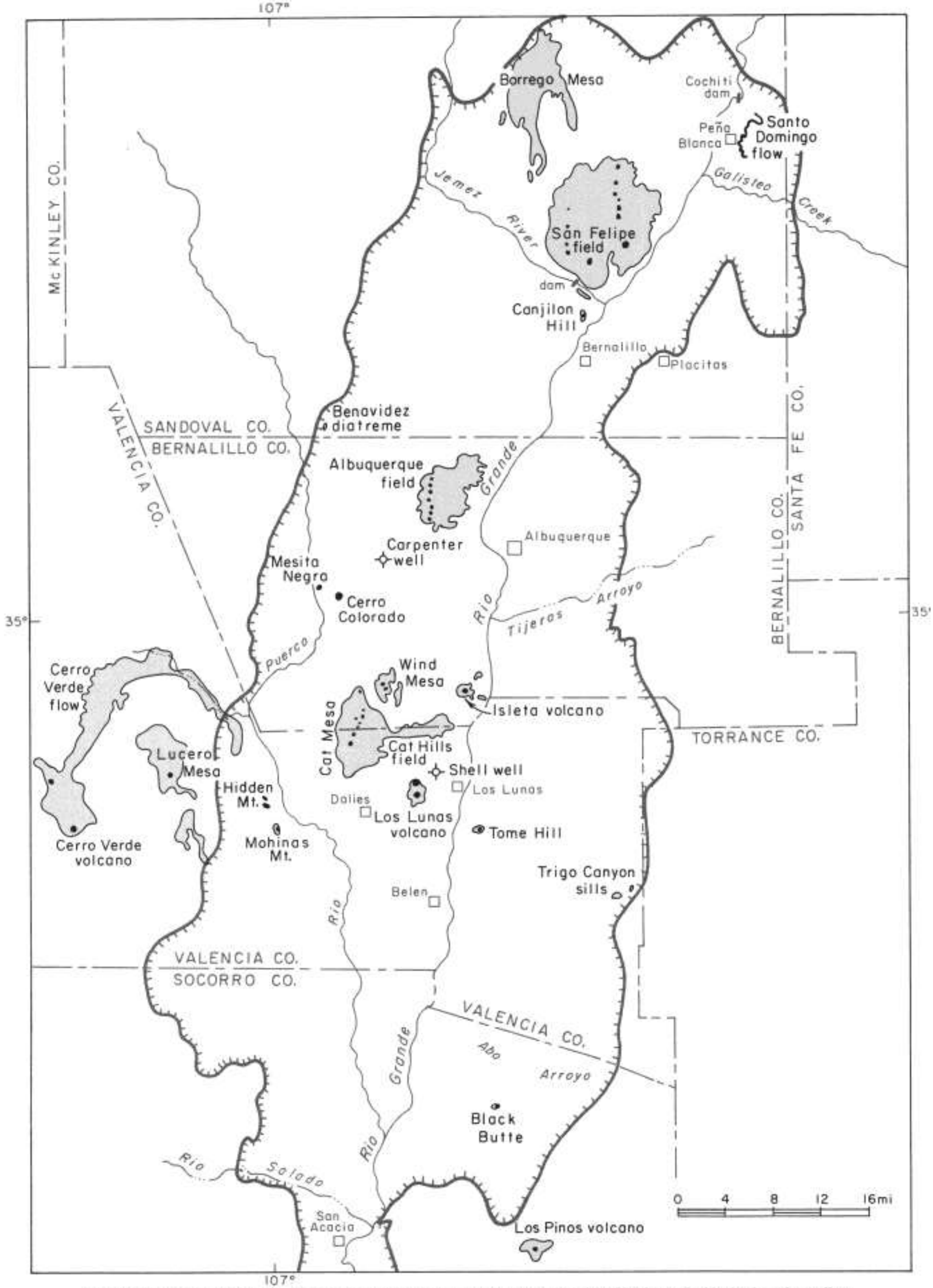

FIGURE 1—LOCATION OF VOLCANIC FEATURES IN THE ALBUQUERQUE BASIN (border of basin marked by hachured gray line; cones and vents located by solid black spots; fields and flows cover light gray areas).

Abstract

During the Pliocene-Pleistocene, numerous eruptions (alkali basaltic, olivine tholeiitic, and minor andesitic) occurred within the Albuquerque Basin of the Rio Grande rift. The principal volcanic fields—San Felipe, Albuquerque, and the Cat Hills-Wind Mesa group—appear to trend about N. 15 ° E., roughly paralleling the axis of the basin. To the west of these fields is a lesser alignment of volcanoes that includes Benevidez diatreme, Mesita Negra, and Mohinas Mountain. Volcanism at Los Lunas, Tome Hill, and Black Butte, all east of the main alignment, is andesitic. Quaternary erosion in the inner valley has exposed a variety of formations and volcanic features. At least 5 or 6 flows and explosive phases are found in many of the volcanic centers. Usually the earliest eruptions are low in viscosity and form widespread fissures. Later eruptions are thicker, are less expansive, have greater surface irregularity, and are restricted to central vents. Many of the eruptions culminate with the formation of cinder cones. The olivine tholeiite at the Albuquerque volcanoes becomes increasingly hypersthene normative with time and has a differentiation trend consistent with the mode of the basalts containing olivine and plagioclase phenocrysts. The olivine tholeiite could have differentiated at depths less than 24 km by settling out of olivine and plagioclase. The alkali basalts at Cat Hills and Isleta must have differentiated at pressures in excess of 8 kb. Modally, the basalts contain olivine and plagioclase phenocrysts with minor augite. The generation of these basalts may be related to the degree of partial melting in the mantle at pressures well in excess of 8 kb. The hypersthene normative lavas that erupted first may have come from mantle partially melted by more than 20 percent whereas the later nepheline normative eruptions tapped mantle less melted. The origin of the andesites in the Albuquerque Basin is uncertain; a shallow origin under hydrous conditions is possible.

Introduction

The Albuquerque Basin (Bryan, 1938, p. 213) is part of the great Rio Grande depression that extends from southern Colorado south through New Mexico into northern Mexico. The basin is one of a number of north-trending intermontane grabens that are roughly axial to the eastern Rockies or Colorado and New Mexico Rockies (Eardley, 1962, p. 399). In the present report the area of the Albuquerque Basin also includes the Santo Domingo Basin (Kelley, 1952, p. 92) and extends from the La Bajada escarpment on the north to the Socorro constriction near the southern ends of the flanking Ladron and Los Pinos Mountains. The area is about 100 mi long (north-south) and 25-30 mi wide (west-east).

Subsidence and filling by continental sediments occurred in late Miocene and Pliocene. Numerous basaltic eruptions accompanied and followed sedimentation, especially in Pliocene and early Pleistocene. However, such eruptions are more numerous outside the Rio Grande depression than in it. Also, such eruptions are more numerous in the parts of the Rio Grande depression north of the Albuquerque Basin.

Approximately a dozen basaltic centers and areas composed of both alkali basalts and olivine tholeiites occur in the basin (fig. 1). Unexpectedly, for the first time, some centers have been determined to be andesite. Most of the centers are lineal, indicating control by structure in trough-filling sediment, older stratigraphic formations, or the Precambrian basement. Some occurrences, although lacking surface volcanic form, appear to represent intrusions in or very near the bases of eroded volcanoes. One or two occurrences are flows that have been covered by basin-fill sediment and subsequently uncovered. A few are dikes and sills.

Six principal areas dominate the picture, in order of size: San Felipe, Cat Hills, Albuquerque, Wind Mesa, Isleta, and Los Lunas. In an effort to determine trends and similarities of eruption and petrology, several flow units have been mapped, sampled, and studied in each area. Although the rocks are predominantly olivine basalt, some progression in petrography and composition is evident through the first to last flow sequences. At each center, the early flows (first two or three) are generally thinner, smoother, or more regular in thickness. The later ones are less expansive, thicker, more irregular, and display more bulging or mounding of their surfaces. Few or no ropy or pahoehoe types are present; likewise, the flows are not blocky or spinose on their surfaces. For the most part the flows are intermediate between as and pahoehoe types. The best preserved surfaces of flows are those in the southern part of the main Cat Hills field where, in successive flow units, slightly different surface patterns appear to result from increasing viscosity.

Numerous cinder cones occur in the Cat Hills, Wind Mesa, San Felipe, and Albuquerque fields. Those of Cat Hills are outstanding in their development and preservation. They consist of scoria cinder or solid ejecta and liquid or pasty spatter bomb ejecta. Most are reddish brown or black; lavender, walnut-brown and other variations are present.

Lucero and Cerro Verde volcanoes, west of the Albuquerque Basin, have sent flows into the western margin of the basin; analyses and descriptions of these rocks are also considered.

North part of basin

San Felipe volcanoes

The San Felipe volcanic field forms the high Santa Ana Mesa north of the confluence of the Jemez River and the Rio Grande (fig. 2 on sheet 1 in pocket; fig. 3). Basal flows of the field are nearly conformable with underlying beds of the Santa Fe Formation. A K-Ar age on one of these flows is 2.5 ± 0.3 m.y. (Bachman and Mehnert, 1978, sample no. 9). The original margin or extent of the flows is eroded in most places. Only in small northwestern and northeastern sectors are the original margins or ends preserved beneath younger sand and gravel. The remaining part of the field covers about 38 sq mi. The area and volume of the eruptions are clearly the largest in the Albuquerque Basin. The mesa stands 220-400 ft above the Rio Grande and Jemez River valleys on the south and east and as much as 1,000 ft above the Jemez River on the southwest. The highest part of San Felipe volcano stands nearly 800 ft above the projected sediments beneath the lava field. The field has been extensively broken by faults. Throws on the faults range up to about 350 ft. Fissure eruptions and alignments of cones also appear to have been controlled by these and similar faults covered by the flows.

As with many volcanic eruptions, several successive events and flow units can be recognized and mapped in the San Felipe field. The earliest flows appear to have had greater fluidity, allowing them to spread more expansively than the later ones. Liquid volcanism was not the first event (Spiegel, 1961, p. 136). A laminated, stratified basalt tuff lies beneath the earliest flow in the eastern part of the field (fig. 4). This deposit is up to about 20 ft thick and is continuous along the east side of the field extending for 9.5 mi from just south of San Felipe Pueblo to well up Borrego Canyon toward the northernmost volcano. Outliers of the tuff with a flow above it occur east of the Rio Grande in the mesa east of San Felipe Pueblo and at La Mesita Butte. The same tuff coupled with an identical flow east of the river strongly supports the correlation of the overlying associated flow with flow 1 west of the river. More important the flow and tuff east of the river are overlain by Santa Fe beds. Spiegel (1961, p. 134) designated the flow and tuff east of the river as Tertiary and, hence, older than the flows across the canyon to the west. However, Bryan (1938, p. 214, fig. 49) thought the Santa Ana mesa flows were in the Santa Fe. Additional outcrops of the tuff occur also in Santa Fe beds north of Borrego Canyon where several lobes of flow 1 terminate. The tuff not only lies beneath the flow but also continues beyond the terminal lobes into the Santa Fe. Gravel and salmon-colored sands lie below and above the flow and tuff horizon.

An inlier of tuff within the flows has been exposed in a small canyon about one mile southeast of the high crater at San Felipe Peak. The exposure may be part of the margin of a tuff ring. Subsidence features similar to those at the Canjilon diatreme are suggested by steeper tuff dips occurring at the inlier. All the exposures along the mesa edge appear to represent air-fall tuff outside or within tuff rings or maars. Tuff is not present along the southern or western exposures of the mesa because these areas were probably too far from the most likely eruption centers and upwind in the prevailing westerly winds during eruptions.

By far the greatest lava eruption has come from the main ridge surmounted at the southern end by San Felipe Peak (elevation 6,434 ft). Buildup of the ridge was accomplished by eruptions from fissures and centers aligned northward. Flow 1 spread farther and wider than subsequent flows. Flow 2 spread widely also but appears to have fallen considerably short of the expanse of flow 1, especially to the south and west. Flow 3

FIGURE 3—AIRVIEW TO EAST ACROSS SOUTH END OF SAN FELIPE VOLCANIC FIELD SHOWING STEP-FAULTED FLOWS IN BASALT-CAPPED MESA (near Santa Ana Pueblo; Jemez River cuts through mesa and joins Rio Grande in middle distance at right; Ortiz Mountains and pediment at far left; entrance to gorge in foreground is now occupied by Jemez dam).

FIGURE 4—San Felipe flow 1 overlying basalt tuff.

forms the backbone of the main ridge. Whereas flows 1 and 2 may have been largely, if not entirely, from fissures, flow 3 appears to have come from several centers and, being more viscous, did not spread as much as flows 1 and 2.

Shortly after eruption from flow 1, three lesser, perhaps satellitic, centers broke through flow 1 on the southeast, southwest, and west. These lesser centers are designated A, B, and C. At the southeast center A, three flow units are mappable; at centers B and C, two units are recognized. Little buildup accompanied these minor centers. Mounding is scarcely discernible at centers B or C; at A, only 150-200 ft can be discerned. The relative ages of flow 2 from the main ridge and flows 1-3 from center A are not clear; they may have been contemporaneous. A small isolated patch identified as flow 2 east of center A underlies flow Al; however, the outlier of flow 2 may have come from center A. If so, then the sequence would have to be determined along the northwest side of center A where flows A2 and A3 abut flow 2 from the main ridge. Along this boundary the evidence is obscure. Two centers occur in the A subfield, but most of the eruption appears to have come from the northern center.

Eruption of center B appears to have come principally from the middle vent of three aligned, closely spaced cones. Eruptions from the C center associated with a cluster of small cinder cones are the largest of the three satellites. The principal problem in this area is the relationship of flow C2 with flow 2 from the main ridge. Because flow 2 in this area is separated from the main field, the identity of flow 2 is uncertain. In fact the similarity of petrography of all the flows makes identification solely on petrography tenuous.

Perhaps the most unusual and interesting eruptions in the San Felipe field are the cinder centers. By normal definition a cinder cone is a conical hill whose slope is at least 10 degrees. Although a few cones along the northern part of the main ridge might meet the slope requirement, most do not. Cinder cones are typically circular patches, low mounds, or slight depressions. Due to erosion, some lack positive relief or depression. In this discussion the cinder centers are divided into cones/mounds with 26 occurring in an eastern area including the main ridge and the A subfield, and 40 in a western area including and extending beyond subfields B and C. Although in places cone distribution could be described as clustered, the dominant arrangement is aligned parallel to, but not along, the numerous faults that disrupt the field. Although the faults are obviously younger than the volcanic eruptions, other older (pre-lava) faults controlled cone alignment. However, these postulated faults did not experience movement at the time of the younger disrupting faults. This reasoning assumes that the centers are post-lava and erupted through the flows. A possible alternative is that the cinder centers existed first and were later engulfed by flow 1—supported by the fact that the centers are mostly subdued, flattish, or depressed. These features stand in marked contrast to the cinder cones of the Albuquerque and Cat Hills fields. Their negative physiographic character is shown in a number of instances but nowhere more clearly than in the cone about one mile south of San Felipe Peak. Here a small canyon has cut the cinder center and exposed the cinders beneath overhanging flow 1. Along the west side in particular, the flow has been tilted upward to some 15 degrees, apparently by bulging action of cinder eruption.

A late origin for the cinder eruptions is favored because of obvious occurrences at Cat Hills and elsewhere, but the negative and subdued forms in the San Felipe field are still a puzzle. When the inter-Santa Fe nature or age of the flows was demonstrated, a possible explanation for the absence of typical cone form presented itself. Because the eruptions occurred on and adjacent to a river plain in a subsiding basin, they were soon crossed by streams. In such an environment, cinder cones soon would have been eroded to lower forms, with ensuing burial; only the bases or considerably subdued forms would have been present by the time of complete burial. As much as several hundred feet of Santa Fe sand and gravel may have covered the San Felipe field by late Santa Fe time.

Another special aspect of the San Felipe cinder eruptions is the common presence of small plugs and dikes—the last phase of the igneous sequence. Some of the cinder centers have small central pluglike fingers and other short dikes. Most striking, however, are ring intrusions, generally concentric with respect to the circular cinder cone. These intrusions are nonvesicular, dense, and aphanitic. Mostly they are banded with inward dips of 20-60°. Thicknesses range up to 50-60 ft. In one cone, two concentric cone sheets have been identified. Owing to the different soil texture of the cinders, the circular patches of little or no relief are readily recognized. In sec. 25, T. 15 N., R. 3 E., one large and several small depressions are occupied by ephemeral lakes. Even though cinders were not found in these depressions, they are believed to be cinder eruptions.

Chemical composition of the San Felipe basalts is shown in table 1. These basalts appear to have modal affinities to alkali olivine basalts but chemically are more akin to the tholeiites of Yoder and Tilley (1962).

Olivine (0.6-9.0 mm) and plagioclase (0.5-1.5 mm) are the dominant phenocrysts. Augite phenocrysts (0.2-1.0 mm) are more abundant in the younger flows, but lack the brownish color of titaniferous augite typical of alkali basalts. Glomeroporphyritic aggregates of olivine and plagioclase (some as large as 3 mm) are common-

TABLE 1—CHEMICAL COMPOSITION AND MODIFIED CIPW NORMS OF SAN FELIPE BASALTS (sample locations shown in fig. 2).

	Flow 1 (sample 1)	Cone sheet (sample 2)	Cone sheet (sample 3)	Plug (sample 4)
SiO_2	50.58	50.66	50.66	50.56
TiO_2	1.44	1.44	1.45	1.49
Al_2O_3	16.44	15.72	16.75	16.85
Fe_2O_3	4.98	5.74	2.78	5.24
FeO	5.67	4.94	7.38	5.16
MnO	0.16	0.15	0.21	0.19
MgO	6.38	5.74	5.70	5.55
CaO	8.79	9.55	9.00	9.10
Na_2O	3.35	3.37	3.28	3.28
K_2O	0.84	0.94	1.08	0.96
H_2O+	0.67	0.92	1.10	0.72
P_2O_5	0.30	0.28	0.37	0.37
Total	99.60	99.45	99.76	99.47
Ap	0.50	0.60	0.79	0.78
Il	2.09	2.05	2.06	2.12
Or	5.03	5.68	6.49	5.78
Ab	30.52	30.94	29.96	30.03
Ne	—	—	—	—
Mt	5.28	6.14	2.96	5.59
Hm	—	—	—	—
An	27.75	25.56	28.29	28.99
C	—	—	—	—
Q	1.56	2.51	—	2.62
Di	11.72	16.81	11.74	11.68
Hy	15.56	9.72	16.64	12.41
Ol	—	—	1.08	—

as are aggregates of pyroxene, olivine, and plagioclase in the later flows. Pyroxenite inclusions containing subhedral to anhedral augite crystals about 0.2 mm long have been found in flow 1 west of the San Felipe cone and in the cone sheet about two miles southeast of the main San Felipe cone. Flow 1, with the pyroxenite inclusion, has isolated grains of augite in thin section, but the other sections of flow 1 do not contain augite phenocrysts. The composition of the plagioclase phenocrysts, as measured by refractive index measurements, averages about An_{63} by weight with a limited range between An_{65-60}. A systematic change in An content with strati-graphic position of the flow units could not be found. The groundmass of most of the basalts is intergranular with plagioclase, pyroxene, olivine, and opaques.

Chemically, these basalts are hypersthene-normative to slightly quartz-normative with less than about one percent of normative olivine. On the alkali-silica plot (fig. 5), they fall just on the tholeiitic side of the arbitrary dividing lines of Macdonald and Katsura (1964) for the Hawaiian basalts.

Because of the lack of titaniferous augite, the quartz-normative character, and the high normative hypersthene to diopside ratio (Coombs, 1963), these basalts are classified here as olivine tholeiites.

The mapping of the satellitic centers as separate entities from those of the main flows is justified on a petrographic basis. In satellitic center A to the southeast, the plagioclase phenocrysts are more rich in An, about 57 percent by weight. The basalts from satellitic center C appear to have been quenched more quickly than those from the main flows. Brown glass is common in the groundmass, giving rise to intersertal to hyaloophitic textures. Augite phenocrysts are notably absent, and plagioclase phenocrysts are less abundant.

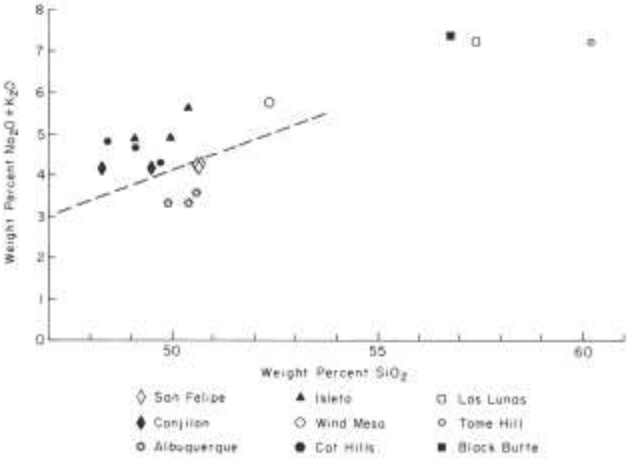

FIGURE 5—PLOT OF ALKALI-SILICA FOR BASALTS AND ANDESITES OF ALBUQUERQUE BASIN.

Canjilon Hill

The Canjilon volcanic center, also referred to as Bernalillo volcano (Herrick, 1898, p. 40; Bryan, 1938, p. 208), rises from the western edge of the Rio Grande floodplain at a point about one mile southwest of the confluence of Jemez Creek with the Rio Grande. This occurrence is an exceptionally well-developed tuff-breccia diatreme, long used by the Geology Department of the University of New Mexico as a plane-table mapping area for field classes. The Canjilon center was also used by Felix E. Mutschler (1956) for a master's thesis.

The diatreme is oval to crudely rhombic in outline (fig. 6, sheet 1; fig. 7), with a long axis of about 4,150 ft oriented N. 5 ° W.; the short axis is about 2,150 ft. This feature intrudes gently dipping, east-tilted Santa Fe sandstone and mudstone. The tuff, breccia, and basalt of the diatreme is more resistant than the surrounding poorly consolidated Santa Fe, causing the feature to stand in relief in an excellent exposure (fig. 7). Highest points are about 200 ft above the adjacent Rio Grande floodplain.

Explosive tuff and breccia dominate; about 250 ft of these rocks is exposed in an overall, centroclinal arrangement in which dips are mostly only up to about 30 degrees. Within and marginal to the basinal tuff-breccia are a number of basalt dikes, sills, flows, and small plugs.

Internally, the diatreme consists of four subcenters, each also composed of centroclinal tephra and flows or sills. Three of these subcenters are aligned along the length of the diatreme. The fourth is a local collapse with basalt plugs and radial dikes in the eastern corner of the diatreme (figs. 8 and 9). The three aligned subcenters of the diatreme consists of: 1) a small circular sag basin at the north end, 2) a central sag and collapse basin with a peripheral cone sheet of basalt, and 3) a southern collapse basin filled with lava flows.

The entire diatreme is but the root or base of a former, much larger tuff ring or maar that most likely based on the same surface as the San Felipe volcanic field just to the north. The San Felipe flow 1 covered the low Canjilon ejecta field. No maar-type beds underlie the basalts of San Felipe at its nearby mesa edges. The lava-lake flows of the southern end of Canjilon are

FIGURE 7—CANJILON HILL (scale, 1 inch to approximately 800 ft; airphoto by Limbaugh Engineers, 1964).

tilted easterly as are the San Felipe lava flows. The slightly lower position of the lake flows, as compared with the San Felipe flows, appears to be due mostly to the subsequent faulting and tilting. However, the lake flows are probably older than San Felipe flow 1 but might have been younger. The K-Ar age of 2.61 ± 0.09 m.y. (Kudo and others, 1977) indicates penecontemporaneous eruption with the basal San Felipe flows having an age of 2.5 ± 0.3 m.y. (Bachman and Mehnert, 1978).

Following the first violent explosive cone or maar development, subsidence, caving, and compaction took place (at the base level represented by the present Canjilon exposures) giving rise to the basins and circular caving surfaces. Some deformation of the partly consolidated tephra by warping, faulting, and jointing occurred during subsidence. Some surficial gravity redeposition of unconsolidated tuff took place in the caving depressions. Late in the process additional small explosions occurred in the lava lake crater and around the small eastern plug.

Based on modal and chemical characteristics shown in table 2 and fig. 5, the basalts of Canjilon Hill are classified as hypersthene-normative alkali olivine. In general, the basalts are very uniform, showing little change with time, both modally and chemically. Phenocrysts (0.6-1.0 mm) of olivine, pale-brown augite, and plagioclase occur in a groundmass of plagioclase, pale-brown augite, olivine, and opaques ranging in size from about 0.1 to 0.5 mm. The groundmass is intergranular, but in places grades into intersertal and diktytaxitic. Some patches of groundmass augite and plagioclase display subophitic texture. The augite is probably titaniferous as suggested by the pale-brown color; chemically, the basalts are rich in alkalis (fig. 5) with a very high normative diopside to hypersthene ratio.

FIGURE 8—OCTOPUS PLUG AT CANJILON HILL (view to west; diameter of plug at top is about 80 ft).

Albuquerque volcanoes

The Albuquerque volcanoes lie 7 mi west of downtown Albuquerque; the 5 large cones of the field form a distinctive western skyline to the city. North-south alignment of cones in the field makes it evident that the

TABLE 2—CHEMICAL COMPOSITION AND MODIFIED CIPW NORMS OF CANJILON BASALTS.

	Octopus plug (sample 4)	Lake flow 1 (sample 5)
SiO_2	48.25	49.46
TiO_2	1.59	1.50
Al_2O_3	17.35	16.53
Fe_2O_3	5.26	2.36
FeO	6.17	8.90
MnO	0.16	0.16
MgO	6.10	6.55
CaO	9.68	9.28
Na_2O	3.56	3.50
K_2O	0.64	0.70
H_2O+	1.03	0.71
P_2O_5	0.22	0.22
Total	100.01	99.87
Ap	0.47	0.45
Il	2.25	2.11
Or	3.83	4.17
Ab	32.40	31.71
Ne	—	—
Mt	5.57	2.49
Hm	—	—
An	29.89	27.59
C	—	—
Q	—	—
Di	13.86	13.97
Hy	4.57	5.03
Ol	7.16	12.48

FIGURE 9—OCTOPUS PLUG AT CANJILON HILL (vertical airphoto).

eruptions rose along fissures. Two alignments and fissure zones are evident: a southern part of four principal cones aligned N. 2° E. and a northern part trending N. 3° E. offset left with respect to the southern part (Kelley, 1974, p. 29-35). Flows from the vents cover an area of about 23 sq mi, mostly to the east of the fissure zone. The eastern edge of the flow field is nearly everywhere eroded; the original expanse, therefore, was greater (possibly much greater).

Several flows can be easily delineated in the field as was first done by Lambert (1968). Eight flows are shown on the geologic map (fig. 10, sheet 1). Flows 1-3 are expansive with respect to the length of the fissure zone, and probably erupted from all along the zone. Later flows 4-6 and an earlier local one identified as 2B came from shorter stretches of the zone or from one or two central vents. The vents shown along the zone are not necessarily all the centers; some small centers that became clogged or dormant in the earlier stages may have been covered by later flows.

At the time of the eruption, dated 0.19 ± 0.04 m.y. (Bachman and Mehnert, 1978, sample no. 11), the fissure zone was either on Ceja Mesa or slightly east of its eastern edge. Little or none of flows 1 and 2 spread westward from the vents, indicating that the Ceja surface sloped toward the east. Most of the flows moved down the alluvial slope from the mesa, concentrating especially in existing broad washes or ravines. Apparently, the Rio Grande may have either cut a shallow valley in the old surface represented by the Ceja Mesa, or the course of the river may have been several miles east of its present position. This latter possibility would have allowed a very low gradient slope from an earlier Ceja edge, especially if the river was again aggrading its course. Broad washes or alluvial slopes probably extended up to the line of fissure eruptions. The eastward projection of several of the lava-capped mesas in fig. 10 suggests the location of the former washes. However, at the height of the spread of flow 1, the lava covered almost the entire slope. Flow 2, although following the ground of flow 1 in much of the area, did find new ground north of flow 1 as shown in the Paradise Hills area where flow 2 lies on Santa Fe gravel.

Flows 1 and 2 are relatively thin (6-20 ft) and relatively smooth on their upper surfaces as compared to the thicker and more hummocky later flows. Thinness, smoothness, and greatest expanse of flows 1 and 2 most likely indicate higher temperature and higher fluidity. Beginning with flow 3, the lava became stiffer and, as a result, could not flow and spread out as readily. The surfaces of the later flows, therefore, became quite hummocky with pressure ridges, mounds, and small knobs.

As a result of the more viscous nature of flow 3, some ridge buildup probably began along the fissure zone, allowing more flow to the west for flows 3 and 4. Flow 4A appears to have come mostly from the fissure between the JA and J cones; unit 4B from the fissure between J and Butte cones; and 4C from the fissure at Vulcan (J). The small lobe 4C east of Vulcan (J) cone could be either later than, or the same time as, 4B. Flows 5 and 6, very small (still later lobes on Vulcan [J] and JA cones), are strictly single or central vent issues. Flow 6 is composed of both cinders and small flows or domes. In this respect most of the Albuquerque cones were low in late explosive activity as compared to the cones in the San Felipe and Cat Hills fields. Cat Hills cones have very little or no lava. The San Felipe cones, although mostly cinder, do have late small dikes, plugs, and possibly small lava tongues. The Albuquerque field has all types, but as at JA and Vulcan (J) cones, considerable late lava is present along with pyroclastics.

Vulcan (J) cone is the highest in the southern alignment, built up about 180 ft above a base on flow 4A. The top, at 6,033 ft, is about 300 ft above the base of the lowest eruption (flow 1) and the top of the Santa Fe or Ceja pediment gravel. Toward the end of the buildup of lava and cinder of the lower part of the cone, a small plug dome rose into the crater and gave the cone its present form. The dome is slightly elliptical with its long axis north-south and has quaquaversal flow structure. The final event was a violent explosion through the center of the dome that split the dome into north-south half-dome remnants. The blasted-out crater is nearly the full width of the dome, leaving little or no east and west rim. Late, short flows issued over the low side rims. Accompanying the emplacement of the dome, and perhaps just prior to the explosion, bulging of the dome by lava from within created semiradial fissures through which small dikes and dribble flows issued along the flanks of the dome (fig. 11).

JA cone consists of three parts: flow 5, flow 6, and a small spatter and cinder cone at the center. This cone appears to have had an even more remarkable late period of bulging and radial cracking accompanied by dike and driblet leakage of the southern cones (Kelley, 1974, p. 31, stereophoto). A few dikes occur also in the cinder cone that stands as a nipple on the bulged upper cone below. The bulging pressure, which gave rise to radial fissures and dikes, probably occurred during or at the end of building of the cinder cone. The final igneous action at the volcano was an explosion in the small cinder cone crater. It blew out the east rim, allowing a chart flaw to rim dawn the eastern flank

FIGURE 11—RADIAL DIKE ON NORTHEAST FLANK OF VULCAN CONE (view is westerly).

Black cone consists of a lower part (flow 5) surmounted by two small cones (flow 6). The lower part consists of black, hummocky, slightly scoriaceous lava and two upper small cinder cones. The larger cone consists of black lava and only minor cinders and spatter. It has a slightly elongate, east-west depression on top of which may be two closely spaced coalescing craters. The other small eruption on Black cone occurs at its northern edge, about 1,000 ft north of the larger pile. Once rich in black cinder and scoriaceous spatter, much of the original conical shape has been destroyed by mining. This cone is almost pure cinder in contrast to the larger southern cone.

The northern aligned segment of eruptive centers consists of 2 small cones, Bond and Butte, in the southern part, and 9 somewhat obscure nubbins, mostly in the northern part of the line. Butte and Bond cones rise 50-60 ft above the field on which they were built. As with the southern Albuquerque cones, an upper, steeper cone rests on a lower gentle mound. The cones consist of lava and cinder and are only about one-quarter the size of the cones at JA and Vulcan volcanoes. Butte's crater is a very shallow pan a few tens of feet in diameter. Bond's vent is only faintly concave at the top; its crater would best be described as filled and vague.

Rocks of flows 1-5 are all olivine basalt, ranging from medium gray in flow 1 to dark gray and black in all succeeding flows. All are vesicular in varying proportions.

Many vesicles are irregular and follow fluidal structures. Dimensions range generally from 1-15 mm. Other vesicles are bubble forms with regular, smooth, and rounded walls. Some have dimensions of several centimeters. Most rocks are at least 80 percent aphanitic, but some parts of flows are fine grained and granular in hand specimen. The most common phenocrysts recognizable in hand specimen are olivine and plagioclase. In some samples, anhedral olivine 1-3 mm in diameter composes more than 10 percent of the rock. Plagioclase occurs in generally elongate phenocrysts ranging from small needle sizes up to 2-3 mm. The plug dome at Vulcan volcano has little or no olivine and contains about 20 percent plagioclase phenocrysts with long dimensions ranging from 1-10 mm. Numerous partially fused inclusions of Santa Fe (?) are found in the basalt and cinders within the cinder pits on the east side of Vulcan and in the northern part of Black cone. These inclusions are gray to frothy glass with partially melted clasts of quartz and feldspar in a matrix of clear glass. Chemically, they are similar to feldspathic sandstone. X-ray diffraction patterns of the glassy inclusions suggest possible existence of cordierite.

The modes and chemical composition of olivine basalts are shown in tables 3 and 4. The basalts are chemically related to olivine tholeiites, but the tholeiitic affinity is not apparent from the petrography.

In general, the basalt contains phenocrysts only of olivine (0.6-1.5 mm) and plagioclase (0.5-2.0 mm) in an intergranular groundmass consisting of plagioclase, olivine, green augite, and opaques. Some systematic changes occur modally and chemically to indicate a differentiation trend typical of olivine tholeiites. Modally, plagioclase phenocrysts increase relative to olivine phenocrysts as the flows get progressively younger. The anorthite content of the plagioclase phenocrysts decreases systematically from the oldest flow 1 with a value of An_{69} to the youngest flow with a value of An_{65}. Chemically, the basalts are hypersthene-normative with almost twice as much normative hypersthene as normative diopside. The normative hypersthene increases from a value of about 18 percent in flow 1 to a value of about 23.5 percent in flow 5. This change is accompanied by a progressive decrease in normative olivine and an increase in normative An/Ab. The basalts plot well into the tholeiitic field on the alkali-silica plot (fig. 5).

TABLE 3—Chemical composition and modified CIPW norms of Albuquerque volcano basalts (sample locations shown in fig. 10).

	Flow 1	Flow 3	Flow 5
SiO_2	50.55	49.88	50.40
TiO_2	1.50	1.38	1.50
Al_2O_3	15.20	15.32	15.65
Fe_2O_3	1.56	3.21	2.47
FeO	8.67	9.92	7.18
MnO	0.17	0.17	0.16
MgO	8.90	9.28	8.55
CaO	8.99	9.28	9.28
Na_2O	2.86	2.78	2.77
K_2O	0.70	0.53	0.55
H_2O+	0.31	0.98	0.54
P_2O_5	0.21	0.22	0.24
Total	99.62	99.95	99.29
Ap	0.44	0.46	0.51
Il	2.10	1.93	2.11
Or	4.15	3.15	3.28
Ab	25.75	25.11	25.11
Ne	—	—	—
Mt	1.64	3.38	2.61
Hm	—	—	—
An	26.66	27.93	28.94
C	—	—	—
Q	—	—	—
Di	13.36	13.55	12.78
Hy	18.16	20.39	23.44
Ol	7.75	4.10	1.23

TABLE 4—Modal compositions (vesicle-free basis) of selected samples of flows from Albuquerque volcanoes, and measured An content of constituent plagioclase phenocrysts (sample locations shown in fig. 10).

	Flow 1	Flow 2	Flow 3	Flow 4	Flow 5
Groundmass	81.2	81.3	82.0	81.4	80.9
Olivine	9.9	9.8	9.1	7.4	7.3
Plagioclase	8.9	8.9	8.9	11.3	12.2
An content	69	69	67	65	65

South part of basin

Isleta volcano

Perhaps most accessible and certainly one of the more interesting eruptive centers is the Isleta volcano (fig. 12 on sheet 1). Bryan (1938, p. 208) referred to the volcano as Acuma Hill. From a distance, this volcano appears to be a simple cone, but closer inspection soon reveals it to be a compound feature consisting of a maar of explosion and subsidence beneath a superimposed cone consisting of several flow units (fig. 13). The Isleta volcano (perhaps erroneously named Perea Mesa on the U.S. Geological Survey Isleta quadrangle) is about 2 mi west of Isleta Pueblo; 1-25 crosses the low eastern edge of the volcano about 13 mi south of Albuquerque. The diameter of exposed portion and cone is about 1-1 1/4 mi. The top attains 5,387 ft in altitude and rises above the projected base about 220 ft on the west and about 440 ft on the east.

Several outlying basalt flows, without an exposed connection to the Isleta volcano, occur to the east. The principal outlier occurs at the top of the tuff, interbedded in overlying late Santa Fe sand and gravel around Black Mesa (termed Paria Mesa by Herrick, 1898, p. 39), about 2 mi northeast of the Isleta cone. This flow, ranging up to 40 ft thick, occupies nearly one square mile; its thickest eroded edge on the east suggests it may have originally extended over a considerable area of what is now the Rio Grande floodplain. Outcrop pinch-out of terminal lobes is evidenced on the west and southwest; the present valley-forming erosion in the central-eastern part of section 10 may have removed a possible original connection to Isleta volcano. Also in the 1-25 roadcuts, erosion channels in the top of the flow suggest the possibility of earlier (Santa Fe) removal of a connection to the volcano. Contrary to the possibility of former direct or surface connection with the cone flows is the fact that the latter are almost completely confined in outcrop to the area inside the arcuate maar subsidence surface. Perhaps the best evidence for a separate source is that composition of the flow precludes an identity with the early flows of Isleta volcano.

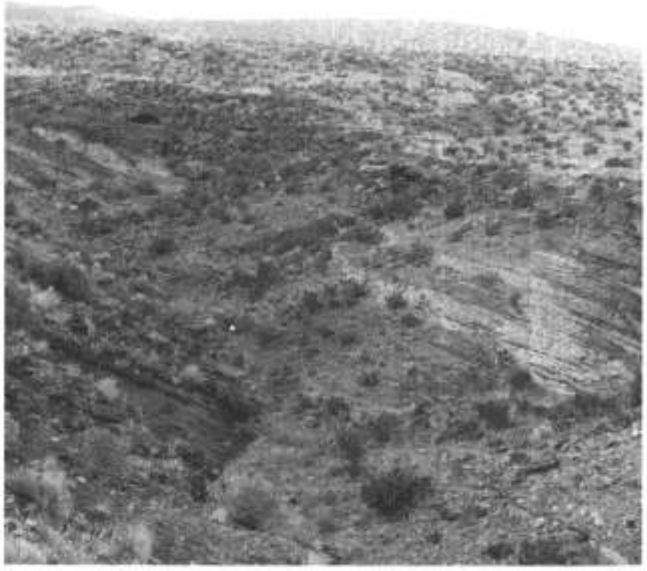

FIGURE 13—DIPPING BASALT TUFF-BRECCIA OF ISLETA VOLCANO (breccia is inside maar and beneath basalt flows; top of Isleta volcano in distant background; collapse ring fissure of east edge is immediately behind viewer).

Isolated flows to the southeast occur on the basaltic Isleta tuff outside the tuff subsidence in the nearby Santa Fe gravel and as a bedrock "island" in the floodplain upon which the Isleta Pueblo was built (fig. 14). On the basis of stratigraphic position, altitude, and composition, all of the flow patches around Black Mesa (east of the Isleta volcano) and at Isleta Pueblo (in section 23) could have come from a common source, the location of which is still uncertain.

The southern circular outcrop west of Coors Road, having considerable reddish-brown cinder associated with a small flow, could be either a small separate eruption satellitic to Isleta volcano or an outlier of tephra, flow 4.

The cliffy edge of the lowermost flows around the east side of the Isleta volcano formed during erosion of the inner valley of the Rio Grande. Highly stratified basaltic tuff-breccia occurs beneath the basalt flows and is interbedded in the surrounding Santa Fe gravel. Herrick (1898, p. 36-37) recognized the volcanic origin of the volcanic gravels and noted that the beds were inclined radially outward from the cone of eruptions. He also noted the large air-fall blocks embedded across the minutely layered tuff beds. After some puzzling over the possible origin, he wrote:

> It would be natural to think of volcanic ash or mud but the materials do not admit to this conclusion. We are shut up to the view that at the time immediately prior to the last eruption of the Isleta crater there was a great out-flow of water from the crater, accompanied by explosive fragmentation of pre-existing lava whose pieces were either intermittently thrown from the crater to be lodged in the pasty mud hurried along by these flows, or caught up in the current and after lodging by their own weight, fine material was settled about them in the process of sedimentation.

Although mentioning some marked unconformities, Herrick did not recognize the continuous subsidence surface around the eastern side of the volcanoes, nor did he recognize the inward-dipping tuff breccia beds within the collapse surface. The concept of detrital flow of tuff, either dry or wet, was probably not considered possible at that time.

Mostly just below the flow ledges, an arcuate, inward-dipping collapse surface forms an almost continuous exposure through about 100 degrees of arc. A possible circular projection of this surface in the sub-crop of the volcano is shown on fig. 12 (sheet 1). Such surfaces are not likely to be a single conical surface but rather an interrupted or somewhat staggered concentric arrangement. The amount of subsidence is unknown. The exposed length of some 7,000 ft is perhaps exceptional. In places, there are small subsidiary sub-parallel slip-off surfaces. Those below the principal surface, in the now-subsiding wall, are probably faults; those

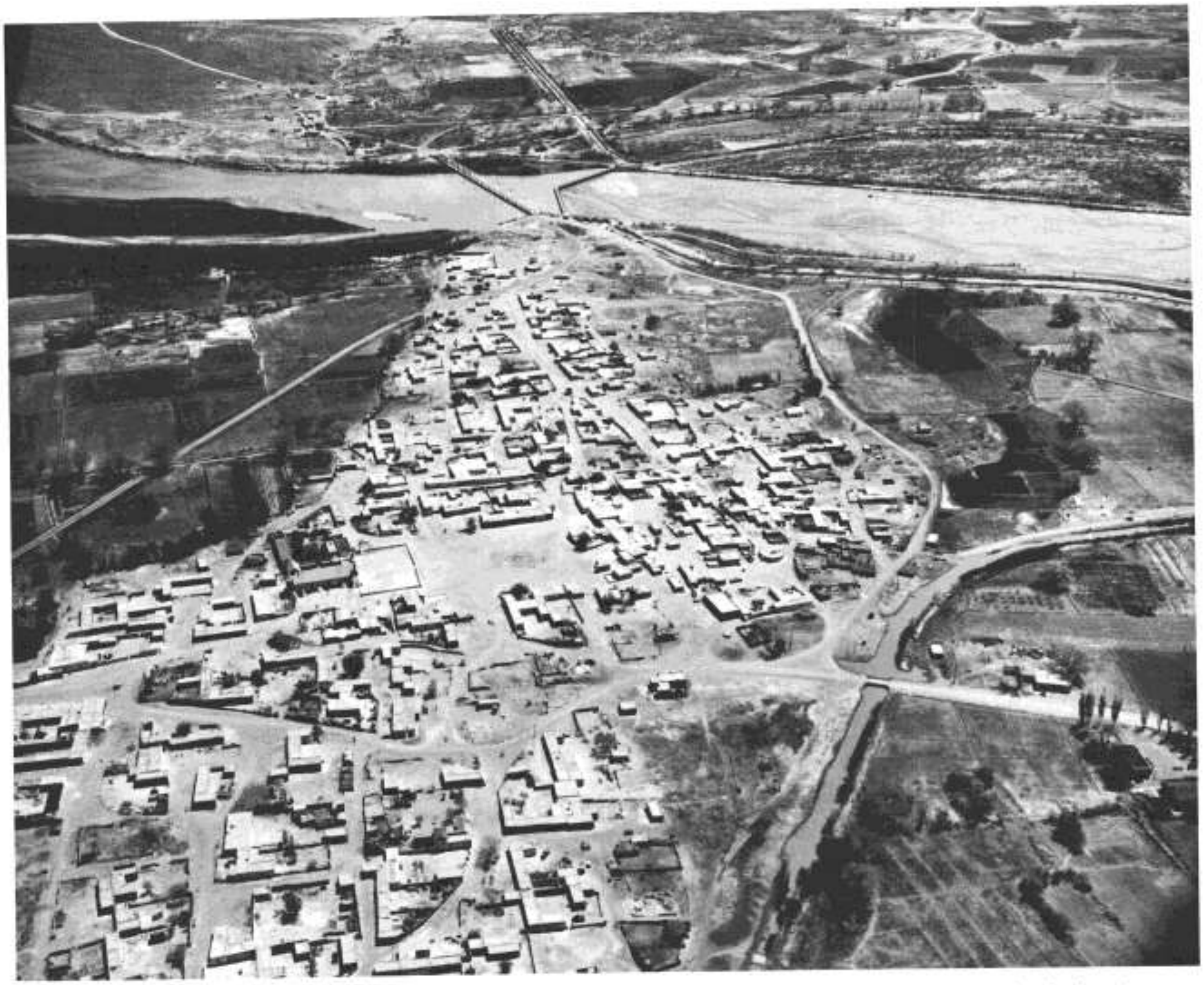

FIGURE 14—Isleta Pueblo circa 1940 (pueblo is built on a basalt "island" in the floodplain of the Rio Grande; view is east).

above the main surface are usually steeper auxiliary slip surfaces that base in the main surface. Dips in the tuff outside the subsidence mass are usually outward and range up to 17 degrees. The main surface of subsidence dips inward at angles between about 22-30 degrees. Stratification above the subsidence surface is usually closely parallel to that surface (fig. 13). In most instances the inside overlying dips are steeper, although opposite, to those on the outside (fig. 15).

All the tuff exhibits thin parallel bedding. Outside the maar the tuff is most likely air fall in origin. Inside the maar some tuff may be air fall. Above the subsidence surface, the tuff may be angle-of-repose material from previously deposited yet unconsolidated air-fall tuff. Much of this flow may have been dry, but at times it may have resembled wet-sand flow.

A thickness of as much as 100-200 ft of flat-lying or gently dipping tuff is exposed outside the maar. On the southeast the tuff is overlain by Santa Fe gravel, perhaps with slight angular unconformity. Along 1-25 northeast of the maar the tuff appears to grade into, or interfinger with, Santa Fe gravel as depicted in fig. 12 (sheet 1).

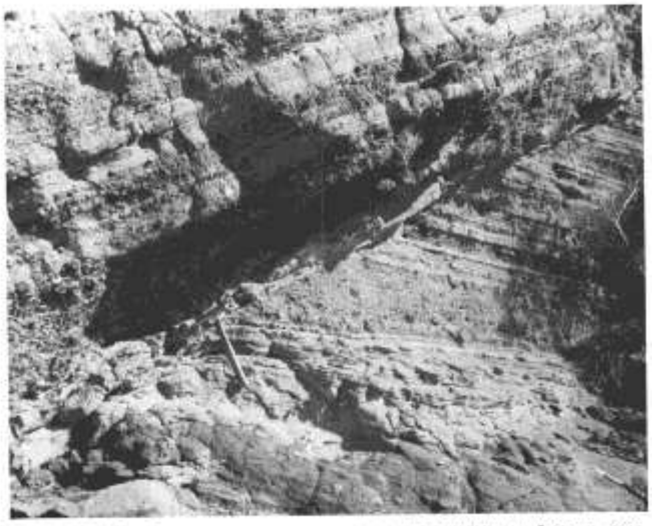

FIGURE 15—Collapse surface "unconformity" at Isleta volcano (inward-dipping maar breccia, above; outside fallout tuff-breccia, beneath).

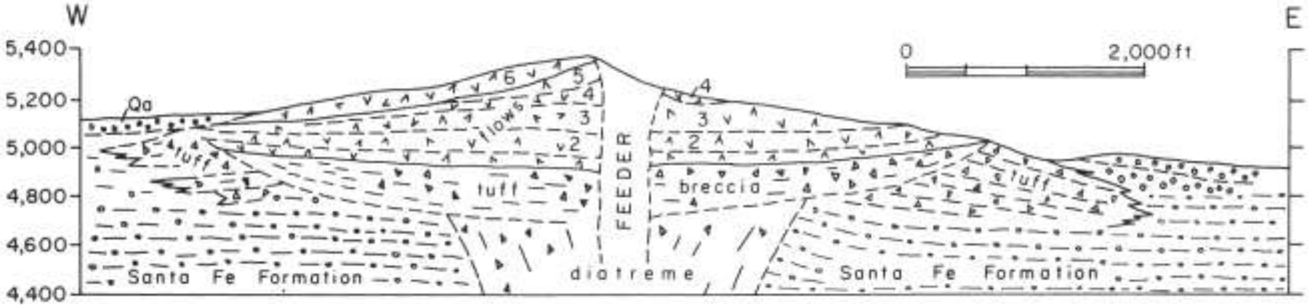

FIGURE 16—Cross section of Isleta volcano (Qa, alluvium).

Six post-maar flow units are delineated in fig. 16. Where exposed, the base of flow 1 appears to incline downward more or less parallel to the dip of the inside tuff beds. Flow 1 and, possibly in part, flow 2 may have been restricted to the maar depression as lava lakes. However, flow 2, as interpreted in the 1-25 roadcut southeast of the volcano, is outside the subsidence and rests on outside tuff near the north end of the roadcut. The K-Ar age of flow 2 is 2.78 ± 0.12 m.y. (Kudo and others, 1977). Flows 1-6 are all interpreted as having erupted from the central area marked by a crude remnant crater just northeast of the summit of the volcano. A cinder cone (flow 4) appears to have developed after flow 3. Flows 5 and 6 are later, perhaps with flow 5 coming from beneath the cone. Flow 6, however, caps the cinder cone as well as flowing principally to the northwest.

Flows 1 and 2 consist of medium-gray to dark-gray, generally finely vesicular, olivine basalt with a scattering of anhedral 1-2 mm olivine grains, some of which display a bluish iridescence. Flows 3 and 5 are likewise olivine basalt but with the general texture appearing slightly coarser and the olivine slightly less in amount. Flow 4 is a pyroclastic scoria bed up to 40-50 ft thick and consists mostly of cinders up to cobble size that are mostly reddish brown but with some black, lavender brown, and tan brown. Flow 4 has been prospected for commercial cinder near the top of the spur south of the summit.

TABLE 5—Chemical composition and modified CIPW norms of Isleta basalts (sample locations shown in fig. 12).

	Flow 1 (sample 1)	Flow 3 (sample 3)	Flow 5 (sample 4)
SiO_2	49.85	50.24	48.97
TiO_2	1.98	2.07	1.84
Al_2O_3	16.40	16.95	16.60
Fe_2O_3	4.03	2.60	3.52
FeO	6.77	6.57	6.64
MnO	0.16	0.15	0.15
MgO	5.96	5.30	6.20
CaO	9.12	8.68	9.68
Na_2O	3.60	3.97	3.60
K_2O	1.31	1.66	1.21
H_2O+	0.54	0.51	1.01
P_2O_5	0.47	0.57	0.43
Total	100.18	99.27	99.85
Ap	0.99	1.20	0.91
Il	2.78	2.91	2.59
Or	7.79	9.91	7.23
Ab	32.56	36.02	32.42
Ne	—	—	0.17
Mt	4.24	2.75	3.72
Hm	—	—	—
An	24.91	23.79	25.87
C	—	—	—
Q	—	—	—
Di	14.06	12.77	15.90
Hy	6.44	0.05	—
Ol	6.23	10.60	11.20

The Isleta basalts have affinities with alkali olivine basalts as evidenced by the petrography, chemistry, and differentiation trend (tables 5 and 6, fig. 5). Unlike the Albuquerque volcanoes, some of the Isleta flows contain green augite phenocrysts with the olivine and plagioclase. Inclusions of wehrlite (generally less than 2 mm long) are found in the younger flow units. Glomeroporphyritic aggregates, some about 4 mm long, of plagioclase and olivine with or without green augite are common. The groundmass is intergranular to pilotaxitic with plagioclase, augite, olivine, and opaques. Some of the groundmass augite has a brownish tint. In the earlier flows, the groundmass minerals are less than 0.1 mm in size; in the later flow the groundmass is somewhat coarser than 0.1 mm.

The plagioclase phenocrysts in flows 1 and 2 have identical composition, both being An_{65}. The plagioclase phenocrysts from flow 3 range in composition between An_{63} and An_{52}, but the plagioclase from flow 5 measures An_{52}. The flow at Black Mesa has a plagioclase composition of An_{52}, suggesting that the Black Mesa flow may not have been connected at all to the main Isleta volcano flows, especially because the only flow (based on the plagioclase phenocrystic composition) that could be related to it is flow 5 which contains augite phenocrysts. The Black Mesa flow does not have any augite phenocrysts.

A differentiation trend is evidenced by the modes and the chemistry. The older flows contain more olivine phenocrysts (as compared with the plagioclase phenocrysts) than do the younger flows. Augite occurs as phenocrysts in the younger flows but is lacking in the older flow units. Chemically, the Isleta flows have more

TABLE 6—Modal compositions (vesicle-free basis) of selected samples of flows from Isleta volcano and measured An content of constituent plagioclase phenocrysts (sample locations shown in fig. 12).

	Flow 1	Flow 2	Flow 3	Flow 5	Black Mesa
Groundmass	78.7	81.6	71.7	82.8	
Olivine	10.7	6.7	3.5	5.8	
Augite	—	—	0.2	0.2	present
Plagioclase	10.6	11.7	24.5	11.3	
An content	65	65	63-52	52	52
Inclusion			0.3		

normative diopside than hypersthene, which decreases and disappears as the flows get progressively nepheline-normative and more undersaturated with time.

Wind Mesa volcano

The volcano of Wind Mesa stands as a low dome near the eastern edge of Ceja Mesa about 6 mi west of the Isleta volcano (fig. 17 on sheet 1). The eruptions, which occur in an area of only about 4 sq mi, are nearly 200 ft thick and appear to consist of several flows of rather uniform character. Complete delineation of the flow pile is prevented owing to disruption of the volcano by north-south block faulting. This faulting consists of a dominating central graben adjoined by a horst on the west and two eastward-tilted blocks on the east. More flows and vents may occur beneath the alluvial-covered surfaces surrounding the horst. Regularity of flows and wide area of thickness suggest classification of the edifice as a small shield volcano.

All the flows consist of dark-gray to black, irregularly vesicular basalt. The groundmass is fine grained with scattered anhedral green olivine phenocrysts up to about 3 mm in diameter, along with smaller pyroxene and plagioclase phenocrysts. Amygdaloidal fillings are rare and consist only of calcite as caliche coatings.

About 10 separated and coalesced, small, circular cinder patches have broken through the flows in the east-central part of the main horsted outcrops. They are generally negative surface exposures 500-1,000 ft in diameter. Occasional small late basalt dikes or fingers cut the cinders. The cinders are predominantly reddish brown and range from granule to cobble in size. Little or no spatter occurs in the cinder.

The Wind Mesa volcano is the first more silicic type to be described here with abundant green augite phenocrysts (tables 7 and 8). One analysis of the oldest flow sampled has a silica content in excess of 52 percent by weight and normative quartz with more normative hypersthene than diopside. Therefore we have classified these rocks as basaltic andesite with possible affinities to the tholeiitic series.

TABLE 7—CHEMICAL COMPOSITION AND MODIFIED CIPW NORM OF WIND MESA BASALTIC ANDESITE (sample locations shown in fig. 17).

	Flow 1 (sample 8)
SiO_2	52.35
TiO_2	1.51
Al_2O_3	16.88
Fe_2O_3	2.86
FeO	4.62
MnO	0.14
MgO	5.45
CaO	8.28
Na_2O	4.04
K_2O	1.73
H_2O+	0.89
P_2O_5	0.69
Total	99.43
Ap	1.44
Il	2.10
Or	10.21
Ab	36.25
Ne	—
Mt	2.99
Hm	—
An	22.82
C	—
Q	0.38
Di	10.99
Hy	12.81
Ol	—

The phenocrysts are generally as large as 1 mm, with augite phenocrysts smaller than the olivine and plagioclase phenocrysts. Glomeroporphyritic aggregates of plagioclase intergrown with augite and of euhedral augite with minor olivine and plagioclase occur commonly. In the youngest flows, pyroxenitic aggregates with opaques become more prevalent. The modal abundance of phenocrystic olivine decreases systematically upward in the flow pile while the ratio of phenocrystic augite to plagioclase and olivine increases. The plagioclase phenocrysts became more sodic in the younger flows, changing from An59 in the oldest flow to below An55 in the youngest flow. In fact, the youngest flow sampled has a range of plagioclase composition between An55 and An,. Apparently Wind Mesa volcanism underwent a differentiation trend toward a more andesitic composition.

Cat Hills volcanoes

The Cat Hills eruptions consist of extensive flows and cones from a north-trending fissure zone (fig. 18). About 26 sq mi of flows remain. Another 2-3 sq mi may have been removed by erosion. The outline of the field is irregular; several long lobes indicate that the dominant flow was in swales on the mesa or long washes down the mesa slope to the east.

Twenty-three cinder cones are aligned slightly east of north in a manner indicating control by fissures, although none is evident at the surface. Seven flows that erupted from these fissures and vents are mapped (fig. 17 on sheet 1). Flows 1 and 2 show wide distribution, therefore probably came from fissures. Flow 1A, which heads in the southern cone, may be an exception. The four flows, numbered 2A through 4, appear to have come either from a single vent or two or more closely spaced vents, especially as suggested by the distribution of flow 4. The latest event was the buildup of the 23 cinder cones, ranging in size from the largest, nearly 500 ft in diameter and 70 ft high (fig. 19), to the smallest, only about 100 ft in diameter and 20 ft high. Craters exist on all cones, several with closed rims and small silted playas and grassy flats on the crater floors. Maximum crater diameter is about 150 ft. Several of the craters have a plaster of lava that appears to have been put on by temporary welling up or splashing of lava to near the rim. Spatter is common on the rims in

TABLE 8—MODAL COMPOSITIONS (VESICLE-FREE BASIS) OF SELECTED SAMPLES OF FLOWS FROM WIND MESA VOLCANO AND MEASURED AN CONTENT OF CONSTITUENT PLAGIOCLASE PHENOCRYSTS (sample locations shown in fig. 17).

	(sample 8)	(sample 9)	(sample 13)
Groundmass	59.3	60.7	89.2
Olivine	5.4	7.7	2.0
Augite	7.3	6.0	6.1
Plagioclase	28.0	25.6	1.4
An content	58.5	58	55-43

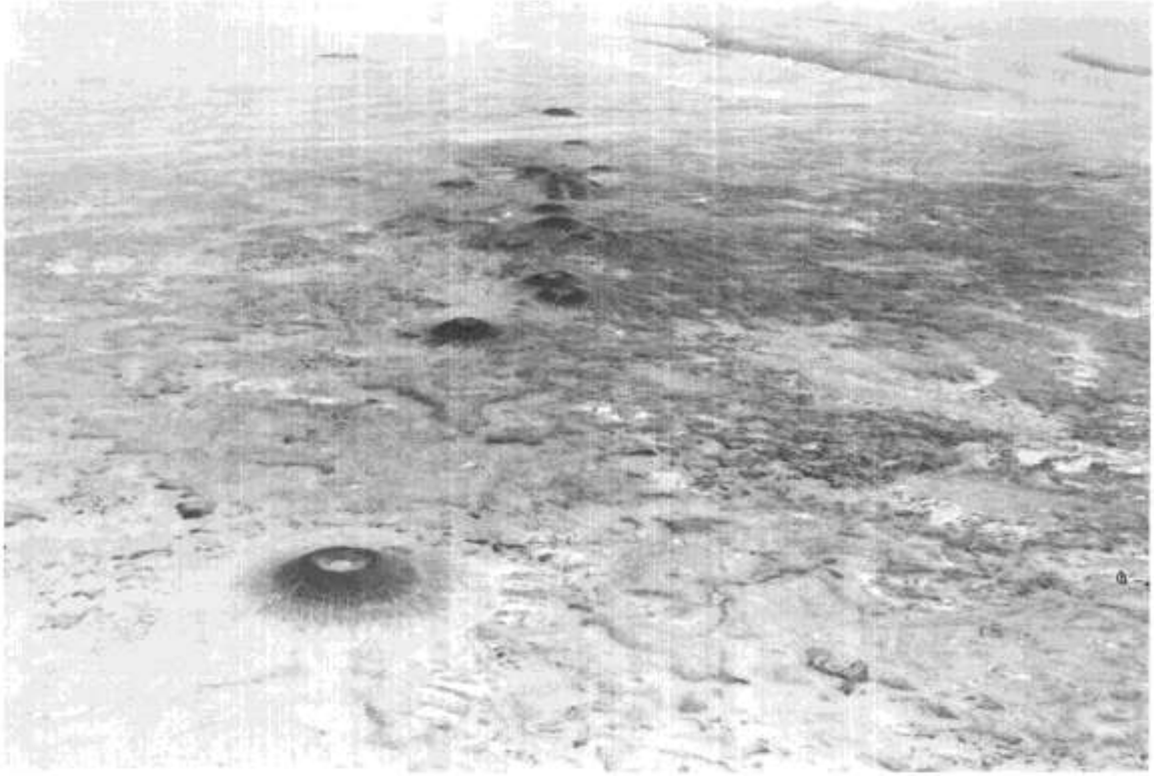

FIGURE 18—AIRVIEW OF CAT HILLS FIELD AND WIND MESA (view is north with Cat Hills in foreground and Wind Mesa in right background).

numerous shapes up to 1-2 ft in maximum dimensions. Cinder on the flanks varies considerably from cone to cone, but the most abundant sizes average 3-4 inches in diameter. Teardrop bombs are essentially nonexistent; most bombs are irregular to crudely rounded and commonly broken. Reddish brown is the dominant color of the cinder, but black, magenta, lavender, and tan brown are common.

Commercial cinders for the manufacture of cinder blocks and for other uses have long been mined from Blackbird Hill, the northern cone in the alignment. Although some mining has been done on the next two cones to the south, the main sources continue to be at Blackbird, where the texture and strength of the cinders are reportedly superior.

Flow 1, with a K-Ar age of 0.140 ± 0.038 m.y. (Kudo and others, 1977), appears to have come from all along the fissure zone. Away from the vents, the flow followed two low swales southward along the mesa and one swale down a narrow wash onto the Los Lunas terrace. In spreading across the terrace, flow 1 appears to have dammed Cedar Wash, which drains a large area in the high part of the northern Wind Mesa area. The damming diverted Cedar Creek where it issues from the Santa Fe terrace, causing the creek to spread its alluvium southward across the flow a mile or so up the wash from the point of damming. The result was to disconnect the spreadout terminal lobe from its source channel. Buildup of the Cedar Creek alluvial fan obstructed the mouth of both Cedar Creek draw and the next draw to the south.

FIGURE 19—LARGEST AND SOUTHERNMOST CINDER CONE OF CAT HILLS FIELD (view is west).

Flows 2 and 2A followed much the same low ground as flow 1 and covered it in most places. Flow 2 jumped the flow 1 channel eastward to Cedar Creek and the adjacent arroyo, only to be turned back southward toward flow 1 along the Cedar Creek fan. The lava dam and lower Cedar Creek were finally breached, and Cedar Creek returned to its original course.

The rocks of all the flow units are olivine basalts and are similar in texture and irregular vesicularity. Hand-specimen examination suggests possibly slightly more olivine in flows 1 through 2; olivine in flows 3B and 4 is paler green.

The flows of the Cat Hills volcanoes are all olivine basalts with alkaline affinities showing a differentiation trend toward a more undersaturated magma as at Isleta volcano. Modes and chemical compositions of the basalts are tabulated in tables 9 and 10 and in fig. 5.

The Cat Hills basalts contain olivine and plagioclase phenocrysts, some as large as 3 mm, in an intergranular groundmass of brown titaniferous augite, plagioclase, olivine, and opaques. Minor glass is present in only a few sections. Modally, the phenocrystic olivine-to-plagioclase ratio decreases upward in the pile from a ratio over 3.0 in flow 1 to around 0.3 in flow 4. Reflecting this increase in modal plagioclase, the An content of the plagioclase phenocrysts changes systematically, becoming more sodic, from a value of An_{67} in flow 1 to An_{54} in flow 4.

Chemically, there is a significant decrease in the normative hypersthene in the younger flows, which become slightly nepheline normative. The normative anorthite content decreases also. The alkali content of these basalts is high, and they plot on the alkali olivine basalt side in the alkali-silica plot.

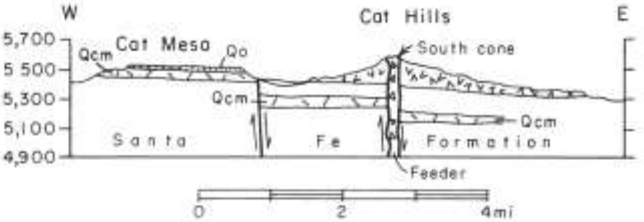

FIGURE 20—CROSS SECTION SHOWING FEEDER FISSURE OF CAT HILLS SOUTH CONE AS SOURCE FOR CAT MESA BASALT (Qa, alluvium; Qch, Cat Hills flows; Qcm, Cat Mesa flow; Qo, Ortiz gravel).

Cat Mesa flow

Cat Mesa is west of Cat Hills and about 12 mi west of Los Lunas (fig. 17 on sheet 1). The volcanics occur as an isolated flow near the top of the mesa. Some 20-30 ft of Santa Fe beds overlie the flow beneath the pediment and caliche-capped mesa. Principal exposure of the flow is along an east-facing fault scarp forming the eastern edge of the mesa. The flow extends north-south along the scarp for about 4 mi and continues through the mesa to the western side, a distance of about 2 mi. In the best fault-scarp exposure, the flow is as much as 30-40 ft thick; it would appear to underlie the valley to the east and probably underlies the flows of the Cat Hills field east of the valley (fig. 20).

In the fault scarp the flow has a banded appearance due, in part, to alterations of irregular dense and vesicular layers in the flow. The basalt is porphyritic owing to numerous plagioclase laths in the aphanitic groundmass and is quite different from basalts exposed in the Cat Hills field adjacent to the east.

A chemical analysis of the Cat Mesa basalt has not been attempted yet. Petrographically, the Cat Mesa basalt is an olivine basalt with alkaline affinities containing abundant large plagioclase phenocrysts (to 5 mm long), smaller olivine (0.4-1.0 mm), interstitial pale-brown titaniferous augite (0.2-0.6 mm), and opaques. The basalt on top and bottom of the flow is more porphyritic with a fine-grained groundmass (less than 0.1 mm) of olivine, augite, plagioclase, and opaques. Only olivine and plagioclase occur as phenocrysts.

TABLE 9—CHEMICAL COMPOSITION AND MODIFIED CIPW NORMS OF CAT HILLS BASALTS (sample locations shown in fig. 17).

	Flow 2 (sample 2)	Flow 3 (sample 3)	Flow 5 (sample 5)
SiO_2	49.66	48.40	49.03
TiO_2	1.65	1.72	1.88
Al_2O_3	15.60	16.07	16.30
Fe_2O_3	2.43	2.64	2.12
FeO	8.70	8.69	7.72
MnO	0.19	0.18	0.15
MgO	7.55	7.80	5.85
CaO	8.59	8.95	9.68
Na_2O	3.18	3.98	3.43
K_2O	1.10	0.83	1.30
H_2O+	0.83	0.46	1.52
P_2O_5	0.52	0.40	0.45
Total	100.00	100.11	99.43
Ap	1.10	0.83	0.96
Il	2.32	2.39	2.68
Or	6.56	4.89	7.85
Ab	28.81	30.10	31.48
Ne	—	3.30	—
Mt	2.56	2.75	2.27
Hm	—	—	—
An	25.28	23.46	25.82
C	—	—	—
Q	—	—	—
Di	11.43	14.55	16.22
Hy	12.24	—	0.85
Ol	9.70	17.73	11.87

Lucero Mesa

Lucero Mesa is formed by a basalt cap erupted on a possible remnant of the Ortiz pediment surface cut on less resistant Triassic and Permian beds on an early Quaternary or late Tertiary erosion surface. All the basalt field appears to have erupted from a single vent, a low cone in the crater in sec. 22, T. 7 N., R. 3 W. near the southern edge of the main mesa segment. Original limits of the flow are eroded on all sides. Four outliers of the basalt sheet occur on lesser mesa segments that extend for some 8 mi south-southeast of the cone. The largest outlier has a basalt lobe extending across the frontal fault zone of the Lucero uplift and resting upon bevelled Santa Fe beds. The K-Ar age of this basalt is 3.7 ± 0.4 m.y. (Bachman and Mehnert, 1978). If this age is valid then the surface would be too old to correlate with those that have generally correlated as Ortiz.

The flows consist of a lower, very expansive sheet up to 30-40 ft thick, a more restricted second flow near the vent, and a third local flow pile at the crater, and along a low ridge extending a short distance northeasterly from the cone. A negative circular area of reddish-brown, pebble-sized cinders about 800-1,000 ft in diameter marks the crater area. Little or no spatter or other fluidal forms are present.

Chemically, the Lucero basalt appears to be a hypersthene-normative basalt with a high albite-to-anorthite ratio, a high diopside-to-albite ratio, and high alkalis (table 11).

The basalt is similar to the other olivine basalts with phenocrystic olivine and plagioclase in an intergranular groundmass of plagioclase, olivine, augite, and opaques. The augite is faintly pleochroic from pale gray to pale brown. Plagioclase phenocrysts (some as long as 6 mm) are most abundant and euhedral. Olivine (as

TABLE 10—MODAL COMPOSITIONS (VESICLE-FREE BASIS) OF SELECTED SAMPLES OF FLOWS FROM CAT HILLS VOLCANOES AND MEASURED AN CONTENT OF CONSTITUENT PLAGIOCLASE PHENOCRYSTS (sample locations shown in fig. 17).

	Flow 1	Flow 2 (sample 2)	Flow 2 (sample 6)	Flow 3	Flow 4	Flow 5
Groundmass	86.6	91.4	89.4	92.8	88.4	85.6
Olivine	10.1	5.4	6.3	4.5	2.2	3.7
Plagioclase	3.3	2.2	4.3	2.7	9.4	10.7
An content	67	59	57	59	58	54

TABLE 11—CHEMICAL COMPOSITION AND MODIFIED CIPW NORM OF LUCERO MESA BASALT.

	sample 1
SiO_2	49.48
TiO_2	1.71
Al_2O_3	15.99
Fe_2O_3	3.24
FeO	7.09
MnO	0.16
MgO	6.45
CaO	9.35
Na_2O	3.51
K_2O	1.22
H_2O+	0.97
Total	99.50
Ap	0.70
Il	2.42
Or	7.31
Ab	31.98
Ne	—
Mt	3.44
Hm	—
An	24.63
C	—
Q	—
Di	16.31
Hy	3.06
Ol	10.16

large as 2.5 mm) is partially altered to iddingsite. Glomeroporphyritic aggregates of plagioclase and olivine are common. The plagioclase phenocrysts increase from flow 1 to flow 3, but the olivine phenocrysts are most abundant in flow 2. The intrusive plug in the cinder cone most closely resembles flow 1. These basalts are typical alkali olivine.

Mohinas and Hidden Mountains

Mohinas Mountain and Hidden Mountain lie south of the Rio Puerco siding on the Santa Fe Railroad about 15 mi west of Los Lunas (Gratton, 1958). Hidden Mountain, about 1.5 mi north of Mohinas Mountain, lies near the junction of Carrizo Arroyo with the Rio Puerco. The altitude of rather flat-topped Hidden Mountain is 5,507 ft; the butte-like eminence rises steeply about 450 ft above the Rio Puerco flats to the east. Mohinas Mountain, whose highest point is 5,527 ft, is larger and more irregular with several compound ridges.

Both mountains consist of basalt and olivine diabase intrusions into sandstone and mudstone of Santa Fe whose complete structure and nature is obscured by much landslide and talus. Volcanic extrusive rocks are not present in place, but the landslide debris, especially around Hidden Mountain, contains some vesicular rocks that may have been extrusive.

Mohinas Mountain is the more interesting of the two features owing to better and more diverse exposures (fig. 21 on sheet 2). Its principal feature is a massive funnel-shaped intrusion. Its peripheral margins have prominent layering, dipping centripetally in most places. Within and somewhat off-centered to the northeast is a circular, inward-dipping cone of silicified and altered Santa Fe sandstone and mudstone. A peripheral band of the sandstone displays inward dips of 65-90 degrees; a principal core mass consists of disarranged blocks and breccia of altered Santa Fe beds. In places, especially around and south of the Santa Fe pendant, the diabase is considerably altered to yellowish-weathering outcrops, resembling surface outcrops of the altered sandstone. The igneous rock, however, is rarely brecciated. Existence of the interior sandstone pendant gives the intrusive mass a cone-sheet form. The pendant undoubtedly pinches out at a depth of a few hundred feet, at which point the intrusion would become a plug.

The cone sheet, as exposed, may have been emplaced only 100-400 ft beneath the ground surface at the time. That surface could have been the one preserved about six miles to the south and the one on top of Bobo Butte five miles to the west. Upward flare of the Mohinas mass may have been near the base of a volcano and represent in some manner the lower part or base of a crater.

Several basaltic sills occur in the Santa Fe of the surrounding area; two are shown in fig. 21 (sheet 2). A special feature of the area is the small breccia pipe at the eastern base of the hill. This pipe is a highly sericitized and kaolinized mass whose fragments appear to consist mostly of highly altered basalt.

Hidden Mountain consists mostly of Santa Fe beds. Where best exposed on the southwest side, the dip is about 20° NE. The main southern part of the hill is capped by a massive dolerite sheet about 1,000 ft in diameter. This mass probably is a shallow intrusive that was also emplaced below a volcanic edifice. A lower north hill on the mountain appears to be a downfaulted flow or edge of the main capping intrusion.

The cone sheet of Mohinas is composed of olivine diabase with minor amounts of plagioclase and olivine phenocrysts up to 4 mm long in a fine-grained diabase to subophitic groundmass. The groundmass is composed dominantly of brown titaniferous augite inter-grown with labradorite ranging from 0.5-1.0 mm long. Subhedral olivine grains (0.2-5.0 mm) occur interstitially with opaques. The olivine diabase is cut by fine-grained syenite dikelets composed dominantly of felty sanidine-anorthoclase, up to 2 mm long, with interstitial subhedral augite and hornblende (0.3-0.6 mm) and opaques. In places augite has been altered to tremolite. The host rock of the breccia pipe is a glassy basalt with microphenocrysts of plagioclase and ferromagnesium minerals. Mohinas is probably another alkali olivine basalt center. Hidden Mountain was not studied petrographically.

Los Lunas volcano

The Los Lunas volcano is a prominent, massive-appearing volcanic pile of andesite located 4 mi west of the town of Los Lunas (fig. 22). Its highest peak at 5,955 ft rises about 1,100 ft above the Rio Grande floodplain. The main center of the eruption is only about 1,000 ft east of the edges of the high western mesa. From a road on the mesa at the western edge of the volcano, the rise to the summit is only about 250 ft. The eruption appears to have occurred very near the edge of the Ceja Mesa with much of the flow cascading down the mesa side and, in part, onto a terrace or former floor at an altitude of about 5,200 ft. The eruption, therefore, is younger than the erosion of much of the inner valley.

FIGURE 22—LOS LUNAS VOLCANO (view to north).

The two oldest flows on the lower surface range in thickness from about 100 ft at the southern end to about 150 ft in the northern outcrop. Flow 3 in this same area is about 50-75 ft thick. East of the north-south fault that dislocates the volcanics at the summit (fig. 23 on sheet 2), the aggregate thickness of all flows through 5 is estimated to be only about 300-400 ft. On the upthrown side west of this fault, a flow thickness of only about 150 ft is preserved, perhaps including equivalents of flows 1 to 3 (fig. 24). In this area and in equivalent outcrops north of the east-west fault, good exposures indicate that the Santa Fe beds beneath the flows had been folded, probably faulted, and eroded prior to the first eruptions and also prior to deposition of the expansive Ortiz blanket of sand, gravel, and caliche of the mesa.

The top of the Santa Fe along the slope west of the high peak is at an altitude of about 5,850 ft (about 200 ft higher than its top beneath the pediment cover on Ceja Mesa)—the highest exposed Santa Fe anywhere in the Rio Grande valley south of the latitude of Albuquerque except locally along the eastern base of the Ladron Mountains. Although one might deduce that 250 ft or more of Santa Fe beds had been removed by erosion of the Ceja surface, as in the tilted Santa Fe near the Los Lunas volcanic center, the vast area of the Ceja Mesa probably did not suffer such extensive stripping. More likely, the high Santa Fe top in the peak was horsted into its position by the bounding faults.

The main eruptions appear to have come from two principal centers: one, just east of the highest peak, appears to have been slightly cut by the north-south fault; the other is on the lower northern peak of the hills, north of the east-west fault.

Separate and different andesites crop out 1/2-1 1/2 mi southwest of the main mountain across a rugged canyon 200-400 ft deep. The largest outcrop, immediately across the canyon, covers about 1 sq mi, dips southerly and is considerably broken by slumping and sliding both down the dip slope and into adjacent canyons. The lower parts of the slumped mass are also mixed with mud flows that abut a steep Santa Fe hill on the southwest. Three smaller areas of similar andesite occur to the south and southwest. Two small centers, 1,0001,500 ft south of the San Clemente Grant line appear to be small plugs intruded into the Santa Fe beds. They have steep, somewhat centripetally inclined banding and sheeting. The southwestern area along the probable southwestern projection of the Los Lunas fault appears to be a sill because it is floored and overlain by Santa Fe beds.

Despite the somewhat jumbled aspect, the main southwestern mass appears to be roughly conformable with underlying Santa Fe beds. Furthermore, southward-dipping Santa Fe beds occur just south of the southern tip of the sloping andesite. These beds project northward above the andesite as though they probably once covered it. Thus, possibly the large slumped andesite (it has no clearly definable vent or cone) was also a sill.

All the southwestern andesites differ from the main eruptions by being less aphanitic, more fluidal in structure, and less altered. Almost all the flow outcrops of the main hill have a nearly pervasive walnut-brown weathering or alteration. This aspect is not common in the southwestern andesites. Kasten (1975, p. 13-14) found that the main flows ranged in silica content by weight from 56.12 to 58.58 percent upward through the flow sequence. An ranged from 51 to 59. Phenocrysts in the predominantly aphanitic groundmass consist of less than 5 percent of such minerals as plagioclase, augite, hypersthene, olivine, and basaltic hornblende. He also found that the southwestern andesites were greater in silica content by weight (between 60.78 to 62.02 percent) and that phenocrysts consisting of plagioclase, minor augite, and hypersthene are considerably more abundant (30-50 percent) than in the flows of the main hill.

A considerable landslide north of the northern center appears to have sliced into a plug of that center as shown in fig. 23 (sheet 2). Along the base of the large cliffs north of the center the plug is partly defined by local autoclastic breccias at what appear to be steep contacts of the plug with the adjoining flow 1.

Rocks of the Los Lunas flows are predominantly dense, aphanitic or felsic, nonvesicular, light-brownish-

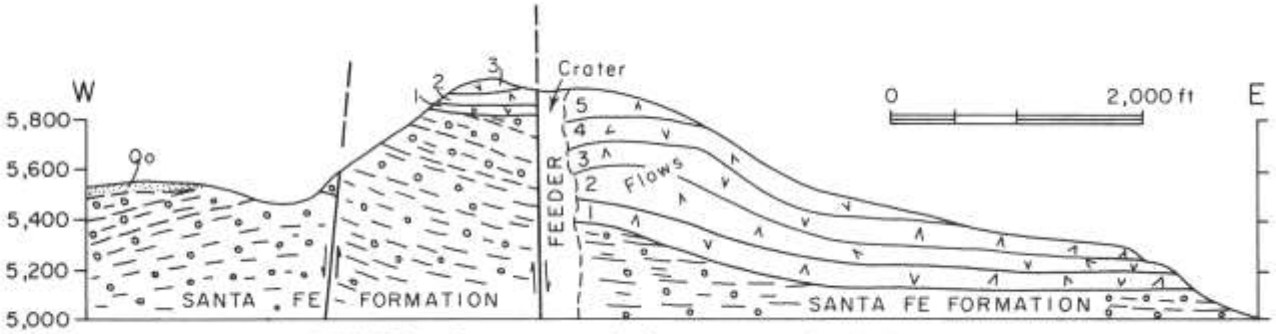

FIGURE 24—CROSS SECTION OF LOS LUNAS VOLCANO (Qo, Ortiz gravel).

gray, walnut-brown, and black andesite. The brown appears to be due to weathering. Bachman and Mehnert (1978) have called these rocks "basalts," and have obtained K-Ar ages ranging from 1.01-1.31 m.y. Flows 3, 4, and 5 in hand specimen are essentially the same as flow 1. Flow 2 is a pyroclastic breccia of various colors but also contains fragments of the dense flows. The best exposures of flow 2 are in the highway borrow pits east of the two preserved lobes of flow 3 and in the canyon reentrant between the southern and central lobes of flow 3. Abundant xenoliths of granitic rocks and amphibolites are common in some flows.

The rather straight north-south termination of the thick flow 1 on the east suggests a fault line; if such a fault exists, flows may be beneath the surface in the terrace followed by 1-25.

Los Lunas volcano represents the first reported andesite in the Albuquerque Basin (for analysis and modes see tables 12 and 13). Phenocrysts of plagioclase, augite and minor hypersthene, olivine, and basaltic hornblende occur in a hyaloophitic to hyalopilitic groundmass of plagioclase, pyroxene, opaques, and brown glass.

The phenocrysts are small, ranging in size from 0.1 to 0.5 mm. Plagioclase is labradorite which changes from An_{55} in flow 1 to An_{52} in flow 5. Olivine is found in trace amounts in flow 1 but is absent in flow 5. On the other hand, hypersthene and basaltic hornblende are more abundant in flow 5. Quartz xenocrysts with reaction rims of pyroxene occur fairly commonly. Apparently the andesite has differentiated to a more silicic type.

Bachman and Mehnert (1978, p. 288) used K-Ar dates of 1.1-1.3 m.y. obtained from andesites of the main mountain to conclude that the Ceja Mesa (Llano de Albuquerque) should not be correlated with the Ortiz surface because the flows were covered by Santa Fe beds that lie unconformably beneath the Ceja surface, gravels, sands, and soils. However, the andesite overlain by Santa Fe is in the southwestern outcrops that are most likely intrusive. Furthermore Bachman and Mehnert (1978) had Kim Manley study "a silicic ash-fall tuff sample that underlies paleosols" of Ceja Mesa west of the high peak of Los Lunas volcano. The sample was identified by Manley as material from the Bandelier Tuff some 60 mi to the north, previously dated as about 1.1 m.y. old. The tuff is not in the Santa Fe beds beneath the angular unconformity at the base of the Ceja Mesa blanket. The very white fine-grained, friable tuff contains locally small alluvial pebbles, angular pebbles, cobbles, and blocks of the Los Lunas andesite. Elsewhere the tuff rests on rounded pebbles of chert which in turn lie irregularly and unconformably upon olive drab or red mudstone of the Santa Fe. Clearly the tuff is a part of the Ceja blanket. This blanket, made up of material (soils, etc.) ranging from the present to more than 1.3 m.y., lies unconformably (commonly angularly so) upon Santa Fe beds. The erosion surface is something older than the dating evidence (1.3 m.y.) and is quite plausibly correlated with the type Ortiz cut surface. The inner valley was already well excavated when the andesites (1.1 to 1.3 m.y. old) flowed from eruptions on the edge of the Ceja Mesa down onto a terrace some 300 ft lower than the mesa and only 300 ft above the present Rio Grande floodplain. The terrace is older than the first andesite flow, hence the Ceja Mesa base is much older.

TABLE 12—CHEMICAL COMPOSITION AND MODIFIED CIPW NORM OF LOS LUNAS ANDESITE (sample locations shown in fig. 23).

	Flow 1 (sample 1)
SiO_2	57.35
TiO_2	1.04
Al_2O_3	15.95
Fe_2O_3	4.08
FeO	2.17
MnO	0.10
MgO	3.41
CaO	5.80
Na_2O	4.90
K_2O	2.28
H_2O+	1.81
P_2O_5	0.80
Total	99.69
Ap	1.70
Il	1.47
Or	13.68
Ab	44.78
Ne	—
Mt	3.15
Hm	—
An	14.99
C	—
Q	6.31
Di	7.14
Hy	5.99
Ol	—

Tome Hill

Tome Hill is about 5 mi south of Los Lunas and about 1 mi east of NM-47. Herrick and Johnson (1900, p. 6) called it Peralta volcano. The resistant hill stands along the side of the floodplain of the Rio Grande. Tome Hill is about 4,000 ft east to west and 1,700-2,200 ft north to south. Its highest point, 5,223 ft, is about 380 ft above the floodplain (fig. 25).

The slopes of Tome Hill are heavily mantled by colluvium, talus, eolian sand, and caliche. Large landslide blocks are imbedded in the mantle; weathered material and colluvium make distinction between such blocks and bedrock difficult and uncertain. Float of foreign-type Santa Fe gravel is especially common in the lower colluvial slopes and on bedrock up to about 5,025 ft on the hill. The hill was probably at least half buried by Santa Fe prior to erosion of the late Quaternary inner valley of the Rio Grande. A short distance to the east,

TABLE 13—MODAL COMPOSITIONS (VESICLE-FREE BASIS) OF SELECTED SAMPLES OF FLOWS FROM LOS LUNAS VOLCANO AND MEASURED AN CONTENT OF CONSTITUENT PLAGIOCLASE PHENOCRYSTS (sample locations shown in fig. 23).

	Flow 1	Flow 3	Flow 4	Flow 5
Groundmass	83.9			87.5
Olivine	0.3			—
Augite	6.6			1.2
Hypersthene	—			1.0
Hornblende	0.2			1.2
Inclusions	0.4			0.6
Plagioclase	8.7			8.5
An content	55	55	52	52

FIGURE 25—TOME HILL (view to west).

the upper half of the hill projects above the eastern mesa level. In addition to abundant gravel on the lower slopes, there is slump mantle of soft sand and mudstone of Santa Fe character. On this basis Santa Fe has been mapped almost completely peripheral to the hill. Such a relationship suggests a base of Santa Fe for the volcanics of the hill; whether or not the Santa Fe passes extensively through the hill or only locally, with the remainder being truncated by the stump or stumps of a volcano, is uncertain.

The volcanic rocks of Tome Hill are gray to black, commonly reddish-brown weathered andesites. They are fine grained, platy to massive, with platy structures mostly parallel to flow layering. Vesicularity is rare and generally minute. Flow banding is common and often of moderate to steep dip. Centripetal dips are common; others outward and crosswise of the body are common also. Two units are mapped (fig. 26 on sheet 2): 1) a lesser, perhaps older andesite, Ta, generally lower and peripheral in outcrops and 2) a preponderant andesite, Ta_e, forming most of the hill. Xenoliths of old crystalline basement rocks are common in the older andesite. With more detailed mapping the upper andesite that holds up most of the hill could be separated into two or three units based on position and platiness.

A crater or inside feeder-like plug is not evident. The source or feeder is most probably under the peak area; a lesser center is not ruled out for the flat area just west of the western side of the small faults that transect the hill. Likelihood of extrusive flows on the hill is scant. Instead the rocks probably are all intrusive, having been emplaced possibly near the base of a volcano or plug dome that has been removed by erosion.

The andesite of Tome Hill is composed of phenocrysts of plagioclase, augite, hypersthene, with or without basaltic hornblende, in a pilotaxitic groundmass of plagioclase, pyroxenes, magnetite, and brown glass (tables 14 and 15). In reporting a K-Ar age of 3.4 ± 0.4 m.y. for these rocks, Bachman and Mehnert (1978) refer to these andesites as "basalts."

The basaltic hornblende is absent in the reddish-brown flow breccia at the top of the hill and in the platy andesite dike, but is most abundant in the andesite closest to the contact with the Santa Fe and in dikes cutting the Santa Fe. Small inclusions of hornblende, granite, biotite-feldspar-amphibole gneiss, some measuring over 4 cm, are also found in the outcrops nearest the contact.

TABLE 14—CHEMICAL COMPOSITION AND MODIFIED CIPW NORM OF THE TOME HILL ANDESITE (sample locations shown in fig. 26).

	sample 2A
SiO_2	60.31
TiO_2	0.92
Al_2O_3	16.95
Fe_2O_3	2.03
FeO	2.99
MnO	0.08
MgO	2.51
CaO	4.88
Na_2O	4.27
K_2O	2.90
H_2O+	1.69
P_2O_5	0.37
Total	99.90
Ap	0.78
Il	1.30
Or	17.40
Ab	38.93
Ne	—
Mt	2.15
Hm	—
An	18.82
C	—
Q	10.16
Di	2.67
Hy	7.80
Ol	—

All phenocrysts are small with maximum length less than about 1.6 mm. Plagioclase phenocrysts are euhedral to subhedral laths with anorthite content between An_{49} and An_{51}. Both augite and hypersthene, some of which are rimmed by augite, have some euhedral crystals averaging about 0.6 mm or less. Glomeroporphyritic aggregates of plagioclase and pyroxene are common.

In general, the groundmass is pilotaxitic with acicular laths of crudely aligned plagioclase, augite, hypersthene, and magnetite set in a matrix of brown glass. Much plagioclase is swallow-tailed, suggesting nucleation and growth being quenched.

Apparently the central part of Tome volcano was intrusive. The concentration near the contact of basaltic hornblende with the inclusions of bedrock in the andesite suggests the possibility that the basaltic hornblende may be a reaction product resulting from the attempts by the magma to assimilate the inclusions under hydrous conditions.

Black Butte

Black Butte, also referred to as Black cone owing to its generally conical outline, and called Turututu Butte

TABLE 15—MODAL COMPOSITIONS (VESICLE-FREE BASIS) OF SELECTED SAMPLES FROM TOME HILL, AND MEASURED AN CONTENT OF CONSTITUENT PLAGIOCLASE PHENOCRYSTS (samples 1-4 are from rocks having abundant inclusions and directly in contact with Santa Fe gravels; samples 5 and 6 lack inclusions and are from rocks in contact with other andesites; sample locations are shown in fig. 26).

	sample 1	sample 2	sample 3	sample 4	sample 5	sample 6
Groundmass	78.7	80.6	79.8	78.8	85.0	93.5
Plagioclase	6.2	1.4	7.7	12.4	2.6	1.8
Augite	tr.	0.5	0.3	0.8	0.9	0.1
Hypersthene	0.3	0.2	0.4	1.8	0.5	2.0
Hornblende	2.2	1.4	3.1	6.4	tr.	—
Opaques	0.2	0.2	0.3	—	0.2	0.9
An content	49	51	51	50	50	49

by Denny (1941, p. 229), is located about 7 mi east of the Rio Grande and about 1 mi south of US-60. Black Butte stands as a lone hill on the expansive eastern mesa surface and is roughly elliptical east-west with dimensions of about 2,000 by 3,000 ft (fig. 27). This butte rises about 350 ft above the surrounding plain; the summit area is undoubtedly the central portion of either a plug dome or the basal portion of a former volcano. Bachman and Mehnert (1978) reported a K-Ar age of 24.3 ± 1.5 m.y. for a flow from Black Butte. If this age is correct then Black Butte is more likely to be a pre-Santa Fe inselberg rather than an intrusion through the Santa Fe and pediment beds.

About 2 mi due west of Black Butte, two small remnants of andesite flows lie on Santa Fe gravel exposed in low knobs above the general pediment level. Their most probable source is the Black Butte center; if true, the intervening portion of the flow has been removed by erosion.

Three rock types occur in the hill (fig. 28 on sheet 2). A gray andesite porphyry probably is dominant; the porphyry is poorly resistant to erosion, and its presence is rather obscure. For the most part, the porphyry probably occupies about the lower two-thirds of the hill. However, it is also present in the upper one-third and at the top where the porphyry appears to be the host for the brown to black vesicular andesite that crowns the hill and yields much obscuring talus and hillside alluvium all the way to the bottom of the hill.

The second rock is a light-gray flow-banded rhyolite that occurs only at the southeastern edge of the hill. The rhyolite fluidal structure dips 10-15° northwest toward the hill. Many dips are also to the southeast. Although the rhyolite may be some part of the Datil Formation that crops out extensively 6-10 mi to the southwest, more likely the rhyolite is a local eruption.

The third type, dark vesicular andesite, intrudes the gray andesite; some of the small dikes are very near to the andesite-rhyolite contact. The fact that the dikes do not intrude the rhyolite suggests that the rhyolite may be the youngest of the three rocks.

The top of Black Butte is slightly saucer shaped, suggesting a much-eroded crater with the vesicular andesite forming a rim (fig. 27). A narrow slope just outside the rim again appears to be mostly the gray andesite. Beneath this slope, in most places around the crown of the hill, is another rim of inward-dipping vesicular andesite. Beneath this rim, the weak gray andesite probably forms the main flanks of the hill. Although poor outcrops prevent full certainty of the relationships, the vesicular andesite of the crown of the hill probably exists as two concentric cone sheets that intrude the gray porphyritic andesite. The hill is not a volcanic cone as its profile suggests from a distance. If a cone and crater were present at one time, erosion has penetrated to a position near the base of such a crater where cone sheets commonly form. Cinder is absent at Black Butte.

FIGURE 27—BLACK BUTTE (light areas along base are result of removal of basalt talus for use as riprap and ornamental stone; view is east).

The chemical composition reveals the andesitic nature of Black Butte volcanism. Petrographically, the andesite has abundant phenocrysts of plagioclase and augite, with a trace of hypersthene found as exsolution lamellae in augite phenocrysts, along with minor olivine (table 16). The gray andesite has more plagioclase and less augite phenocrysts than the dark andesite of the cone sheet and dikes. The phenocrysts range in size from 0.2 to greater than 2.0 mm. The largest phenocrysts are plagioclase (An_{58-62}), with augites having maximum dimensions of about 1.5 mm. Olivines (altered to iddingsite in many cases) are generally smaller than 1 mm. Glomeroporphyritic aggregates, some greater than 4 mm, of plagioclase, augite, olivine, and pyroxene and olivine are common. Oscillatory and patch zoning in plagioclase are common.

The texture of the finer grained groundmass ranges from felty to intersertal to hyalopilitic with dominantly sodic plagioclase, opaques, and some brown opaque-filled glass. Two pyroxenes may be present in the groundmass because of presence of clear non-pleochroic

TABLE 16—CHEMICAL COMPOSITION AND MODIFIED CIPW NORMS OF BLACK BUTTE ANDESITE AND RHYOLITE (sample locations are shown in fig. 28).

	Flow 1	
	(sample 1)	(sample 7)
SiO_2	56.75	77.08
TiO_2	1.14	0.16
Al_2O_3	15.53	12.38
Fe_2O_3	5.02	1.22
FeO	2.32	0.16
MnO	0.10	0.09
MgO	4.10	0.17
CaO	5.80	0.07
Na_2O	3.56	4.10
K_2O	3.71	4.36
H_2O+	1.30	0.51
P_2O_5	0.52	0.01
Total	99.85	100.31
Ap	1.11	0.03
Il	1.62	0.23
Or	22.30	26.05
Ab	32.52	37.23
Ne	—	—
Mt	3.31	0.25
Hm	1.35	0.69
An	15.72	0.25
C	—	0.91
Q	6.52	33.89
Di	8.09	—
Hy	7.47	0.47
Ol	—	—

pyroxenes with faintly pleochroic varieties. The younger andesite has the higher augite-to-olivine ratio, suggesting some differentiation toward a more silicic andesite.

The rhyolite is essentially aphyric devitrified glass with only trace amounts of phenocrystic sanidine, quartz, augite, amphibole, and opaques. Inclusions of andesitic material similar to the main andesite of Black Butte are not uncommon in the rhyolite, supporting the hypothesis that the rhyolite is younger than the basalt. Vapor-phase crystals fill stretched lithophysae measuring several centimeters in length.

Scattered basalt bodies

Benavidez diatreme

The Benavidez diatreme, named and described here as an intrusive for the first time, is located in secs. 26 and 35, T. 12 N., R. 1 W. in Sandoval County. The feature was first described by Bryan and McCann (1937, p. 817-818) as "a small outlier of tuff, 250 ft thick nearly surrounded by faults" thought to have been a remnant of pre-Santa Fe local volcanic basin of deposition derived from unknown local volcanoes.

The outcrops appear most certainly to be a breccia intrusive into lower Santa Fe sandstone and mudstone. In plan the body is oval and about 2,200 by 3,100 ft. The bulk of the rock is a basaltic tuff-breccia, containing considerable incorporated Santa Fe gravel beds and in its upper part Santa Fe sandstone, gravel, and basaltic breccia likely deposited in a kind of double crater of a once-existing low maar of tuff cone. This part is now preserved as a central mesa rising above the major peripheral area of breccia (fig. 29). The breccias surrounding the mesa are considerably disturbed, but inward dips are common in numerous places, especially up the flanks of the mesa. In places, the breccia is in steep intrusive bands associated with disturbed steep-standing gravel beds.

Petrographically, the intrusive host appears to be basaltic with phenocrysts (0.2-0.5 mm) of abundant augite, plagioclase, and opaques, in an intergranular to intersertal groundmass of plagioclase, pyroxene, opaques, and brown glass. Serpentine, which could represent altered olivine, is common. Some of the cores of augite phenocrysts have serpentine also. A large inclusion (6 mm) of gabbro with plagioclase and augite (1.0-2.0 mm across) was found in thin section as were several quartz and calcite inclusions with reaction rims of pyroxenes. Several patches of brown glass with plagioclase microlites are also common.

FIGURE 29—BENAVIDEZ DIATREME (view to southwest).

Mesita Negra

This tilted basalt flow or sill in middle Santa Fe beds is located along I-40 just east of Rio Puerco. The sheet is stripped of its cover on the high northern part of the mesa but plunges into the subsurface at the highway edge. The sheet is as much as 30 ft thick along its southwestern and southern exposure where a quarry for crushed rock aggregate has been dug. The feeder or source of the sheet is not visible, but may be at or a short distance in the subsurface beneath the highway.

Santo Domingo flow

This flow occurs in Santa Fe beds about 1 mi east of Pella Blanca. The flow was thought by Anderson (1960, p. 32) to be an outlier that came from centers on the mesa of Cerros del Rio a few miles to the northeast. The flow crops out for a distance of about 3 mi. It is a black vesicular basalt up to 15 ft thick.

Borrego Mesa

Two basalt flows cap prominent Borrego Mesa high on the southwest flanks of the Jemez Mountains. In places the flows are separated by layers of tuff, breccia, and gravel. Soister (1952, p. 36-43) first mapped and described these flows. The lower flow forms nearly vertical cliffs and is 30-70 ft thick. It is banded because of alternations of scoriaceous and dense flows.

The upper flow unit forms most of the cap of Borrego Mesa. This flow ranges from 15-40 ft thick according to Soister (1952, p. 44) and it is a dark-gray to black olivine basalt. Compared to the lower flow, the upper flow is less banded and only slightly vesicular.

Placitas area

About 1 mi northwest of Placitas is located a prominent basalt dike about 1 mi long and up to 30 ft wide, trending northeasterly across the strike of both Mesaverde and Santa Fe beds.

Trigo Canyon area

A short basalt dike and a possible sill occur in rhyolitic tuff near the base of the Manzano Mountains near the mouth of Trigo Canyon. The dike strikes northerly, parallel to the base of the mountains and is about 40 ft wide and consists of black amygdaloidal basalt. The sill occurs near the bottom of a small arroyo a short distance to the west of the dike and is up to 40-50 ft thick.

Cochiti dam area

Near the eastern end of Cochiti dam is a partial exposure of a small basaltic tuff diatreme in Santa Fe beds. Most of the body appears to lie beneath the river and dam. The south wall is well exposed and reveals steep subsidence contacts.

Carpenter well

Several intervals of basalt have been penetrated by petroleum exploration wells. The most notable of these occurrences is in the Carpenter Atrisco Grant well in sec. 28, T. 10 N., R. 1 E., drilled in 1948 on Ceja Mesa at an altitude of 5,785 ft to a depth of 6,652 ft. Dark basic rock was encountered at 3,350-3,455 ft, with additional possible penetrations of basaltic rock shown by cuttings at depth intervals of 4,580-4,590, 4,910-4,940, 5,170-5,200, 5,500-5,630, and 6,320-6,350 ft.

Dalies area

Near Dalies (sec. 5, T. 6 N., R. 1 E.), sometime between 1932 and 1937, the Big Three Oil Company drilled the Dalies Townsite No. 2 well to a depth of 6,113 ft. A driller's log records "black lava" or "broken lava" between 1,972-2,122 ft.

Well northwest of Los Lunas

In the Shell Oil Company well drilled about 3 mi northwest of Los Lunas and completed in 1975 to a depth of 16,346 ft, "volcanics" are reported to have been cut in the Santa Fe in the depth interval of 3,300-3,355 ft.

Well northwest of Albuquerque volcanoes

In late 1977 a water well on the Black ranch was completed to 1,057 ft. The location is 5 mi N. 40° W. of Vulcan cone in the Albuquerque volcanic field. Thirty-five feet of "malpais" was logged at a depth of 830-865 ft. The basalt could be either a separate flow or a sill injected into the Santa Fe from the fissure followed by the Albuquerque volcanoes only 3 mi to the east.

Summary

Occurrence and succession

The principal eruptions in the Albuquerque Basin occur along a line trending about N. 15° E., roughly paralleling the overall axis of the basin. The principal volcanic fields are San Felipe, Albuquerque, and the Cat Hills-Wind Mesa group. Lying to the west of these fields is a lesser alignment of volcanoes including Benavidez, Mesita Negra, and Mohinas. East of the main alignment is a smaller, more scattered group of andesite volcanoes extending from Isleta to Black Butte. Several of the eruptions near the general axial position of through-going Rio Grande drainage of Santa Fe to present time have early tuff-breccia maar-type deposits, namely, Cochiti, San Felipe, Canjilon, and Isleta. Their positions near the Rio Grande suggest interaction with river or ground waters in bringing about the occurrences. However, the occurrences are most likely coincidental because many examples of such deposits are known that are not directly related to large quantities of surface or near-surface waters.

In the most completely preserved basalt fields at San Felipe, Albuquerque, and Cat Hills, an orderly progression of five to six flows and explosive phases is found. The progression begins with fissure eruptions of low-viscosity lava that spread widely, followed by successive flows of increasing viscosity, decreasing expanse, greater thickness, greater surface irregularity, and restriction of eruptions to central vents. The extrusive process culminated in a higher gas phase that resulted in cinder cones. The final action in many instances was late gas-exhausted intrusion and extrusion of small dikes and fingers in cones. Ring dikes or cone sheets are common and quite well developed at San Felipe; radial dikes that may come out as driblet flows are common at the large Albuquerque cones.

In many respects the andesite and basalt eruptions of the Albuquerque Basin are the best in the state owing to Quaternary inner valley erosion that resulted in many levels of exposure. In the more deeply dissected centers at Mohinas, Black Butte, and Canjilon, large ring dikes appear to represent the basal level of removed large volcanoes. At Canjilon and Benavidez, breccia diatremes are exposed to approximately the bases of probable former craters.

All the andesite and basalt eruptions, with the possible exception of Black Butte and a few dikes and sills in pre-Santa Fe rocks, are either Santa Fe or post-Santa Fe. The oldest are the andesite and rhyolite of Black Butte and the basalt flows of Borrego Mesa interbedded with sandstone of the lower part of the Santa Fe Formation. The youngest eruptions (Los Lunas, Albuquerque, and Cat Hills) lie on the long surface of Ceja Mesa but flow down inner valley slopes onto lower terraces. Cerro Verde is also in this category because it erupted west of the basin, sending a flow down Rio San Jose into the basin. San Felipe, Canjilon, Isleta, and Tome are younger than the Borrego Mesa flows but older than those lying on the Ceja Mesa surface.

Petrology

The Albuquerque Basin occupies a transition zone in the Rio Grande rift between the southern dominantly alkali-basaltic province and the northern rift where tholeiitic volcanism appears to be dominant (Aoki, 1967; Lipman, 1969). Andesites, which occur in greater abundance on the Colorado Plateau, were found for the first time in the basin.

The Albuquerque volcanoes are olivine tholeiites, distinct from the alkali basalts as illustrated in the AMF diagram (fig. 30). The San Felipe basalts represent the other olivine tholeiite in the basin, but their AMF ratios cluster with the alkali basalts being very Fe rich. The andesites plot on a calc-alkaline-type trend in line with the olivine tholeiite of the Albuquerque volcanoes. Whether this implies a genetic relationship between the two cannot be determined with the data available at the present time.

The uniqueness of the Albuquerque volcanoes is illustrated again by plots (figs. 31 and 32) of the normative components of plagioclase (Ab + An), clinopyroxene (Di + Hd), hypersthene (En + Fs), and olivine (Fo + Fa), some of the end members of the well-known basalt tetrahedron (Yoder and Tilley, 1962, fig. 2). In figs. 31 and 32, the trend of the Albuquerque volcanoes diverges from the alkali basalt trends of Cat Hills and Isleta volcanoes.

Differentiation in the Albuquerque volcanoes is consistent with a thermal barrier existing near the olivine-plagioclase-clinopyroxene (olivine-gabbro divide) face of the basalt tetrahedron (also called the plane of critical undersaturation). This barrier exists at pressures less than 8 kb and any olivine tholeiite can fractionate out only olivine, plagioclase, and clinopyroxene, resulting in a trend away from the olivine-gabbro divide. The phenocrysts in the basalts of the Albuquerque volcanoes are olivine and plagioclase; olivine-plagioclase aggregates are common. Therefore, the olivine tholeiites of the Albuquerque volcanoes have differentiated at depths less than about 24 km by the settling out of dominantly olivine and plagioclase.

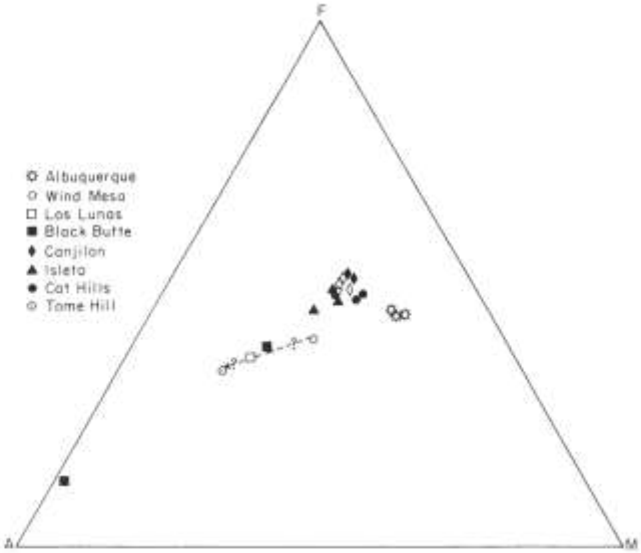

FIGURE 30—AMF DIAGRAM OF BASALTS AND ANDESITES OF ALBUQUERQUE BASIN.

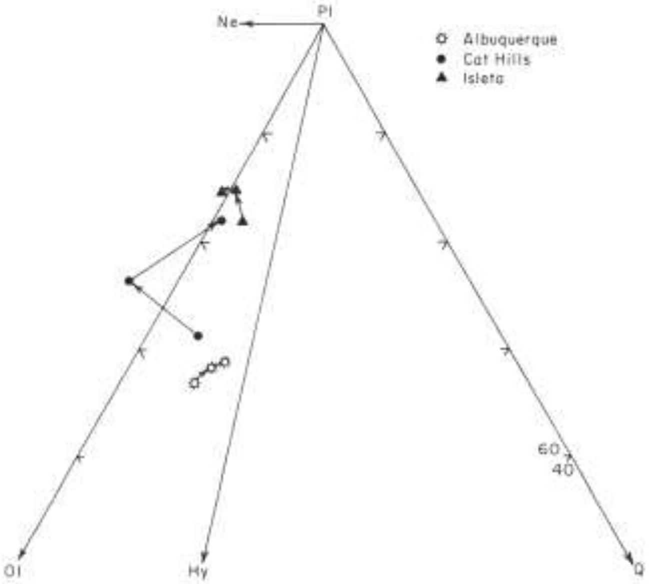

FIGURE 31—NORMATIVE PLOTS OF DIFFERENTIATION TRENDS ON PLAGIOCLASE-OLIVINE-QUARTZ FACE OF BASALT TETRAHEDRON FOR BASALTS OF ALBUQUERQUE, CAT HILLS, AND ISLETA VOLCANOES.

On the other hand, the differentiation trend of Cat Hills and Isleta volcanoes toward the olivine-gabbro divide and away from the clinopyroxene-hypersthene-plagioclase plane (hypersthene-gabbro divide) cannot be explained as easily. Such a trend could result at pressures greater than 8 kb where the olivine-gabbro plane no longer exists as a thermal divide. According to Boyd and others (1964), the hypersthene-gabbro divide becomes a thermal barrier at about 8 kb and can possibly persist to pressures above 15 kb (Green and Ringwood, 1967). Hypersthene-normative magmas must fractionate hypersthene and plagioclase to become nepheline normative. However, only olivine-plagioclase and clinopyroxenite aggregates are found in the Cat Hills and Isleta basalts. This fact—the absence of hypersthene as phenocrysts—indicates that the orthopyroxene fractionation of Green and Ringwood (1964,

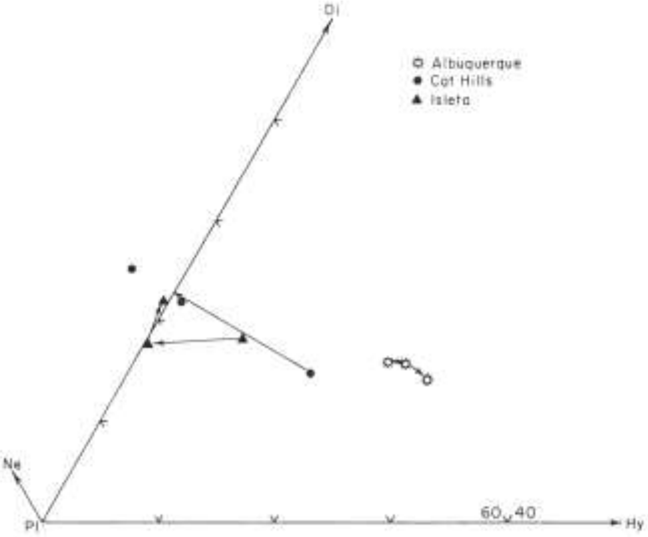

FIGURE 32—NORMATIVE PLOTS OF DIFFERENTIATION TRENDS ON DIOPSIDE-PLAGIOCLASE-HYPERSTHENE (HYPERSTHENE-GABBRO) FACE OF BASALT TETRAHEDRON FOR BASALTS OF ALBUQUERQUE, CAT HILLS, AND ISLETA VOLCANOES.

1967) and norite fractionation may be unlikely. To explain such trends, O'Hara (1968) prefers to fractionate out olivine-hypersthene or olivine-hypersthene-clinopyroxene, but the lack of harzburgitic and lherzolitic inclusions in the basalts argues against this possibility.

At higher pressures (greater than 27 kb), the hypersthene-gabbro thermal barrier gives way to the eclogite and olivine-eclogite divides. This means that fractionation of eclogite or garnet could yield the observed trend, but most observers believe that this type of fractionation at depth will yield non-basaltic liquids (O'Hara, 1968, p. 94; Green and Ringwood, 1967, p. 154).

More relevant is the development of alkali basalts and of the nepheline-normative character of the initial liquid (less than 10 percent) formed by partial melting of the mantle between 10 and 20 kb (O'Hara, 1965, 1968; Green and Ringwood, 1967). As partial melting increases at these pressures, however, the liquids formed become increasingly saturated and hypersthene normative. It is likely the alkali basalts of the Albuquerque Basin were formed under these pressure conditions. If so, the observed trend from hypersthene normative in the early eruptions to nepheline normative in the latest eruptions must be related to degree of partial melting and not to a fractional crystallization mechanism. The earliest eruptions must tap a more extensively melted hypersthene-normative liquid than the later eruptions, which must tap only the first melts that are nepheline normative.

The origin of the andesite of the Albuquerque Basin cannot be resolved at this time without further investigation. Because of the absence of a subducted plate under the rift, one mechanism could involve the formation of quartz-normative andesitic liquids by partial melting of water-bearing continental mantle at shallow depths (Boettcher, 1973). In view of the field and petrographic data, however, the fractionation of basalts under hydrous conditions, with or without accompanying assimilative processes, cannot be ruled out altogether. A shallow, even crustal, origin is possible here.

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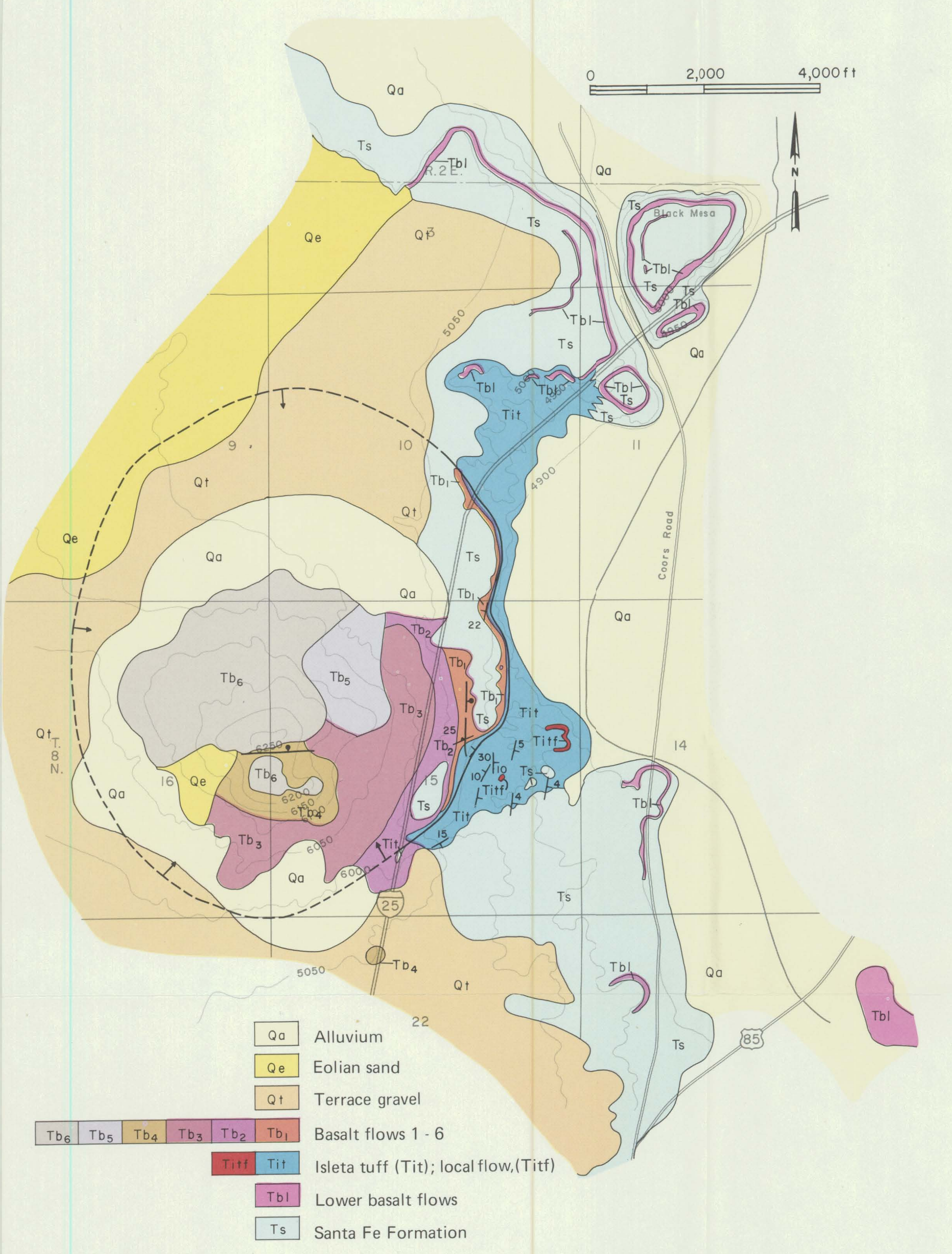


FIGURE 12—GEOLOGIC MAP OF ISLETA VOLCANO.

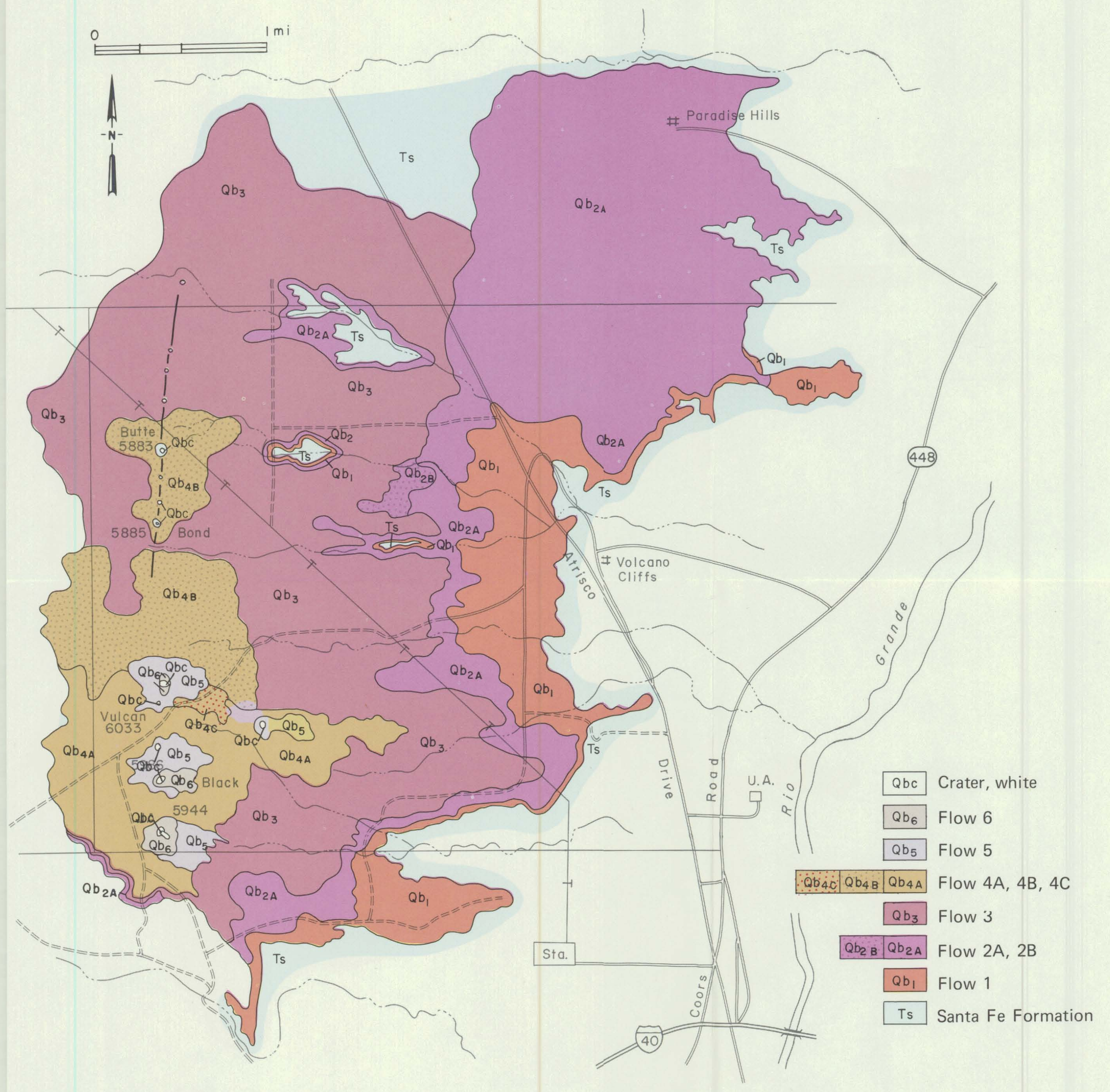


FIGURE 10—GEOLOGIC MAP OF ALBUQUERQUE VOLCANIC FIELD.

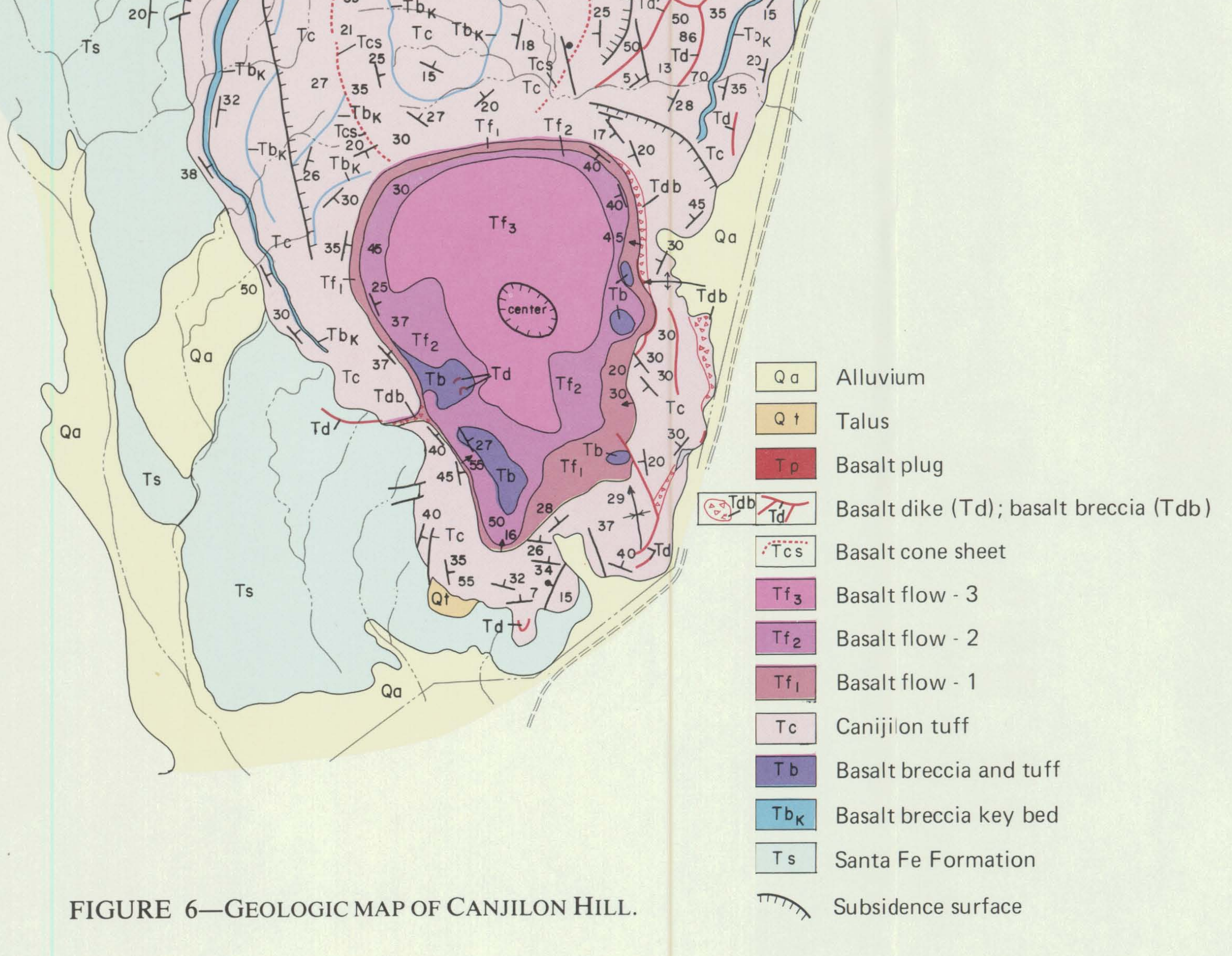


FIGURE 6—GEOLOGIC MAP OF CANJILON HILL.

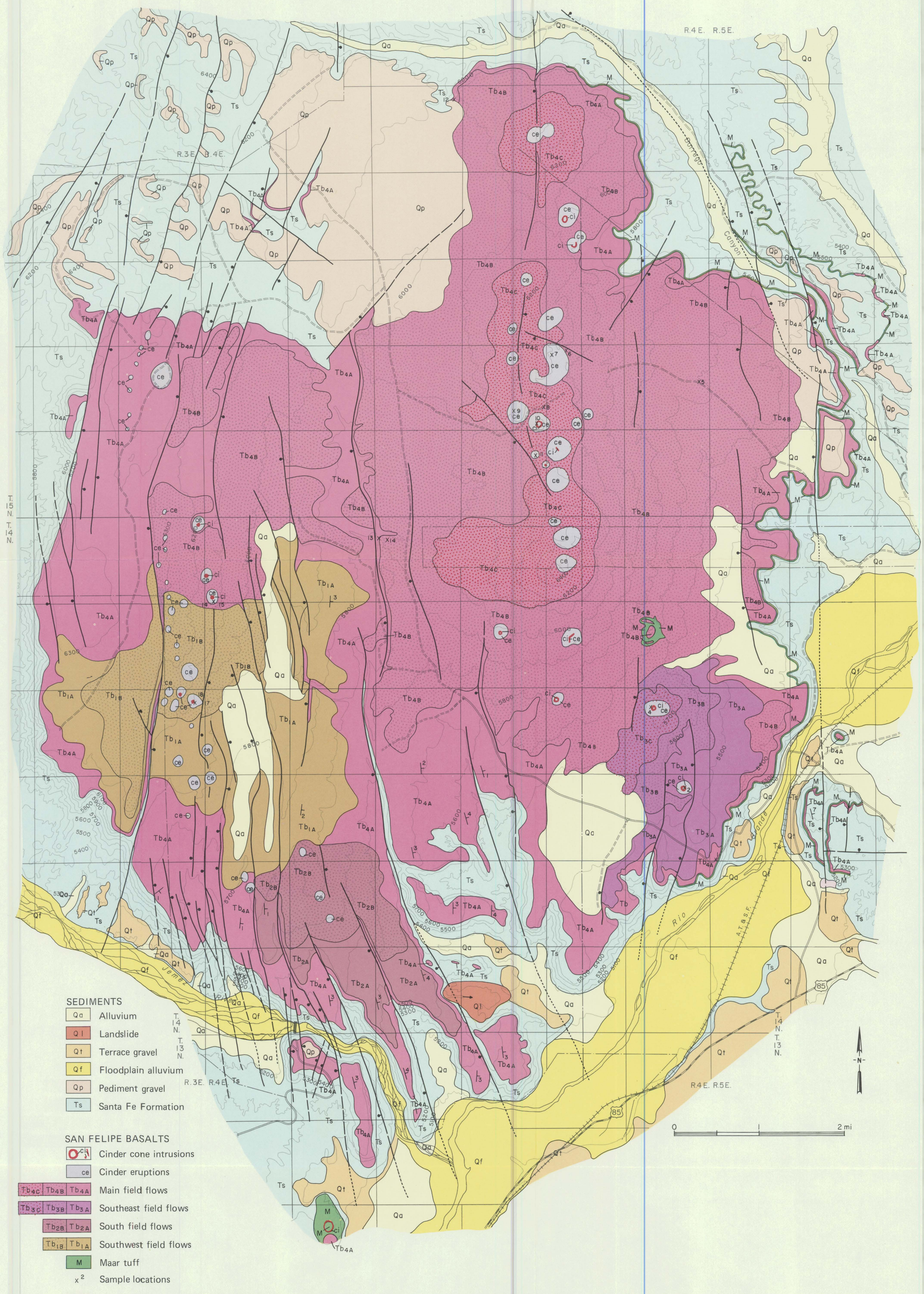


FIGURE 2—GEOLOGIC MAP OF SAN FELIPE VOLCANIC FIELD.

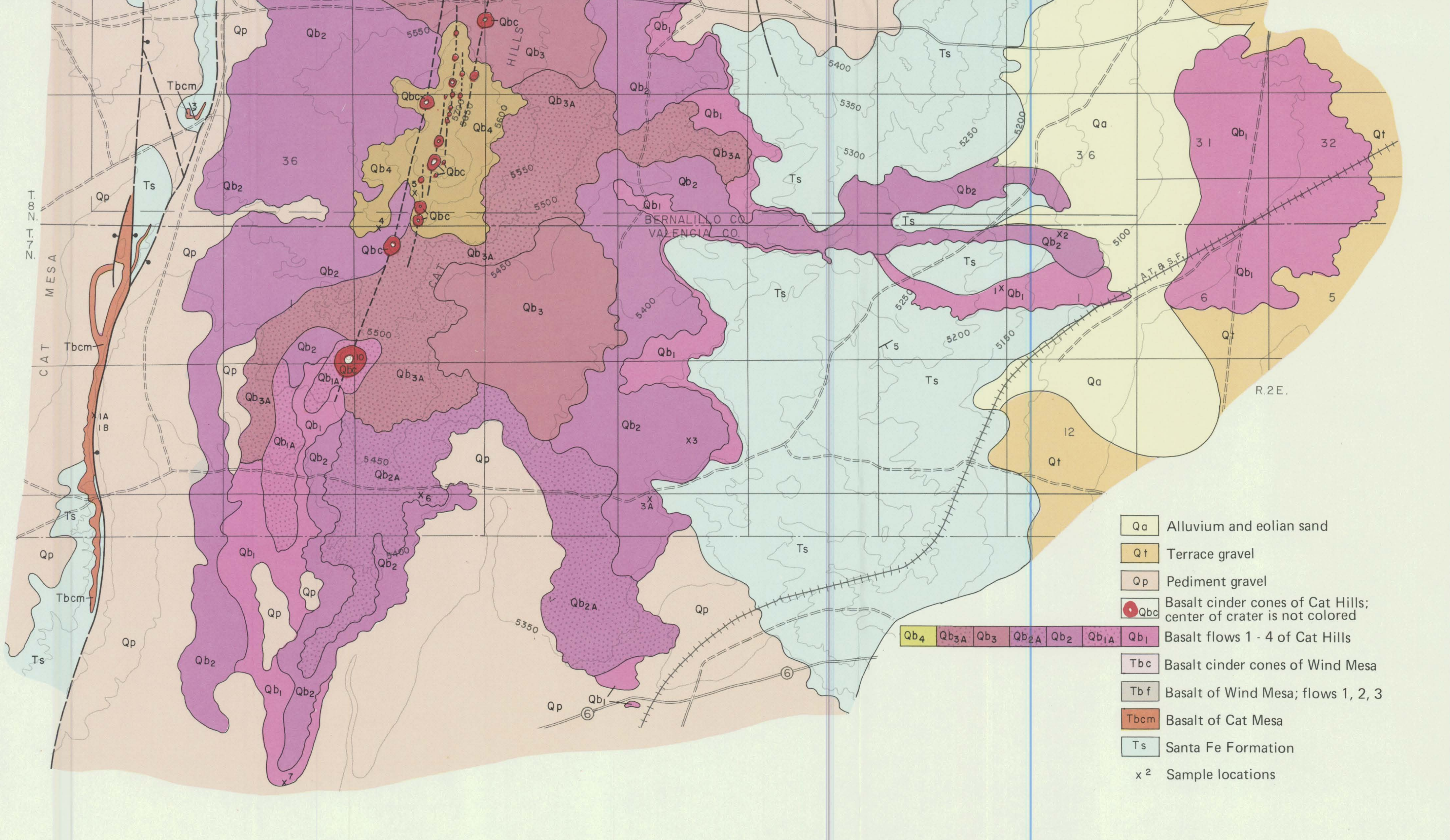
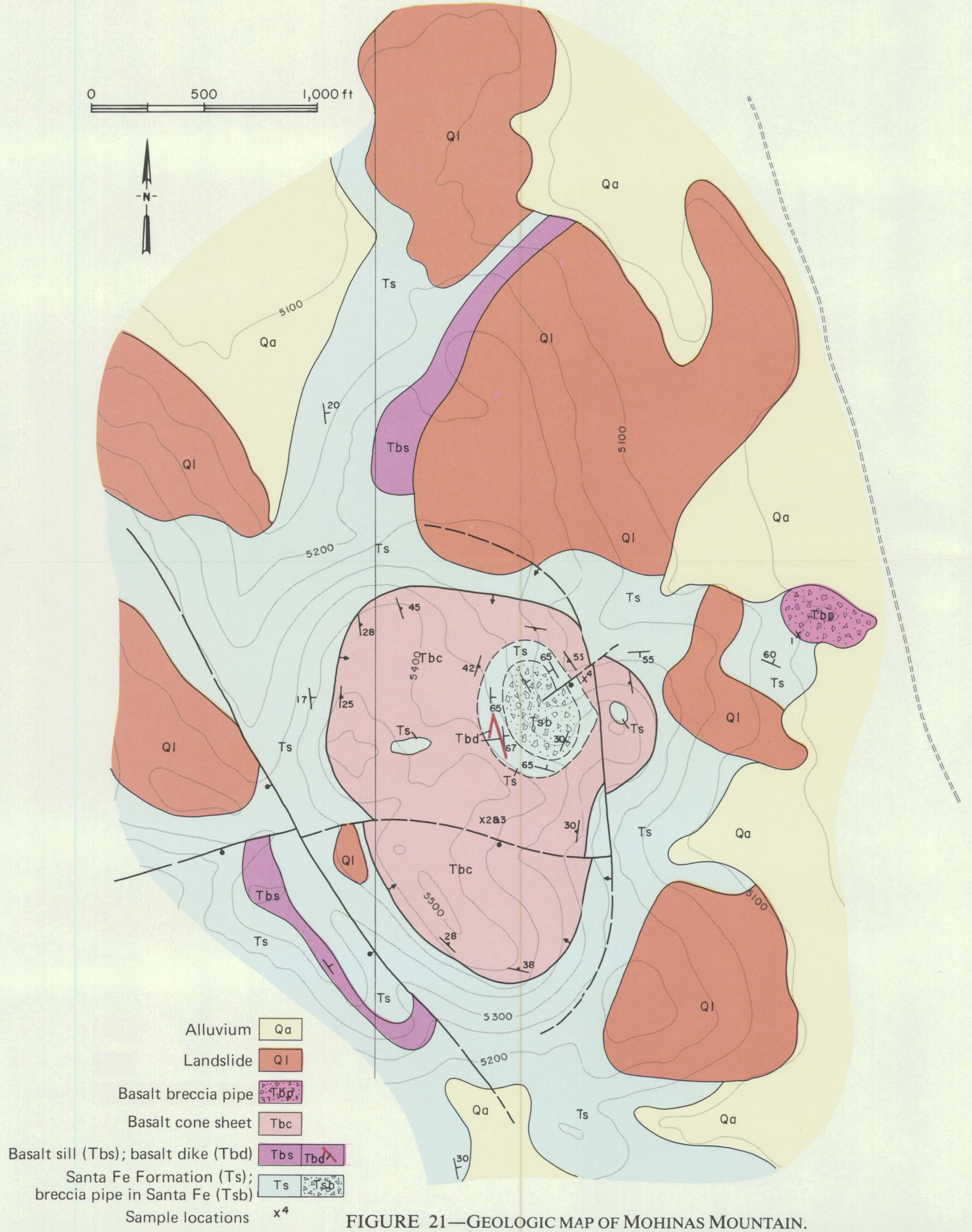


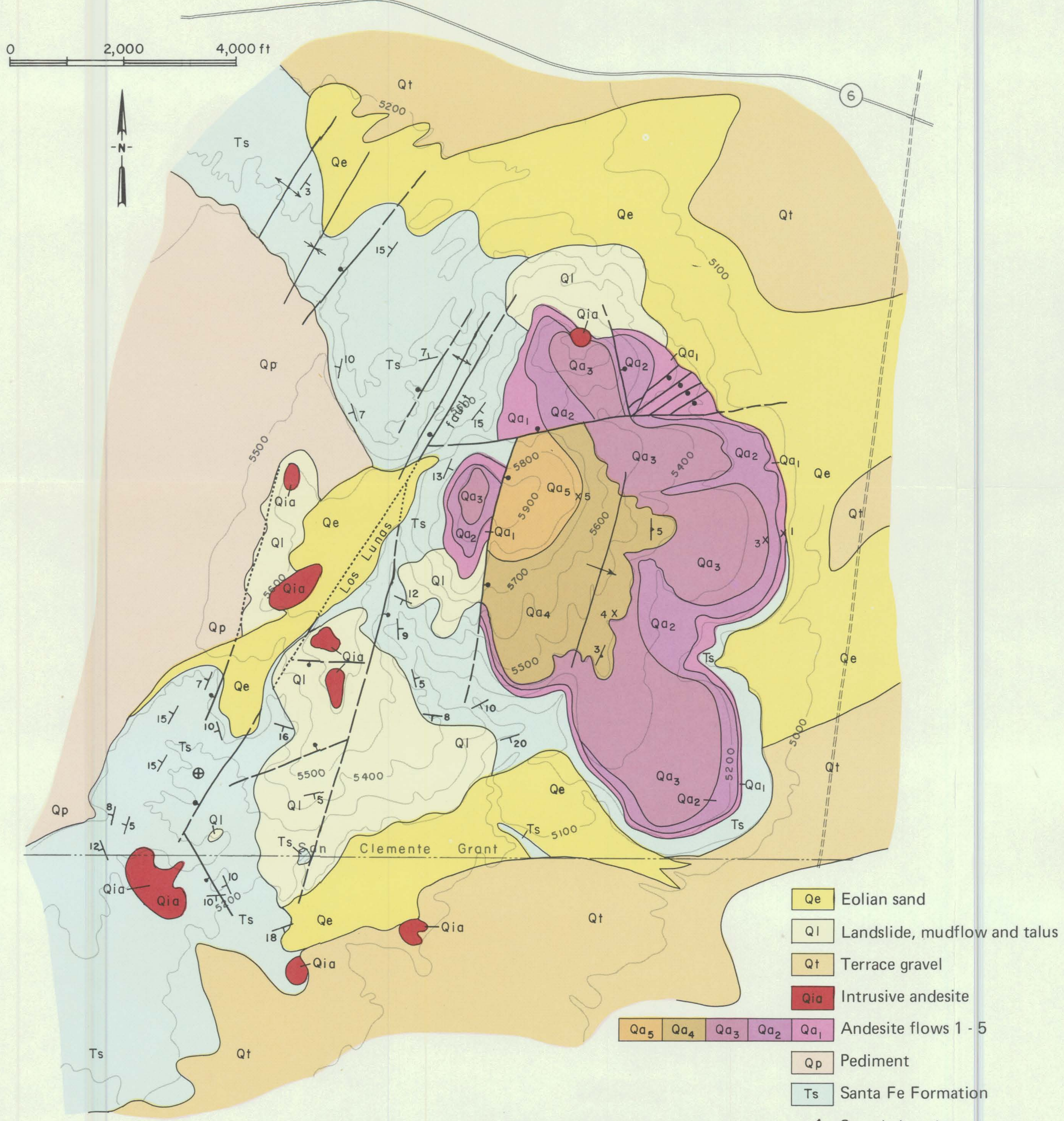
FIGURE 17—GEOLOGIC MAP OF WIND MESA, CAT HILLS, AND CAT MESA.

by V.C. Kelley and A.M. Kudo, 1978



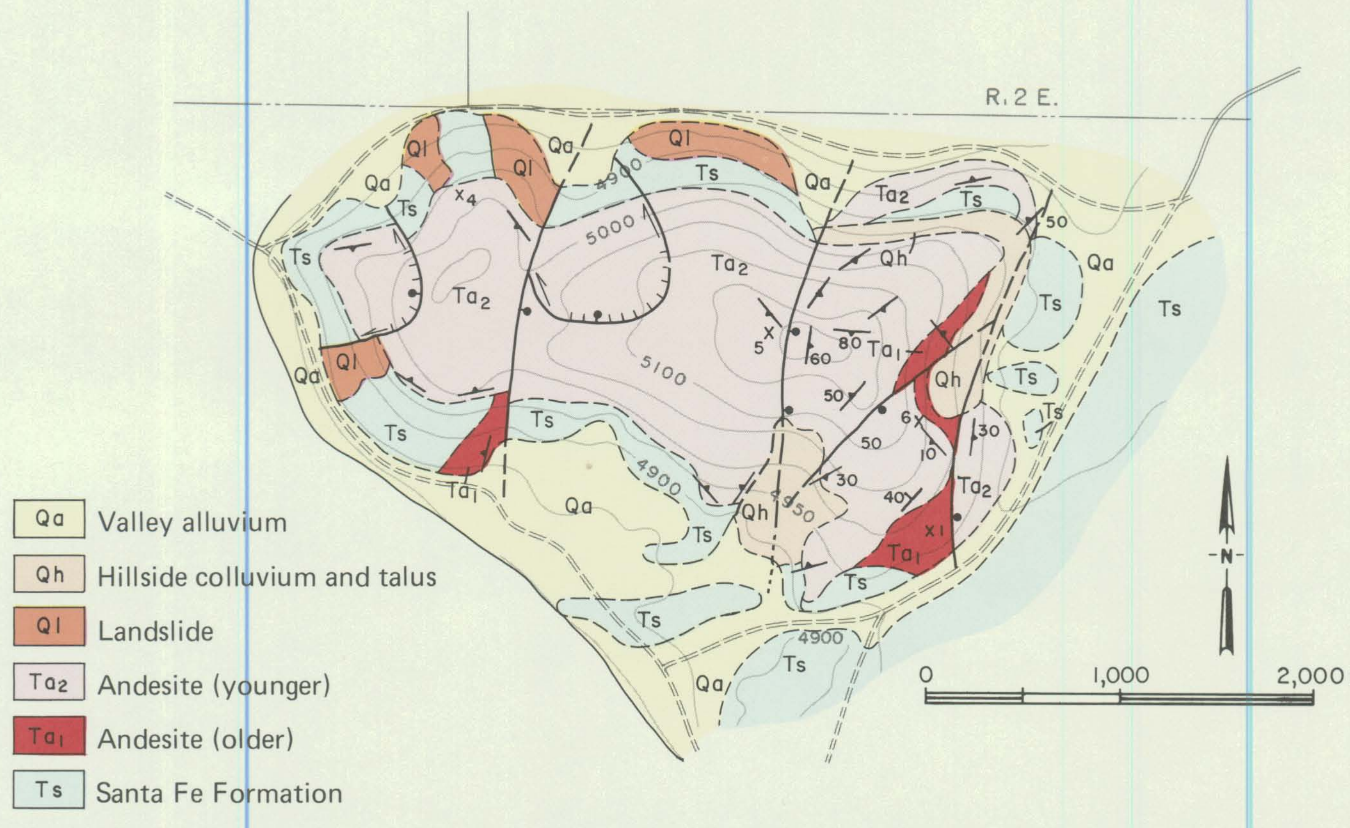
Alluvium	Qa
Landslide	Ql
Basalt breccia pipe	Tbp
Basalt cone sheet	Tbc
Basalt sill (Tbs); basalt dike (Tbd)	Tbs Tbd
Santa Fe Formation (Ts); breccia pipe in Santa Fe (Tsb)	Ts Tsb
Sample locations	x⁴

FIGURE 21—GEOLOGIC MAP OF MOHINAS MOUNTAIN.



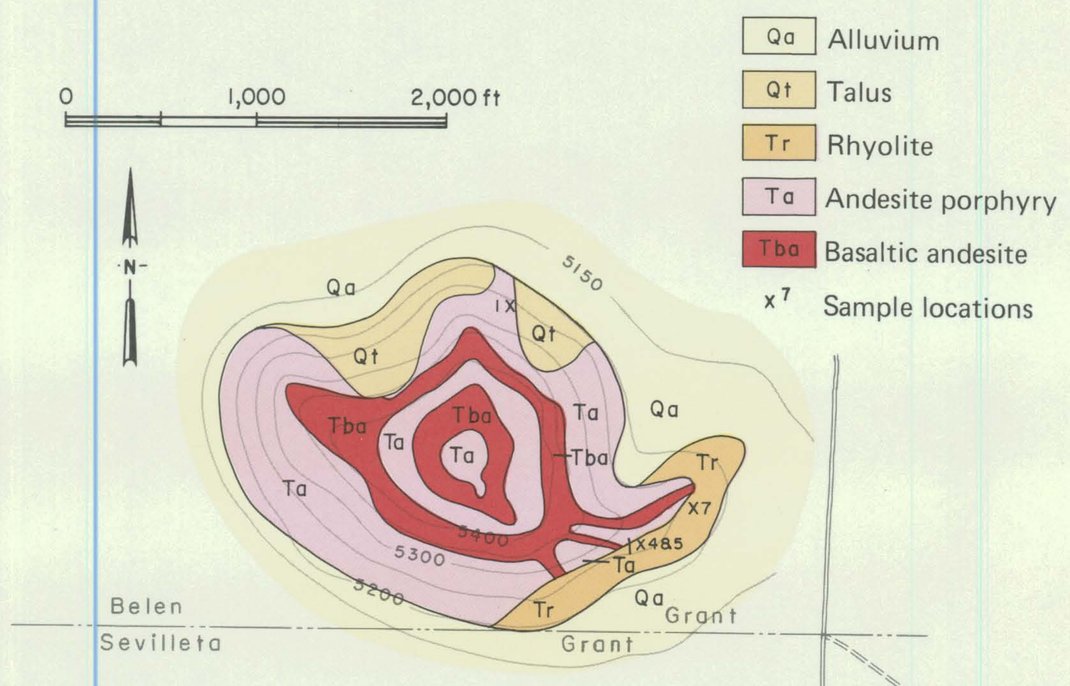
Qe	Eolian sand
Ql	Landslide, mudflow and talus
Qt	Terrace gravel
Qia	Intrusive andesite
Qa5 Qa4 Qa3 Qa2 Qa1	Andesite flows 1 - 5
Qp	Pediment
Ts	Santa Fe Formation
x⁴	Sample locations

FIGURE 23—GEOLOGIC MAP OF LOS LUNAS VOLCANO.



Qa	Valley alluvium
Qh	Hillside colluvium and talus
Ql	Landslide
Ta2	Andesite (younger)
Ta1	Andesite (older)
Ts	Santa Fe Formation
x4	Sample locations

FIGURE 26—GEOLOGIC MAP OF TOME HILL.



Qa	Alluvium
Qt	Talus
Tr	Rhyolite
Ta	Andesite porphyry
Tba	Basaltic andesite
x⁷	Sample locations

FIGURE 28—GEOLOGIC MAP OF BLACK BUTTE.

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