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New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico

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ABSTRACT

The aerial distribution, dissection, and stratigraphic relations of Pliocene and younger mafic volcanic flows indicate that the Rio Grande in central New Mexico became a throughflowing drainage system during late Pliocene time (between about 3.0 and 4.5 m.y. ago). K-Ar dates indicate that the course of the Rio Grande was established more than 4.0 m.y. ago in central New Mexico and about 3.0+ m.y. ago in north-central New Mexico. The Ortiz geomorphic surface was probably graded to the ancestral Rio Grande about 3 m.y. ago and is considerably older than the Llano de Albuquerque surface. The central Rio Grande region has been warped and faulted since late Pliocene time. A complex fault block in the southeastern part of the Albuquerque-Belen Basin includes volcanic rocks more than 20 m.y. old that originated from southwestern New Mexico before rifting of the Rio Grande depression.

INTRODUCTION

The Rio Grande and its principal tributaries, the Rio Salado, Rio Puerco, and Jemez River, form a major drainage system in central New Mexico that has been studied by numerous geologists both for its economic importance and for its well-displayed geomorphic and geologic features. The Rio Grande generally follows a valley of diverse structural and geomorphic history, and these studies have fostered a wide variety of geologic concepts. We emphasize here the history of the drainage system during the past 3 to 4 m.y., as demonstrated by the field relations of volcanic rocks dated by K-Ar methods.

The present Rio Grande flows through a series of intermontane basins partly filled with Cenozoic fanglomerates and related piedmont deposits of the Santa Fe Group. The river breached some of these basins relatively late in their history, resulting in an integrated drainage system that postdates deposition of the main part of the Santa Fe Group.

Many of the basic concepts of the geologic history of this region were established by Bryan (1938), Bryan and McCann (1937, 1938), Denny (1941), Wright (1946), Kottlowski (1958), Spiegel and Baldwin (1963), Hawley and others (1969), Chapin and Seager (1975), and Hawley (1975).

LABORATORY METHOD

All analytical and sample-preparation work was performed in the laboratories of the U.S. Geological Survey in Denver. Argon analyses were made on a Nier-type 15-cm 60° mass spectrometer under static conditions using isotope dilution techniques. A programmable desk calculator, interfaced with the mass spectrometer, was used in the data acquisition and the age and standard-deviation calculations. The K_2O content of the samples was determined by a flame photometer with a Li internal standard. The argon extraction procedure follows closely the one described by Evernden and Curtis (1965). The plus-or-minus value for each age determination is the overall standard deviation of analytical precision at the 95% confidence level, calculated from the uncertainty of the Ar^{38} tracer and argon measurements and the estimated errors of the potassium analyses and discrimination factor; however, it does not include any uncertainty in the decay constant. The largest percentage of the analytical error arises from the potassium determination, except where the radiogenic argon content falls below 20%. Table 1 gives a summary of the analytical data, K-Ar dates, and sample localities.

GEOLOGIC SETTING AND INTERPRETATION OF K-AR DATES

Early Basins in Rio Grande Region

During early Tertiary time (Eocene and Oligocene?) the central Rio Grande region was characterized by broad internally drained basins. Remnants of these basins are represented by red beds and conglomerates of the Galisteo and Baca Formations. Sediments deposited in these early basins do not indicate volcanism in the region, and the configuration of the basins is poorly understood. Volcanism began in the region about 37 m.y. ago, and from Oligocene through Miocene[1] time smaller basins developed over pre-existing structures (Chapin and Seager, 1975, p. 312). Volcanic rocks of this age are conspicuously represented in southwestern New Mexico by the Datil-Mogollon province. Volcanism of approximately equivalent age is represented in north-central New Mexico by the Abiquiu Tuff of Smith (1938) and the Espinaso Volcanics of Stearns (1953). Most of these middle Tertiary volcanic deposits consist of intermediate breccias and flows and of rhyolitic to latitic ash-flow tuffs; basaltic andesite flows are abundant in the upper parts of the volcanic piles.

Beginning in late Miocene time (Chapin and Seager, 1975), these broad middle Tertiary basins were fragmented into several smaller intermontane basins, which are still recognizable in the present landscape as the Albuquerque-Belen, La Jencia, San Marcial, Engle, and Palomas Basins (Fig. 1). Faulting and volcanism accompanied the formation of these basins and continued intermittently through Pliocene and into Quaternary time. The volcanism was largely

[1] In this paper, the Pliocene-Pleistocene boundary is placed arbitrarily at 1.8 m.y. B.P., and the Miocene-Pliocene boundary is at 5.0 m.y. B.P.

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TABLE 1. ANALYTICAL DATA, K-AR DATES, AND SAMPLE LOCALITIES

Sample no. (Fig. 1)	DKA Lab no.	Location (lat N, long W)	Rock type or mineral	Na_2O (%)	K_2O% (%)	Ar^{40}rad (10^{-10} mol/g)	Ar^{40}rad (%)	Age (m.y. +2σ)	Comments
1	3080	35°15′, 106°17′	Basalt	2.95, 2.96	1.43, 1.42	0.207	50.5	9.8 ± 0.4	North-trending dike cutting Abiquiu Formation.
2	3070	35°47′, 106°14′	Basalt	3.32, 3.33	0.98, 0.98	0.038	13.7	2.6 ± 0.4	Basalt flow rests on ancestral Rio Grande river gravel in Puye Formation. Alamo Canyon, minor western tributary to White Rock Canyon south of town of White Rock
3	3292	35°41′, 106°18′	Basalt	4.40, 4.42	2.03, 203	0.074	28.7	2.5 ± 0.3	Basalt flow rests on river sand and gravel and overlain by river gravel in Puye Formation. Basalt derived from Cerros del Rio field. White Rock Canyon at mouth of Medio Canyon
4	3297	35°39′, 106°07′	Basalt	3.96, 4.01	2.23, 2.24	0.085	24.6	2.6 ± 0.3	Two samples of basalt at same locality. Sample 3297 is basaltic cinders; sample 3295 basalt flow. Basalts overlie Ancha Formation, which may be equivalent to upper part of Puye Formation. Camel tracks are in basaltic cinders underlying this localty
	3295	35°39′, 106°07′	Basalt	3.63, 3.66	2.11, 2.11	0.078	54.5	2.5 ± 0.2	
5	3067	35°38′, 105°58′	Andesite	4.11, 4.12	5.03, 5.07	1.89	84.3	25.3 ± 0.6	Two samples, same locality of andesitic flow in Arroyo Hondo south of Santa Fe. Mapped as porphyritic augite andesite by Spiegel and Baldwin (1963, p. 36, Pl. 4)
	3068	35°38′, 105°58′		3.90, 3.85	3.54, 3.45	1.29	86.3	24.9 ± 0.6	
6	3071	35°33′, 107°17′	Basalt	4.87, 4.85	2.01, 1.99	0.084	40.7	2.8 ± 0.2	Basalt flow on Mesa Chivato, north of Mt. Taylor. Rests on geomorphic surface correlative with Ortiz surface (Bryan and McCann, p. 8, Fig. 2). Indicates minimum age for Ortiz surface in this area
7	3058	36°30′, 106°11′	Basalt	3.77, 3.67	1.54, 1.50	0.063	33.0	2.8 ± 0.1	Basalt flow from Cerros del Rio field. Rests on Ortiz surface as defined by Bryan and McCann (1938, p. 8, Fig. 2). Surface is cut on Ancha Formation. Indicates minimum age for Ortiz surface in this area
8	3127	35°27′, 106°08′	Hornblende	1.97, 1.98	1.03, 1.03	0.725	77.0	47.1 ± 3.2	Latite intrusive from southern part of Cerrillos Hills. (Re-entrant north of knob known locally as Devil's Throne)
9	3294	35°23′, 106°33′	Basalt	3.01, 2.98	0.82, 0.82	0.030	21.1	2.5 ± 0.3	Basalt flow, south part of Santa Ana Mesa. Basalt rests on surface correlated with Ortiz surface by Bryan and McCann (1938, p. 8, Fig. 2)
10	3126	35°21′, 106°11′	Hornblende	1.75, 1.74	1.06, 1.07	0.539	64.2	34.0 ± 2.2	Latite intrusive (sill), west side of Ortiz intrusive complex, Ortiz Mountains
11	2324	37°10′, 106°45′	Basalt		0.45, 0.45	0.0012	1.0	0.19 ± 0.04	Basalt flow, Albuquerque volcanoes. Rests on dissected surface younger than Llano de Albuquerque surface. Indicates minimum age for Llano de Albuquerque (Bachman and others, 1975)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.0	0.32 ± 0.2	[illegible]
13	2321	[illegible]	[illegible]						Basalt flow in Rio San Jose, tributary to Rio Puerco. Flow follows [illegible]

12	3064	34°54', 107°35'	Basalt	2.51,	2.55	0.77,	0.78	0.0037	2.0	0.32 ± 0.2	Basalt flow in Rio San Jose, tributary to Rio Puerco. Flow follows modern drainage system
13	2321	35°48', 106°48'	Basalt			2.53,	2.57	0.038	4.0	1.01 ± 0.10	Basalt flow, Cerro de Los Lunas
	2322	35°48', 106°46'	Basalt			2.33,	2.30	0.045	9.0	1.31 ± 0.05	Underlies Llano de Albuquerque surface and indicates a maximum age for that surface (Bachman and others, 1975)
	2323	35°47', 106°47'	Basalt			2.54,	2.51	0.042	22.	1.12 ± 0.04	
14	3065	34°46', 106°42'	Basalt	3.95,	3.96	3.10,	3.10	0.154	13.6	3.4 ± 0.4	Basaltic plug, El Cerro (Tome)
15	3281	34°44', 107°14'	Basalt	3.61,	3.59	2.37,	2.34	0.249	38.5	7.2 ± 0.6	Basalt flow, Mesa Gallina
16	3276	34°43', 107°06'	Basalt	3.22,	3.22	1.13,	1.12	0.062	33.6	3.7 ± 0.4	Basalt flow, Mesa Carrizo. Basalt rests on deposit of travertine and indicates a minimum age for the travertine along Comanche fault zone. Other deposits of travertine in area are much younger
17	3069	34°42', 106°28'	Basalt	3.17,	3.18	1.79,	1.78	0.561	65.3	21.2 ± 0.8	Basalt flow standing vertically in faulted sequence of lower Sante Fe sandstones and conglomerates
18	3296	34°26', 107°26"	Basalt	3.08,	3.08	0.73,	0.74	0.034	12.8	3.1 ± 0.5	Basalt flow capping Mesa del Oro
19	3280	34°24', 106°41'	Basalt	3.06,	3.04	3.46,	3.41	1.241	75.9	24.3 ± 1.5	Basalt flow at Black Butte (Turututu)
20	3216		Biotite	1.17,	1.18	7.44,	7.39	2.897	82.8	26.3 ± 1.1	Andesite at base, or underlying, Popotosa Formation
21	3062	34°16', 106°58'	Basalt	5.25,	5.27	3.32,	3.32	0.222	64.8	4.5 ± 0.1	Basalt flow at San Acacia underlies axial river deposits
22	3128	34°15', 106°49'	Sanidine	4.85,	4.57	9.25,	9.27	3.547	82.6	25.8 ± 1.0	Vitrophyre in Tertiary volcanic sequence east of Joyita uplift, Socorro County
23	3061	34°08', 106°30'	Basalt	4.41,	4.45	2.11,	2.14	0.109	27.2	3.5 ± 0.2	Basalt flow on Black Mesa, eastern Socorro County
24	3278	34°05', 107°23'	Basalt	4.20,	4.19	1.74,	1.72	0.419	69.9	16.3 ± 1.1	Basalt flow, highly dissected, capping lower Miocene gravels west of Magdalena
25	3059	34°01', 106°59'	Basalt	3.15,	3.22	0.75,	0.78	0.045	23.5	4.0 ± 0.3	Basalt flow, Black Mountain, Socorro Canyon about 10 km (6 mi) southwest of Socorro. Overlies fluvial sand and gravel of ancestral Rio Grande and indicates minimum age for river deposits at this locality
26	3060	33°40', 106°58'	Basalt	3.16,	3.21	1.69,	1.73	0.056	34.3	2.2 ± 0.10	Basalt flow, Black Butte at San Marcial, east side of Rio Grande. Overlies cross-bedded fluvial sand and gravel of ancestral Rio Grande and indicates minimum age for river system at this locality
27	3063	33°33', 106°59'	Basalt	3.41,	3.47	1.29,	1.27	0.014	9.7	0.76 ± 0.1	Basalt flow in Jornada del Muerto; may be partially exhumed
28	3275	33°21', 107°11'	Basalt	2.66,	2.73	1.13,	1.15	0.048	39.2	2.9 ± 0.3	Basalt flow at Mitchell Point, west side of Rio Grande. Basalt is interbedded with sand and gravel of ancestral Rio Grande and indicates minimum age of river system at this point
29	3277	33°09', 107°06'	Basalt	3.16,	3.11	1.14,	1.13	0.035	16.8	2.1 ± 0.4	Cinder cone southwest of Engle about 6 km (3.5 mi)

Note: Na_2O, K_2O determination with flame photometer by Violet Merritt. K-Ar age determination by H. H. Mehnert. Constants: K^{40}: $\lambda_\epsilon = 0.584 \times 10^{-10}$/yr; $\lambda_\beta = 4.72 \times 10^{-10}$/yr; atomic abundance: $K^{40}/K = 1.19 \times 10^{-4}$.

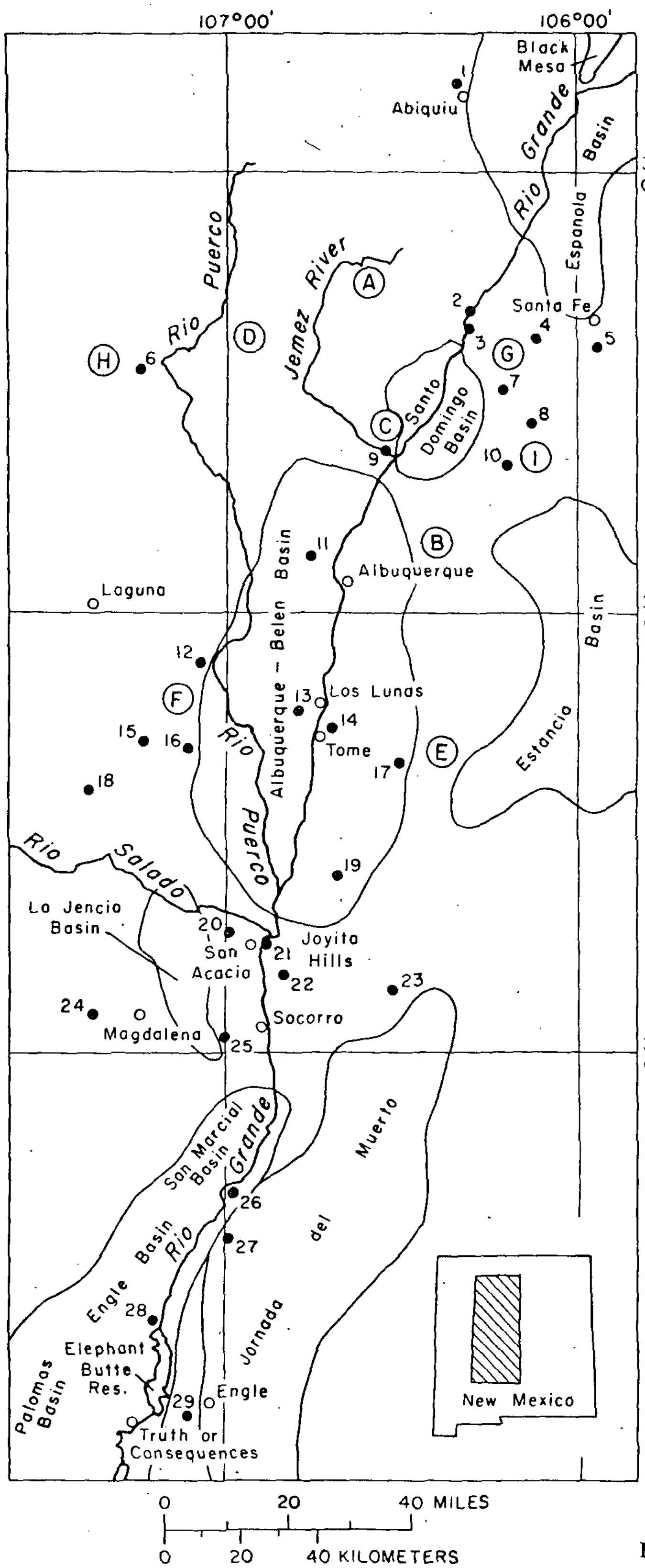
basaltic except for the rhyolitic ash-flow tuffs and pumice of the Jemez caldera and the silicic domes and flows of the Socorro Peak area.

The present intermontane basins have been partly filled with fanglomerate and other bolson deposits, which are assigned to various formations of the Santa Fe Group, ranging from Miocene to Pleistocene in age. However, the Santa Fe Group is poorly understood south of the Española Basin, and correlative units from basin to basin are poorly defined.

Breaching and widespread erosion of the intermontane basins occurred during entrenchment of the Rio Grande drainage system in late Pliocene and early Pleistocene time. Remnants of the ancestral axial Rio Grande stream deposits interfinger in places with fan and piedmont deposits in the upper Santa Fe. These axial deposits include the Totavi Lentil of the Puye Formation and other river gravels in the Puye and Ancha Formations of the Santa Fe Group in White Rock Canyon and adjacent areas, the upper gray member of the Santa Fe Formation in the northern part of the Albuquerque-Belen Basin (Bryan and McCann, 1938), local stream deposits of Blancan provincial age (of Wood and others, 1941) in the southern part of the Albuquerque-Belen Basin (Needham, 1936), and the Camp Rice Formation of Strain (1966) in south-central New Mexico.

Ortiz Surface

After the intermontane basins were breached by the Rio Grande system in Pliocene time, an extensive graded surface was formed. In the vicinity of the Ortiz Mountains and the Cerros del Rio, this is called the "Ortiz surface" (Bryan, 1938; Bryan and McCann, 1937, 1938), but the wording of the original definition of this surface allows several logical interpretations of its position in the landscape.



A, Jemez Mountains; B, Sandia Mountains; C, Santa Ana Mesa; D, Nacimiento Mountains; E, Manzano Mountains; F, Lucero Mesa; G, Cerros del Rio; H, Mesa Chivato; I, Ortiz Mountains

Sample Localities
(solid dots on map)

1. Basaltic dike cutting Abiquiu Formation, Canyon del Cobre
2. Basalt flow in Puye Formation, Ancho Canyon
3. Basalt flow in Puye Formation, White Rock Canyon, mouth of Medio Canyon
4. Basalt flow and cinders, east side of Cerros del Rio
5. Trachyte(?), Hondo Canyon
6. Basalt flow, Mesa Chivato
7. Basalt flow, southern part Cerros del Rio
8. Cerrillos Hills
9. Basalt flow, Santa Ana Mesa
10. Sill, Ortiz Mountains
11. Basalt, Albuquerque Volcanos
12. Basalt, Rio San Jose
13. Basalt, Cerros de Los Lunas
14. Basalt, Cerro Tome
15. Basalt, Gallina Mesa
16. Basalt, Lucero Mesa near Comanche fault zone
17. Basalt, Kennedy Campground, front of Manzano Mountains
18. Basalt, Mesa del Oro
19. Basalt, Black Butte (Turututu)
20. Andesite, in Popotosa Formation
21. Basalt, San Acacia
22. Vitrophyre in "Datil volcanics," Joyita Hills
23. Basalt, Black Mesa
24. Basalt, Council Rock
25. Basalt, Black Butte, Socorro Canyon
26. Basalt, Black Butte near San Marcial
27. Basalt, Jornada del Muerto basalt field
28. Basalt, Mitchell Point
29. Basalt, Cinder cone

Figure 1. Index map showing major geographic features and localities sampled.

Bryan and McCann (1938, p. 78) stated:

> The Rio Grande depression is characterized by the presence of remnants of once broad erosion surfaces. These remnants stand at widely different elevations and their degree of preservation is variable from place to place. However, they all slope toward the general position of the Rio Grande and belong to a succession of erosional surfaces representing successive stabilized grades of this master stream. In the region south of White Rock Canyon the oldest and highest of these remnants appear to be parts of the Ortiz surface, a widely developed and excellently preserved surface in the vicinity of the Ortiz Mountains, first described by Ogilvie (1905). Although Ogilvie described but one surface in the type area, there appear in fact to be three, and it is the highest of these that is here named the Ortiz surface. It slopes outward on all sides away from the mountain and, if restored to its original condition, would be a low cone, the "conoplain" of Ogilvie. It cuts the hard rocks at the foot of the mountains and extends westward across the deformed Santa Fe Group.

The wording of the original definition of the Ortiz surface — in particular, the last sentence — has been variously interpreted by other workers. For example, a prominent unconformity underlying the fan deposits (the Tuerto Gravel of Stearns, 1953, and the Ancha Formation) in the type area near the Ortiz Mountains has been interpreted as the "Ortiz surface," in keeping with the statement that the surface extends across the Santa Fe Group (Spiegel and Baldwin, 1963). Spiegel and Baldwin (1963, p. 60) stated that "the 'Ortiz surface' . . . is actually compound, representing a sequence of erosion, deposition, and probably erosion again." In a diagram showing the nomenclature of the Santa Fe Group, they indicated one lower and two upper "Ortiz" surfaces (Spiegel and Baldwin, 1963, p. 58, Fig. 20).

We recognize that the Ortiz surface is a complex geomorphic feature, but we believe that only one surface is properly identified as the Ortiz. This restriction is important to an understanding of the geologic history of the region. Bryan and McCann (1938, p. 8) stated specifically that the Ortiz is the highest of three surfaces. Although this surface could be interpreted as including the surface formed by lava flows in the Cerros del Rio field, Bryan and McCann (1938, Fig. 2) clearly indicated the Cerros del Rio as "lava capped remnants of the Ortiz surface." These words obviously mean that lavas of the Cerros del Rio rest on the Ortiz surface.

Accordingly, we here restrict the term "Ortiz surface" to the upper surfaces of the Puye Formation in the Cerros del Rio region, "river gravels," Ancha Formation, and Tuerto Gravel. The basalt of the Cerros del Rio overlies the Puye, river gravels, and part of the Ancha (Fig. 2). The Ortiz surface appears to slope outward on all sides from the Ortiz Mountains. We have traced this surface in its type area and have observed strong calcic paleosols on the Ancha Formation and below the basalt at many places. High remnants of the Tuerto Gravel are cemented in part by similar paleosols. The paleosols suggest a relatively long period of stability after deposition of the Ancha and Tuerto, and the surface on which they accumulated was probably of regional extent. The interbedding of gravels of the ancestral Rio Grande with the Ancha Formation and its equivalents (Fig. 2) suggests that the Ortiz surface was graded to the ancestral Rio Grande during Ancha time.

We also follow the precedent of Bryan and McCann (1938, Fig. 2) in correlating the surfaces that underlie the basalt flows at Santa Ana Mesa (Fig. 1, loc. C), Mesa Prieta, and Mesa Chivato (Fig. 1, loc. H) with the Ortiz surface. Surfaces below basalts at Mesa Carrizo (Fig. 1, loc. 16) and Mesa del Oro (Fig. 1, loc. 18) may also be correlative with the Ortiz, but extension of the term Ortiz beyond the Albuquerque-Belen Basin is premature because of faulting and warping of the surface over large areas of the Rio Grande depression by post-Ortiz tectonism. For example, as will be shown later, the correlation of the Ortiz surface with the Llano de Albuquerque surface (Bryan and McCann, 1938, p. 8) is not valid.

K-Ar dating shows the Ortiz surface to be about 3 m.y. old (Fig. 1; Table 1). Basalt on this surface at Cerros del Rio is variously dated at 2.8 ± 0.1 m.y. (Fig. 1, loc. 7), 2.6 ± 0.3 m.y. (loc. 4), and 2.5 ± 0.2 m.y. (loc. 4, cinders). Basalt at Santa Ana Mesa that rests on a surface correlative with the Ortiz is 2.5 ± 0.3 m.y. old (loc. 9), and basalt at Mesa Chivato is 2.8 ± 0.15 m.y. old (loc. 6). Volcanic

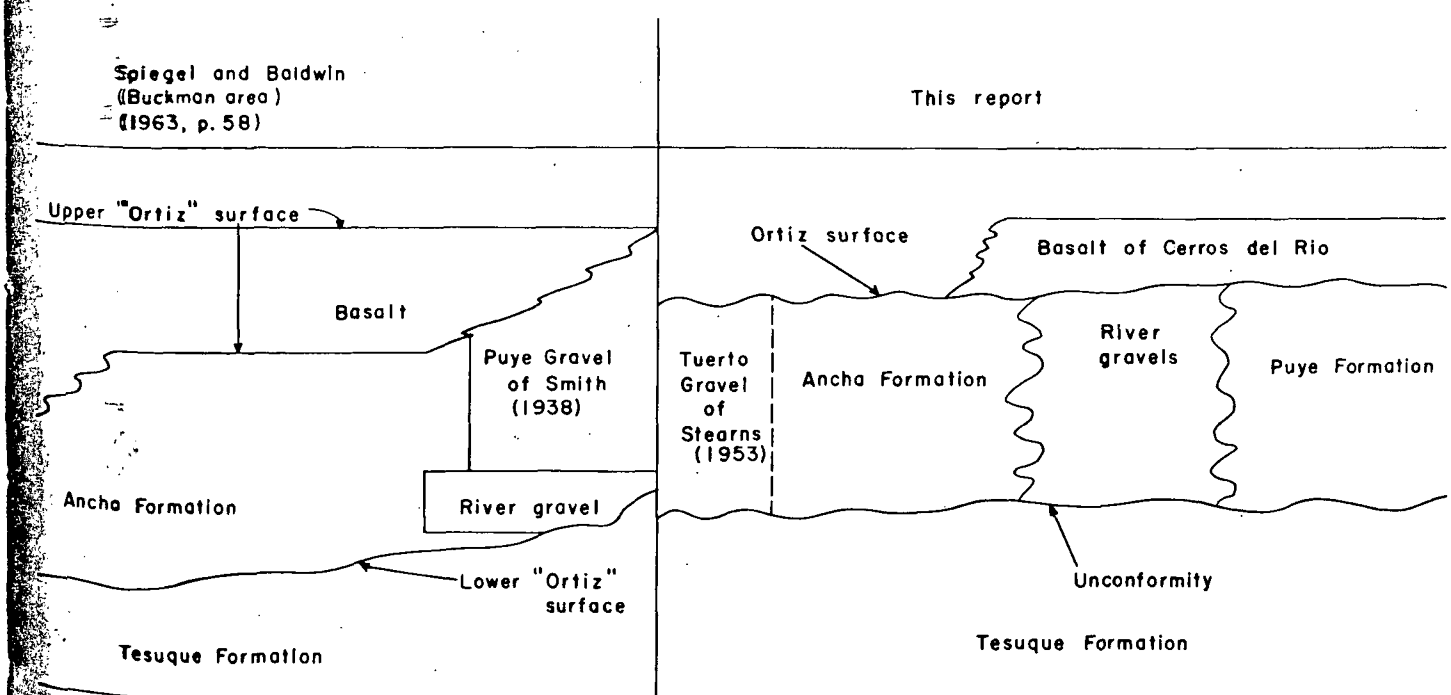


Figure 2. Diagram showing stratigraphic relations and position of Ortiz surface.

ash near the top of the Ancha Formation and directly underlying the Ortiz surface in Ancha Canyon (about 12 km north of loc. 4) has been dated at 2.7 ± 0.4 m.y. by the fission-track method (Manley, 1976a).

Faulting of Ortiz Surface

Tectonism, volcanism, and erosion were dominant processes in the central Rio Grande region following development of the Ortiz surface. The Guaje Pumice Bed of the Otowi Member of the Bandelier Tuff (Bailey and others, 1969) erupted about 1.4 m.y. ago (Doell and others, 1968); its eruption marked the beginning of Quaternary rhyolitic volcanism of regional significance. This volcanism was accompanied by uplift of the Jemez Mountains and was followed by collapse in the Santo Domingo Basin and the northern part of the Albuquerque-Belen Basin. Basalts of the Cerros del Rio and the underlying Ortiz surface were warped and faulted in White Rock Canyon (Fig. 1, near loc. 3). The basalts at Santa Ana Mesa were cut by numerous faults and have a cumulative downward displacement toward the east. The Ortiz surface appears to have collapsed and to be covered by fluvial deposits east of Santa Ana Mesa in the Santo Domingo Basin, and possibly in the Albuquerque-Belen Basin.

Age of Rio Grande Drainage System

Relations of stream deposits with dated volcanic rocks indicate that the Rio Grande became a major through-flowing stream during Pliocene time. In White Rock Canyon (Fig. 1, loc. 3) ancestral Rio Grande stream deposits in the Puye Formation range from sand to well-rounded cobble gravel and include clasts of Precambrian quartzite, granite, and rhyolite. The gravels resemble the Totavi Lentil of the Puye Formation as described by Griggs (1964), but they are present at many horizons in the Puye Formation. The source of these sediments is to the north or northeast, indicating that the Rio Grande drained southward, at least intermittently, from the Española to the Santo Domingo Basin while the basalts of Cerros del Rio were being erupted.

In Ancho Canyon, a tributary to the Rio Grande at the north end of White Rock Canyon, a basalt of the Cerros del Rio field dated at 2.6 ± 0.4 m.y. (Fig. 1, loc. 2) rests on a stream deposit of cobble conglomerate that contains exotic pebbles from the north. At the mouth of Medio Canyon near the southern end of White Rock Canyon, a basalt flow 2.5 ± 0.3 m.y. old (loc. 3) interfingers with alluvial sand and cobble gravel with similar exotic pebbles. These data indicate that the ancestral Rio Grande is at least 2.5 m.y. old in this area. At the southern end of Black Mesa in the Española Basin (Fig. 1), basalt dated as about 2.78 m.y. old (Manley, 1976b) rests on stream deposits that may be related to the ancestral Rio Grande. The surface below this basalt is interpreted to be the Ortiz surface.

In the Socorro area, the ancestral Rio Grande may be bracketed between about 4.0 and 4.5 m.y. ago. At Black Mesa near Socorro, basalt 4.0 ± 0.25 m.y. old (loc. 25) rests on alluvial sand that appears to be related to the ancestral Rio Grande drainage system. At San Acacia a basaltic flow that underlies these ancestral Rio Grande deposits is dated as 4.5 ± 0.1 m.y. old (Fig. 1, loc. 21). At Black Mesa on the east side of the San Marcial Basin, strongly cross-bedded alluvial sand underlies a basalt that is 2.2 ± 0.1 m.y. old (loc. 26).

The Camp Rice Formation of Strain (1966) has been traced northward from the El Paso, Texas, region into the lower Palomas Basin (Seager and Hawley, 1973). A further northward extent is suggested by exposures at Mitchell Point, where basalt interbedded in alluvial sand apparently equivalent to the Camp Rice Formation is dated as 2.9 ± 0.3 m.y. old (loc. 28).

Modifications in Gradient of Rio Grande

At most places from the Santo Domingo Basin south to Elephant Butte Reservoir, the Rio Grande has remained near its present channel since Pliocene time. The westernmost deposits of the Rio Grande underlie the Llano de Albuquerque in the Albuquerque-Belen Basin (Fig. 2) at elevations as much as 150 m above the present flood plain. Fluvial deposits on the east mingle with fan deposits derived from the Sandia and Manzano Mountains (Fig. 1, loc. B southward to loc. E). Also, about 6.5 km northeast of Socorro, sand deposits of late Pliocene (Blancan) age (Needham, 1936) from the ancestral Rio Grande are interbedded with fan deposits derived from the Joyita Hills and adjacent uplands. The sands rise 85 m in altitude northward over a distance of about 11 km along the east side of the Rio Grande, representing a gradient of about 7.7 m/km (about 40 ft/mi), compared with the existing gradient of about 1.0 m/km (about 5 ft/mi). It appears that these Pliocene channel sands have been uplifted near the Joyita Hills during Quaternary time. Reilinger and Oliver (1976) suggested a present uplift rate of about 4 to 6 mm/yr in this area. A date of 0.76 ± 0.1 m.y. (loc. 27) for a basalt flow in the Jornada del Muerto, along the margin of the modern Rio Grande flood plain, suggests that the Rio Grande south of Socorro has been near its present altitude during the past 760,000 yr.

Llano de Albuquerque and Correlative Geomorphic Surfaces

A period of widespread tectonic stability during middle Pleistocene time is expressed by a complex geomorphic surface, the Llano de Albuquerque, which probably formed as part of a broad basin floor in the Albuquerque-Belen Basin (Fig. 3). This surface is about 140 to 150 m above the present flood plain of the Rio Grande. Some previous workers (Bryan and McCann, 1938; Spiegel, 1961, p. 136) have correlated the Llano de Albuquerque surface with the Ortiz surface, but dates obtained during our study demonstrate otherwise. Mafic flows at Los Lunas (Fig. 1, loc. 13) dated as 1.1 to 1.3 m.y. old (Bachman and others, 1975), are overlain by alluvial sediments of the Santa Fe Group that form the Llano de Albuquerque surface (Fig. 4). In addition, a silicic ash-fall tuff that underlies paleosols of the Llano de Albuquerque surface at Los Lunas is identified as an air-fall unit of the Tsankawi Pumice Bed of the Tshirege Member of the Bandelier Tuff (Kim Manley 1976, written commun.), which is dated as about 1.1 m.y. old (Doell and others, 1968). These dates indicate that the Llano de Albuquerque surface is less than 1.1 m.y. old. The stable interval represented by the Llano de Albuquerque began about 500,000 yr ago (Hawley and others, 1976), as indicated by correlatives of this surface that overlie Pearlette type O volcanic ash (about 500,000 yr old) in southern New Mexico.

The Llano de Albuquerque is approximately equivalent to the basin-floor (La Mesa) surface in the southern part of the Rio Grande depression. A relatively thick calcic paleosol (pedogenic caliche) forms a caprock on the Llano de Albuquerque. The caliche ranges in degree of development from a strong stage III to a weak stage IV (Gile and others, 1966) and contains about 70% as much

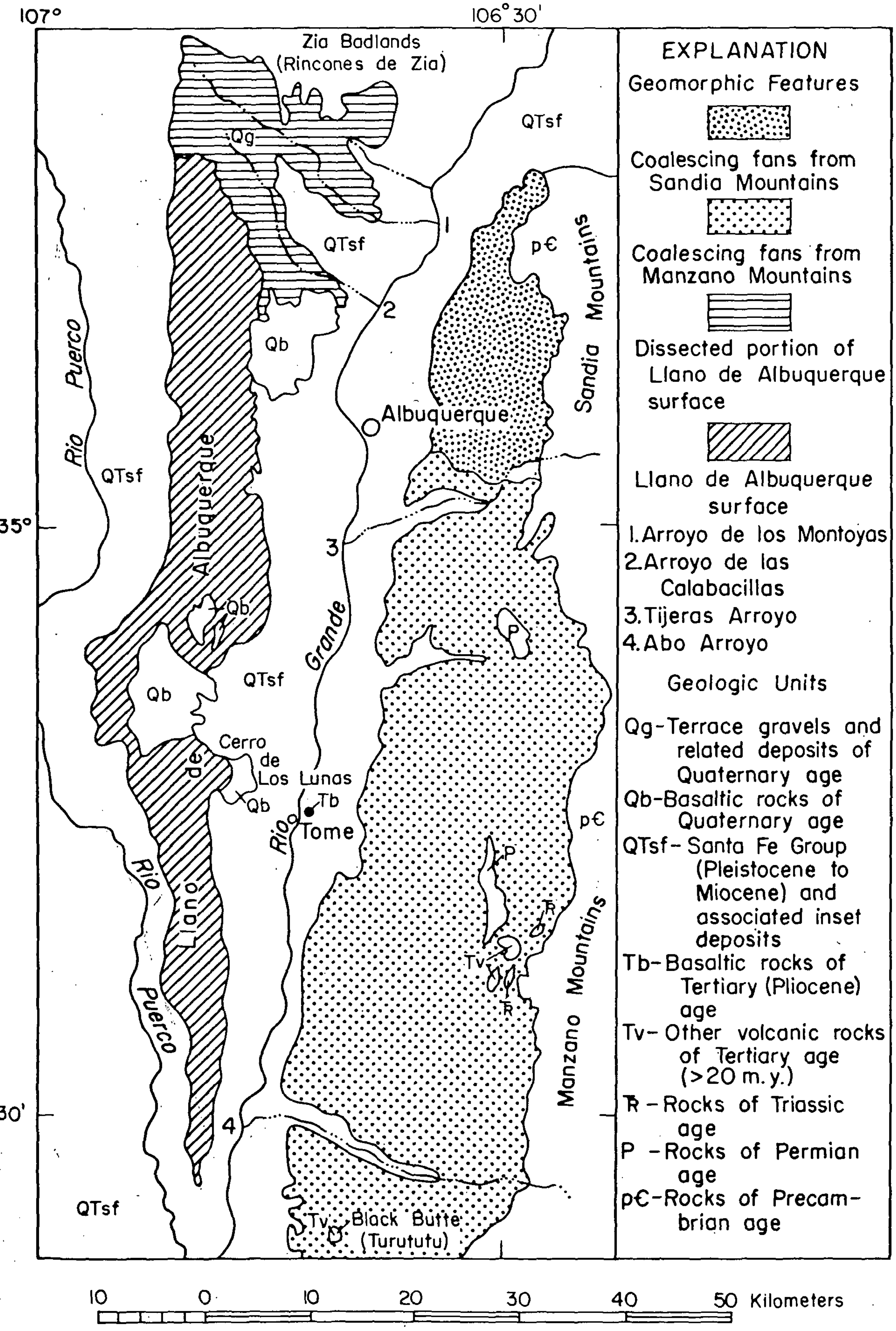


Figure 3. Index map of central part of Albuquerque-Belen Basin, showing geomorphic features of Pleistocene age and associated deposits.

$CaCo_3$ as the caliche underlying the La Mesa surface. However, the paleosols of both areas are generally comparable in morphology. The lower carbonate content in the caliche at the Llano de Albuquerque may be attributed either to a different rate of $CaCO_3$ influx or to a difference in present or former climates at that latitude. Basalt flows of the Albuquerque volcanoes (Fig. 1, loc. 11) are 0.19 m.y. old; they rest on and flowed over the dissected edge of the Llano de Albuquerque (Bachman and others, 1975). This date provides a minimum age for the Llano de Albuquerque.

The Llano de Albuquerque has been strongly dissected from the vicinity of Arroyo de las Calabacillas (Fig. 3) northward to the rim of the Zia Badlands (Ceja of the Rincones de Zia of Bryan and McCann, 1938, p. 3). Alluvial gravel and conglomerate in channels that dissect the Llano de Albuquerque in the western part of this area contain clasts that could have been derived only from Mesa Chivato and adjacent areas to the west (Fig. 1, loc. H) or from the Nacimiento Mountains to the north (Fig. 1, loc. D). Some of these gravels may have been reworked from the underlying Santa Fe Group, but they rest unconformably on the Santa Fe along the rim of the Zia Badlands. These gravels were deposited by a southeasterly flowing stream that crossed the modern Rio Puerco and Jemez Creek systems, an observation also made by Bryan and McCann (1938). Indirect evidence from K-Ar dates indicate that this ancestral drainage system was initiated less than 500,000 yr ago. Basalt from the vents of the Albuquerque volcanos may rest on stream gravels of this ancestral drainage system. The presence of this

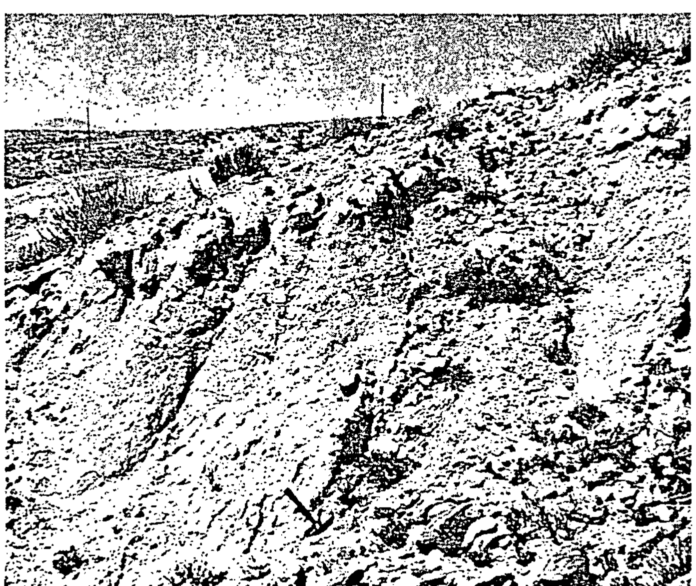


Figure 4. Mafic lava flow from Los Lunas volcano interbedded with alluvial deposits of Santa Fe Group (Miocene-Pleistocene). Hammer rests on volcanic rock overlain by Santa Fe siltstone; volcanic rock fragments cover background.

drainage system extending from Mesa Chivato and the Nacimiento Mountains to the neighborhood of Albuquerque indicates that neither the Rio Puerco nor Jemez Creek followed their present course, and, possibly, neither existed during middle Pleistocene time. We conclude that in the northern part of the Albuquerque-Belen Basin the structural basin has been uplifted along its western edge or that this part of the Rio Grande depression has subsided since middle Pleistocene time.

The Llano de Manzano is a low-relief surface formed by coalescing fans derived from the Manzano Mountains along the east side of the Rio Grande from Albuquerque to Black Butte (Turututu). This surface is graded to an altitude about 110 m above the present flood plain and is younger than the Llano de Albuquerque surface. Quantitative studies of calcic paleosol on the Llano de Manzano suggest that the surface may be about 200,000 to 300,000 yr old.

Both the Llano de Albuquerque and the Llano de Manzano have been offset by high-angle Quaternary faults. Some faulting on the Llano de Albuquerque has been recurrent and may have taken place at intervals within the past 400,000 to 25,000 yr (Machette, 1976).

SIGNIFICANCE OF OTHER K-Ar DATES RESULTING FROM THIS STUDY

Many features that have been dated do not bear directly on the chronological development of the Rio Grande drainage system but add to the understanding of regional geology.

In the northern part of the study area, the Abiquiu Tuff of Smith (1938), a unit of weathered silicic volcanic debris of Tertiary age, underlies the Santa Fe Group (Miocene-Pleistocene). A conspicuous mafic dike that cuts the Abiquiu is dated as 9.8 ± 0.4 m.y. old (Fig. 1, loc. 1) and provides a minimum age for this formation. However, the Abiquiu is probably much older.

Two samples from a steeply dipping andesitic flow in Arroyo Hondo Canyon, south of Santa Fe, yield dates of 25.3 ± 0.6 and 24.9 ± 0.6 m.y. B.P. (Fig. 1, loc. 5). The flow rests on the Galisteo(?) Formation (Eocene and Oligocene?) as mapped by Spiegel and Baldwin (1963, Pls. 1, 4). Farther south in the Cerrillos Hills (Fig. 1, loc. 8), the Galisteo is generally overlain by latitic flows or other volcanic debris of the Espinaso Volcanics (Oligocene). The K-Ar ages suggest that the flows in Arroyo Hondo are late Oligocene and may be equivalent to part of the Espinaso Volcanics.

Latite sills from the Cerrillos Hills (Fig. 1, loc. 8) and the Ortiz Mountains (Fig. 1, loc. 10) are 47.1 ± 3.2 m.y. and 34.0 ± 2.2 m.y. old, respectively. The sample from the Cerrillos Hills (sample 8) may have been contaminated by inclusions, and the Oligocene age of the latite on Ortiz Mountain is probably more representative of the age of their intrusions. The Ortiz Mountains and Cerrillos Hills may have been source areas for the Espinaso Volcanics.

From San Acacia and the Joyita Hills northward to the front of the Manzano Mountains are many outcrops of volcanic rocks that are known, or suspected, to be of Oligocene or Miocene age. Because they occur mostly as isolated inliers, the following volcanic rocks were dated to determine their relative age relationships: (1) a steeply dipping to vertical basaltic flow about 21 km southeast of Tome and about 3 km west of the front of the Manzano Mountains previously was thought to be of Quaternary age (Read and others, 1944), but yields a K-Ar age of 21.2 ± 0.8 m.y. (Fig. 1, loc. 17); (2) a basaltic flow at Black Butte, locally known as Turututu, is 24.3 ± 1.5 m.y. old (Fig. 1, loc. 19); (3) an andesite flow near the base of the Popotosa Formation west of San Acacia is 26.3 ± 1.1

m.y. old (Fig. 1, loc. 20); and (4) a vitrophyre near the top of a middle Tertiary volcanic sequence in the southeastern part of the Joyita Hills is 25.8 ± 1.0 m.y. old (Fig. 1, loc. 22). Although the sampled rocks are from within the Rio Grande depression, they are similar in both lithology and age to volcanic rocks to the west in central and western Socorro County. They are not correlative with the younger basalts and andesites in the Rio Grande trough. The distribution of the older volcanics suggests that they were once widespread in the Rio Grande region, before extensive late Miocene and Pliocene faulting.

Basaltic volcanism that extended in an east-west belt across the southern part of the Albuquerque-Belen Basin during Pliocene time is represented by isolated flows east of the Rio Grande depression (Fig. 1, loc. 23) and across the central part of the depression (Fig. 1, locs. 14 and 21). Extensive Pliocene flows west of the Albuquerque-Belen Basin are dated as from 3.1 to 4.5 m.y. old (Fig. 1, locs. 16 and 18). The 7.2 ± 0.6–m.y. age of a flow on Gallina Mesa (Fig. 1, loc. 15) is anomalous. To the south, near Engle, a relatively young cinder cone is dated as 2.1 ± 0.4 m.y. old (Fig. 1, loc. 29).

The youngest basalt flow studied is 0.32 ± 0.2 m.y. old (Fig. 1, loc. 12); it was erupted from Cerro Verde in eastern Valencia County and descended the relatively modern drainage system of the Rio San Jose, a tributary to the Rio Puerco.

SUMMARY

New K-Ar dates reported here provide a base for interpreting the late Tertiary and Quaternary history of the Rio Grande drainage system in central New Mexico. This history is particularly relevant to current studies of tectonics, geomorphology, and related soil formation. These dates indicate the following. (1) The Ortiz geomorphic surface in north-central New Mexico is about 3 m.y. old and is correlative with surfaces on Santa Ana Mesa and Mesa Chivato in nearby areas. (2) The Rio Grande became a through-flowing stream in central New Mexico about 3 m.y. ago to 4.5 m.y. ago. (3) The Llano de Albuquerque geomorphic surface in the Albuquerque-Belen Basin is probably about 500,000 yr old and is distinctly younger than the Ortiz surface. The degree of development of calcic soil (pedogenic caliche) that formed on the Llano de Albuquerque during the past 0.5 m.y. is useful for comparing its age with that of other Quaternary surfaces in the area. (4) The Rio Puerco drainage is younger than the Rio Grande drainage and is probably less than 0.5 m.y. old. (5) High-angle faults displace Quaternary geomorphic surfaces in many parts of the study area. Important fault movements accompanied collapse of the Santo Domingo Basin and the northern part of the Albuquerque-Belen Basin, recurrent offset of the Llano de Albuquerque surface, and displacement of fans in the southern part of the Albuquerque-Belen Basin.

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