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THE LATE CENOZOIC HISTORY OF THE ESPAÑOLA BASIN, NEW MEXICO

by

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The Late Cenozoic History of the Española Basin, New Mexico

Thesis directed by Professor William C. Bradley

The Española Basin is a structural and topographic basin along the Rio Grande rift. Rifting began in early Miocene time. During the Miocene a major drainage flowed from the Sangre de Cristo Mountains westward possibly as far as the San Juan Basin. Deposits of this drainage have not been previously recognized and are herein named the Cejita Member of the Tesuque Formation. It is characterized by well-rounded Precambrian quartzite and Paleozoic sedimentary clasts. Age determinations on pumice deposits in the piedmont facies of the Tesuque Formation, which interfinger with and overlie the Cejita Member, are 10.8 and 12.7 m.y.

The Chamita Formation, with fission-track ages of 5.2 and 5.6 m.y., was deposited by streams flowing from the Sangre de Cristo Mountains. This drainage was being blocked by the growth of the Jemez Mountains volcanic field. Following deposition of the Chamita Formation the center of the Española Basin was down-dropped. A period of erosion ensued which resulted in a wide-spread, graded surface upon which the younger deposits from a subsequent depositional cycle, unconformably rest.

The deposits overlying the unconformity include the first ancestral Rio Grande gravels, basalt flows of the Cerros del Rio field and Servilleta Formation, and sedimentary deposits of the Puye and Ancha Formations. Radiometric ages for these formations have been determined: the Cerros del Rio flows are as old as

2.6 m.y.; the Servilleta Formation in the Española Basin is 2.8 m.y.; the base of the Puye Formation is 2.9 m.y.; and the Ancha Formation includes a pumice 2.7 m.y. old and is overlain by a basalt with an age of 2.0 m.y. Lake deposits at the top of the Puye Formation imply a basin-wide lake in existence about 2.0 m.y. The Bandelier Tuff and Cerro Toledo Rhyolite were erupted between 1.4 and 1.1 m.y. Since their eruption and the cutting of White Rock Canyon through the Cerros del Rio field, the Española Basin has been eroded into the topographic basin present today.

This abstract is approved as to form and content. I recommend its publication.

Signed William C. Bradley
William C. Bradley

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CHAPTER I

INTRODUCTION

The Rio Grande rift consists of an alignment of Cenozoic structural and topographic basins that extend from central Colorado to southern New Mexico (Chapin, 1971; Chapin and Seager, 1975). Although related tectonically, the basins have evolved as separate entities. A regional understanding of the geologic history along the rift requires a knowledge of: 1) individual basin histories prior to integration by the Rio Grande, 2) the time of integration, and 3) the history since integration.

The Española Basin is the northernmost rift basin entirely within New Mexico. It extends from Santa Fe northward for 40 km along the Rio Grande. The basin is bounded on the east by the Sangre de Cristo Mountains and on the west by the Nacimiento uplift. The western half of the structural basin is filled with volcanic rocks of the Jemez Mountains which define the western edge of the topographic basin. The topographic Española Basin is 32 kilometres wide and is the subject of this dissertation (Fig. 1).

Several areas in and around the Española Basin have been studied in recent years. Cenozoic sediments in the east-central part of the basin have been described by Galusha and Blick (1971), in the northeastern portion by Miller and others (1963), and in

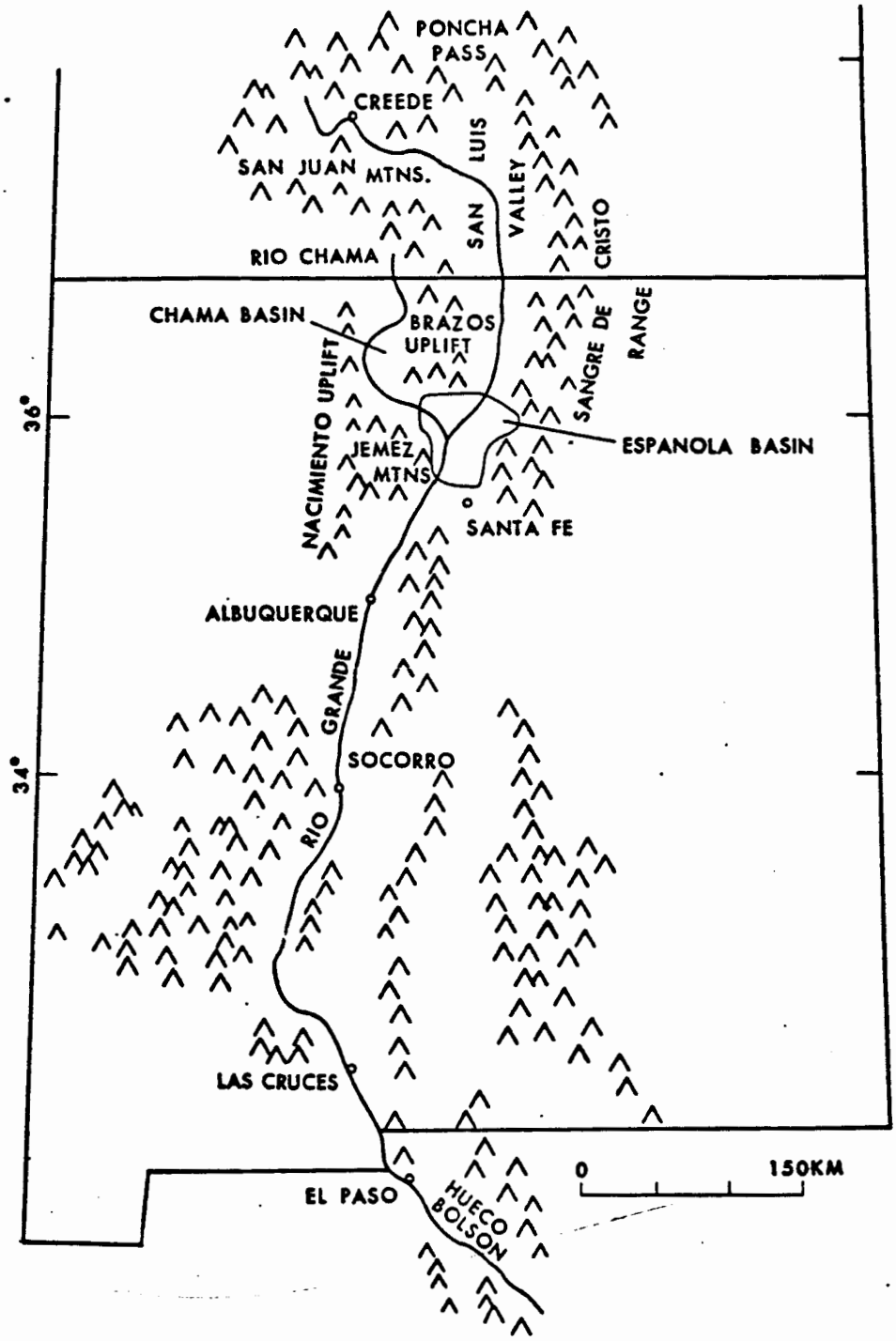


Figure 1. Regional map of New Mexico and southern Colorado.

the southern portion by Spiegel & Baldwin (1963). The Cerros del Rio volcanic field has been studied by Griggs (1964), and the Jemez Mountains by Griggs (1964), Bailey and others (1969), and Smith and others (1970). None of the foregoing studies attempted to compile a late Cenozoic history of the Española Basin.

The Present Study: Purpose and Rationale

The purpose of the present study is to determine the late Cenozoic history of the topographic Española Basin. To compile this history it was necessary to reexamine and remap several deposits. The main area of intensive study was a plateau in the northeastern part of the basin that was mapped in reconnaissance by Miller and others (1963). This area was selected for three reasons: 1) it is one of the largest areas in the basin which has not received detailed study; 2) it exposes a thick stratigraphic section of basin-fill sedimentary rocks; and 3) included in the deposits are volcanic ashes and axial stream gravels that greatly improve our understanding of the geologic history of the basin.

CHAPTER II

GEOGRAPHY

The Española Basin has been eroded by the Rio Grande and Rio Chama into sediments of the Tertiary Santa Fe Group. The basin is surrounded on all sides by high areas including four mountainous regions and four plateaus (Fig. 2). Altitudes vary from 1,675 m where the Rio Grande leaves the basin to 3,810 m in the mountains. Plateaus rise 610 to 760 m above the valley bottom.

The west side of the Española Basin is formed by the Jemez Mountains whose volcanic rocks rest on the Sante Fe Group and the mainly Precambrian rocks of the Nacimiento uplift. These volcanic rocks range in age from Miocene to Quaternary. Two overlapping calderas have been recognized: the older Toledo caldera and the Valles caldera (Bailey and others, 1969; Smith and others, 1970). The Pajarito Plateau, on which the towns of Los Alamos and White Rock are located, extends into the basin from the Jemez Mountains (Fig. 2). This plateau is a piedmont surface underlain by the Pliocene Puye Formation and partially capped by the Quaternary Bandelier Tuff (Fig. 4).

The southern margin of the basin is a plateau area composed of two types of rocks. On the west, butting against the Pajarito Plateau, are the predominantly basaltic rocks of the

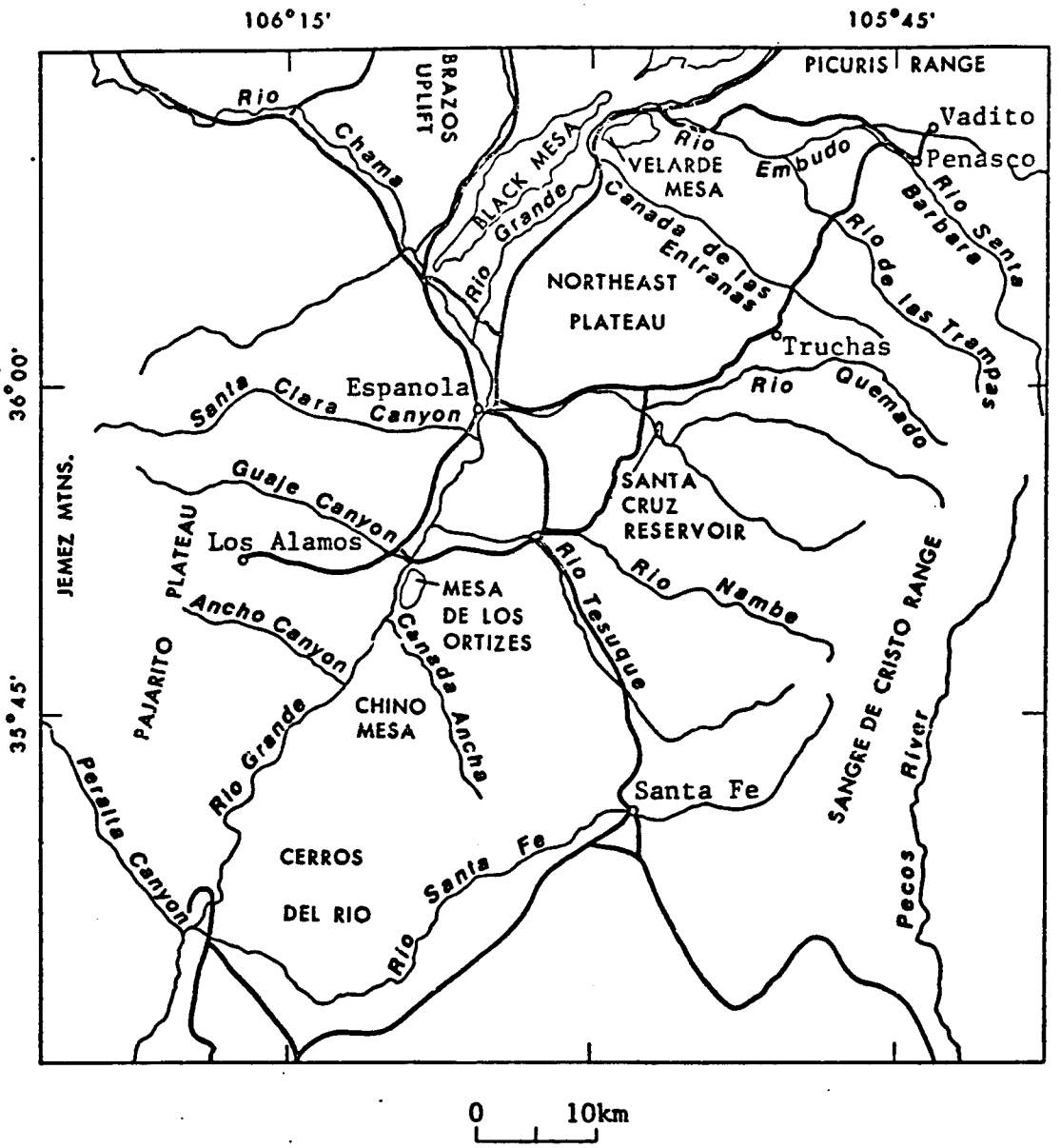


Figure 2. Place names in the Española Basin, New Mexico.

Cerros del Rio volcanic field. Through these the Rio Grande exits from the basin in the 305 m deep White Rock Canyon. Graded to the surface of this volcanic field are Santa Fe Group and younger piedmont deposits on which the town of Santa Fe is situated. These sediments, derived from the Sangre de Cristo Mountains, have been deeply eroded in the center of the basin.

The Sangre de Cristo Mountains constitute the eastern edge of the basin (Fig. 2). They contain rocks of Precambrian, Mississippian, and Pennsylvanian age. The majority of the Precambrian rocks are exposed in a belt of foothills along the western side of the mountains. Only in the area of the northeast piedmont plateau are the Precambrian foothills covered by sedimentary rocks. This surface extends from the Sangre de Cristo Mountains to the Rio Grande in the northernmost part of the basin. A valley, the Dixon sub-basin containing the Rio Embudo, separates the plateau from the Picuris Range to the north. The plateau is composed of sedimentary rocks of Tertiary and Quaternary age. On it are a number of small villages such as Truchas, Trampas, and Peñasco.

The north boundary of the Española Basin is the least well-defined. It consists of several geographic features. The easternmost is an east-west trending outlier of Precambrian rocks known as the Picuris Range. To the west is Black Mesa, capped by basalt of the Pliocene Servilleta Formation. The Rio Grande enters the Española Basin between Black Mesa and the Picuris Range. Northwest of Black Mesa is the Precambrian-cored Brazos

uplift (Fig. 1), a southern prong of the San Juan Mountains of Colorado. Separating the Brazos uplift and the Jemez Mountains is the Rio Chama, which joins the Rio Grande north of Española, the only major town on the valley floor.

Average annual precipitation ranges from over 102 cm in the mountains to 30 cm in the center of the basin. Average snowfall is more than 152 cm to 38 cm in the two areas, respectively (Forest Service, 1971). The mountains support an aspen-spruce-fir-Ponderosa pine forest that changes to a piñon pine-juniper forest near 2,350 m altitude. Still lower in the basin, near the Rio Grande, the piñon-juniper forest becomes sparse and cottonwoods predominate along streams.

CHAPTER III

CHRONOLOGIC TERMINOLOGY

There are currently differences of opinion on the placement of Epoch boundaries within the Tertiary Period. Both the Miocene-Pliocene and the Pliocene-Pleistocene boundaries are of particular importance for this dissertation. The Miocene-Pliocene boundary is given as 4.9±0.4 m.y. by Gill and McDougall (1973), and 22.5 m.y. by Berggren (1972). Evernden and others (1964) gave K-Ar ages ranging from 4.1 to 10.0 m.y. for the Pliocene Hemphillian Land-Mammal Age. Fission-track ages reported here for Hemphillian age strata fall within this range. For the purposes of this paper, the Miocene-Pliocene boundary will be 9 m.y. This choice is in accordance with Tedford (personal commun., 1975).

The Pliocene-Pleistocene boundary has varied among authors from 2.5 m.y. (Stipp and others, 1967) to 1.8 m.y., the base of the Olduvai Event (Berggren, 1972; Berggren and Van Couvering, 1973; Evernden and Evernden, 1970). For this paper, 1.8 m.y. will be used.

CHAPTER IV

GENERAL GEOLOGY OF THE ESPAÑOLA BASIN

Precambrian Rocks

The east and northeast sides of the Española Basin contain extensive exposures of Precambrian rocks (Montgomery, 1963). These include metasedimentary and metaigneous rocks with numerous plutonic rocks and pegmatite dikes. The metamorphic rocks were divided into two formations by Montgomery (1963): 1) the Ortega, an older and dominantly metasedimentary unit; and 2) the Vadito which is younger and includes both metasedimentary and metavolcanic rocks.

The Ortega metasedimentary rocks are found along the western slope of the Sangre de Cristo Range. They are predominantly quartzites with beds of sillimanite-kyanite gneisses, quartz-muscovite-biotite schists and phyllites, and staurolite-rich schists and gneisses.

The Vadito Formation consists of a lower unit of conglomerate, quartzite, and schist; and an upper unit of interlayered mafic flows, and volcaniclastic metasedimentary rocks (Long, 1974).

The plutonic rocks of Precambrian age include granite, metadacite and two quartz monzonites (Long, 1974). Montgomery (1963) termed these plutonic rocks the Embudo Granite and considered them related to the same parent magma with one

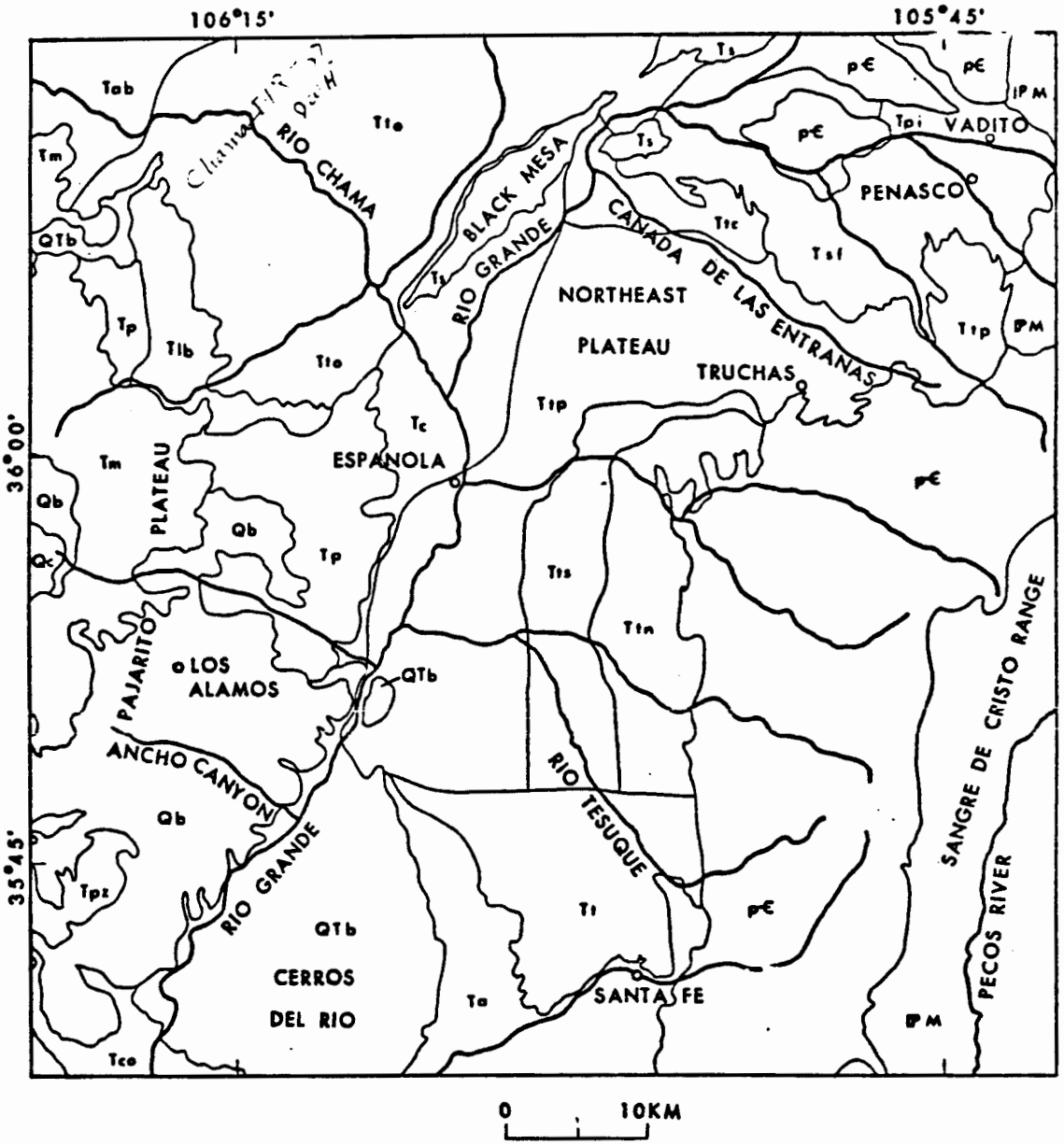


Figure 3. General geologic map of the Española Basin, New Mexico.

EXPLANATION

SEDIMENTARY ROCKS

Tsf — SANTA FE GROUP

- Tc — CHAMITA FM.
- Ttc — TESUQUE FM.: CEJITA MBR.
- Tto — OJO CALIENTE SANDSTONE
- Ttp — POJOAQUE MBR.
- Tts — SKULL RIDGE MBR.
- Ttn — NAMBE MBR.

Tab — ABIQUIU TUFF

Tpi — PICURIS TUFF

Tp — PUYE FM.

Tco — COCHITI FM.

Tpa — PALIZA CANYON FM.

Ta — ANCHA FM.

PM — PENNSYLVANIAN AND MISSISSIPPIAN ROCKS

p€ — PRECAMBRIAN ROCKS

IGNEOUS ROCKS

Qc — CERRO TOLEDO RHYOLITE

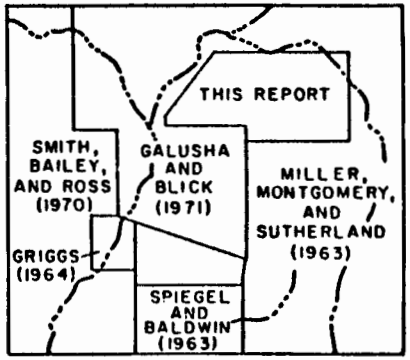
Qb — BANDELIER TUFF

QTb — BASALT

Ts — SERVILLETA FM.

Tm — TSCHICOMA FM.

Tlb — LOBATO BASALT



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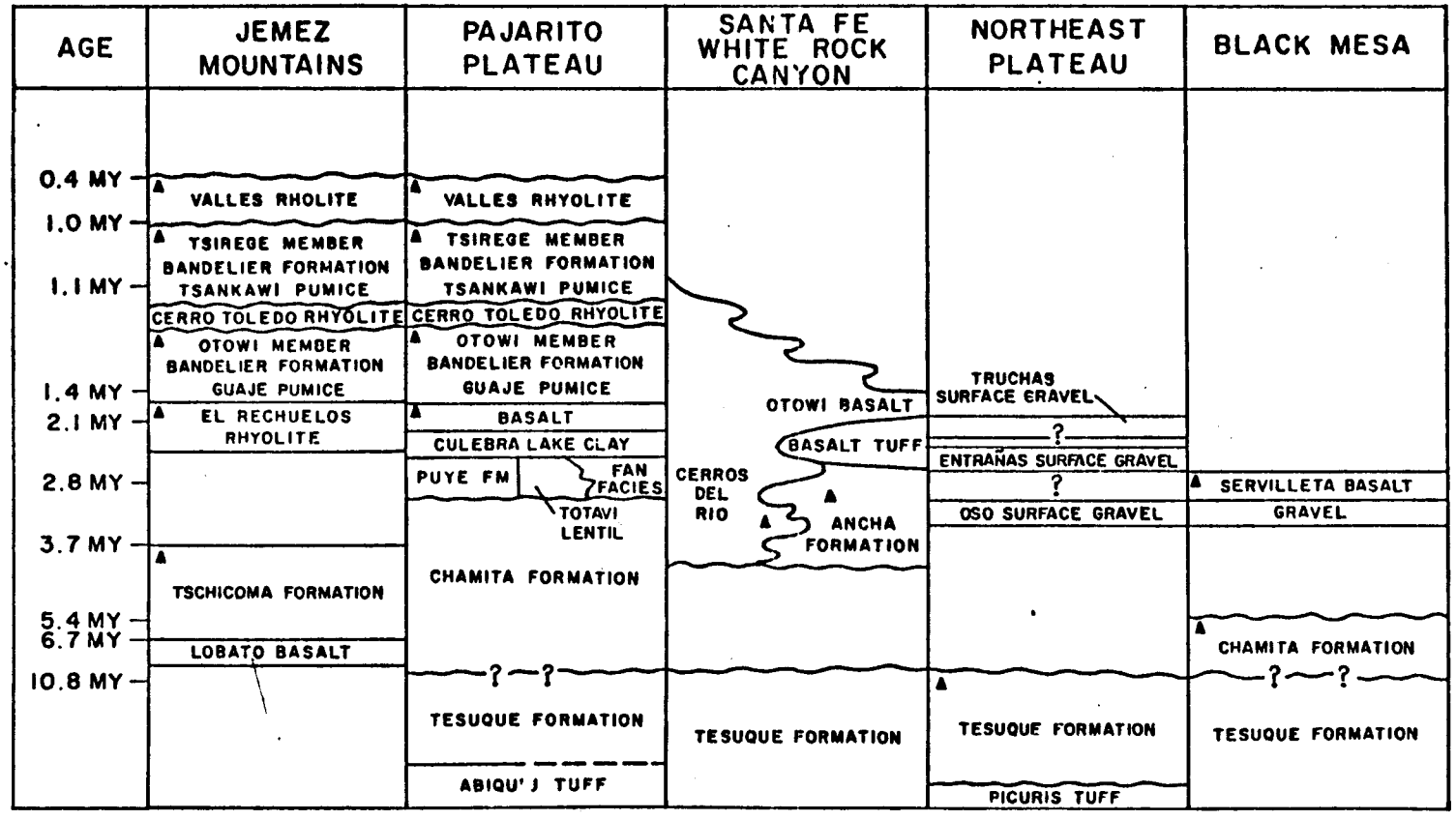


Figure 4. Suggested stratigraphic correlation for the Española Basin, New Mexico. Δ units for which radiometric dating is available.

protracted episode of intrusion. Long (1974) divided the "Embudo granite" into four major units and several pegmatite bodies. These are, in chronological order, the Cerro Alto Metadacite, the Puntiagudo Granite Porphyry, the Rana Quartz Monzonite, and the Peñasco Quartz Monzonite. These four units and subsequent pegmatites represent five episodes of granitic magmatism.

A few dates are available for the Precambrian rocks. A dike genetically associated with the "Embudo granite" has been Rb-Sr dated by Ahrens (1949) at 800 m.y. and K-Ar and Rb-Sr dated by Aldrich and others (1958) at 1,350 to 1,260 m.y. The Rana Quartz Monzonite and Peñasco Quartz Monzonite give Rb-Sr mineral ages of 1,208±63 m.y. and 1,212±23 m.y. respectively (Fullagar and Shiver, 1973). These ages were reinterpreted by Long (1974), in light of field relationships, to give ages of 1,673 m.y. and 1,400 m.y. respectively. Long (1974) argued that these represent a maximum age of a major thermal event.

Paleozoic Rocks

Paleozoic formations in the Española Basin consist of Mississippian and Pennsylvanian rocks exposed in the Sangre de Cristo Mountains. The Paleozoic strata nonconformably overlie Precambrian rocks and are overlain unconformably by Cenozoic strata. The following descriptions are taken from Sutherland (1963).

Mississippian formations, the Del Padre Sandstone, Espiritu Santo Formation, and Tererro Formation, contain limestones,

dolomites and conglomerates. Exposures are limited to only a few locations. No fossils have been found in the pre-Tererro formations. Endothyrid faunas in the Tererro Formation indicate a Late Mississippian, Meramecian age.

Pennsylvanian formations (La Pasada, Flechado, Alamitos, and Sangre de Cristo Formations) crop out extensively. They consist of arkosic and subarkosic conglomerates and sandstones, shales, orthoquartzites, and limestones. The Pennsylvanian section thickens from 690 m in the Pecos Valley to 1,980 m near Taos (Sutherland, 1972). In the valley of the Rio Santa Barbara, the Pennsylvanian section consists primarily of the nonarkosic, clastic Flechado Formation (about 610 m thick), which interfingers southward with the La Pasada Formation and the arkosic Alamitos Formation (about 1,220 m thick). Limestones included in the Alamitos Formation contain fossils of late Desmoinesian age.

Early and Middle Cenozoic Rocks

Most of the Española Basin is filled with Cenozoic sedimentary deposits that contain a few lava flows, or sills, and numerous ash and pumice beds. Early Tertiary formations are exposed on both the southwest and northwest edges of the basin. They include the Eocene(?) El Rito and Galisteo Formations, which may be correlative. Stearns (1943) gave the Sangre de Cristo Mountains and the Nacimiento uplift as source areas for the Galisteo. Bingler (1968) suggested the source for the El Rito was the

Precambrian core of the Brazos uplift. Both formations were derived from highland areas that are also highlands today. Topographic basins existed between these highlands but their positions probably did not coincide exactly with present rift basins.

The Abiquiu Tuff (Smith, 1938) (early Miocene?) unconformably overlies the El Rito Formation in the northwestern portion of the Española Basin and is overlain by the Santa Fe Group. Smith (1938) found no sharp contact between the Abiquiu Tuff and the Santa Fe Group but Galusha and Blick (1971) have found sharp contacts at several localities.

The Abiquiu Tuff (Smith, 1938) is a sand and gravel deposit rich in pumice fragments and clasts of volcanic rocks. The source of the volcanic clasts is unknown but the most probable areas are the San Juan Mountains of Colorado, where volcanic centers were active from late Eocene to Pliocene time (Lipman and others, 1970), and the Questa volcanic center which was active around 23 m.y. ago (Pillmore and others, 1973).

The Picuris Tuff is similar to, and probably correlative with, the Abiquiu Tuff. The Picuris Tuff crops out in isolated patches along the eastern margin of the Española Basin (Cabot, 1938; Montgomery, 1953). Clast compositions are predominantly volcanic, but with high percentages of granite.

The Santa Fe Group

An excellent summary of studies done on the late Tertiary deposits of the Española Basin is presented by Galusha and Blick (1971, p. 16-27). The deposits were first studied by geologists accompanying military expeditions and railroad surveys in the mid-1800's. They described the area as a badlands formed by the erosion of poorly cemented sands and marls and called them the Santa Fe marls (Hayden, 1869, p. 66-67). Paleontologic data supported a Miocene-Pliocene age for a majority of the sedimentary rocks. With time, the term Santa Fe marls became Santa Fe Formation and then Santa Fe Group (Spiegel and Baldwin, 1963, p. 38). The oldest deposits were given other formation names such as the Abiquiu Tuff.

The term Santa Fe Formation, or Group, has been extended by some geologists to include all the late Tertiary and Pleistocene sedimentary and volcanic deposits along the Rio Grande rift exclusive of the present valley system (Bryan, 1938, p. 205; Spiegel and Baldwin, 1963, p. 39). This is unfortunate because the term as so used includes a variety of deposits that: 1) may or may not be correlative from basin to basin; and 2) are seldom considered for their differences and individual histories. Such usage of the Santa Fe Group is convenient, however, because the late Cenozoic deposits are similar in apperance and difficult to date and correlate. I prefer to follow the usage of Galusha and Blick (1971) in restricting the Santa Fe Group to the Tesuque and Chamita Formations and their age equivalents.

The Tesuque Formation was divided into five members by Galusha and Blick (1971). The two oldest members, the Nambe, and Skull Ridge, are considered to be middle and late Miocene in age, respectively, based on the presence of Hemingfordian and Barstovian fossils. An early Pliocene deposit was termed the Pojoaque Member. These three members are preserved mainly in the center of the topographic Española Basin. They are buff to pink-colored arkosic sandstones and conglomerates of fluviatile origin, and are slightly indurated by carbonate cement. Beds of ash and pumice, commonly altered to bentonite or calcium carbonate, are present. Conglomerates are typically granitic; the source area was the Precambrian granitic rocks of the western Sangre de Cristo Mountains.

Of equivalent age to the Pojoaque and part of the Skull Ridge Members is the Chama-el rito Member. This member is found only in the northwestern portion of the Española Basin. It is a lithologically distinct facies with a volcanic provenance in northern New Mexico and perhaps in the San Juan Mountains of Colorado (Galusha and Blick, 1971, p. 65). In addition to these source areas, volcanic clasts may have been derived from reworking of the Abiquiu Tuff and Los Pinos Formation--a volcaniclastic deposit on the Brazos uplift--and from contemporaneous volcanism in the area of deposition. Galusha and Blick (1971) interpreted the Chama-el rito Member to be a large alluvial fan whose distal end intertongued with the Pojoaque Member.

The Ojo Caliente Sandstone overlies the Pojoaque and Chama-el rito Members and interfingers with them. The upper boundary of the Ojo Caliente is an unconformity at the base of the Chamita Formation.

The Ojo Caliente is exposed along the southwest side of Black Mesa and in the Dixon sub-basin where it is distinguished and correlated by three red clay layers. It thins to the south, and is not found in the southern part of the Española Basin. The Ojo Caliente Sandstone is characterized by well-sorted, fine to coarse grained quartz sand, little induration, calcium carbonate concretions, and large scale cross-bedding. Galusha and Blick (1971) have suggested an eolian origin. The ages of fossils from the Ojo Caliente are Clarendonian (early Pliocene).

A new member of the Tesuque Formation is introduced in this dissertation. This unit, the Cejita Member, is late Miocene in age; it will be discussed in detail in Section III.

The Chamita Formation unconformably overlies the Ojo Caliente Member of the Tesuque Formation and is unconformably overlain by several different post-Santa Fe Group deposits including the Servilleta and Puye Formations. Galusha and Blick (1971) named the Chamita Formation and described it in the type locality south of Black Mesa between the confluence of the Rio Chama and the Rio Grande. The formation consists of sands and gravels and two thick zones of pyroclastic beds termed the lower and upper tuffaceous zones (Galusha and Blick, 1971, p. 71). The lower tuffaceous zone (24 m thick) contains tuffaceous sediments and at least four distinct lapillistone layers. (Terminology used here follows that proposed by Fisher, R.V., 1961). The upper tuffaceous zone (30 m thick) is composed of at least three lapilli tuff beds separated by tuffaceous sediments. In contrast

with the Tesuque Formation, the Chamita Formation sands and gravels are quartzitic, and gravel beds may include cobbles and rounded clasts.

Studies done as part of this dissertation (Fig. 5) show that the change in composition between the Tesuque and Chamita Formations was not simply from granitic to quartzitic clasts but to a more heterolithic composition including quartzite, quartz, granite, volcanic rocks, Paleozoic sedimentary rocks and trace amounts of schist. Gravel beds below and within the lower tuffaceous zone contain primarily quartz clasts with lesser amount of quartzite and Paleozoic rocks. In the upper tuffaceous zone the dominant lithology is quartzite with lesser amounts of Paleozoic rocks and little quartz. The volcanic clasts are small, angular pebbles of intermediate to silicic compositions.

The source areas for the Chamita Formation were the Sangre de Cristo Mountains and the Picuris Range. The volcanic clasts are unlike those of the Jemez Mountains but could have come from reworking of the Picuris Tuff or the older Santa Fe Group deposits exposed on the southern flanks of the Picuris Range. The Paleozoic lithologies were derived from the Sangre de Cristo Mountains. Directions of eleven flute casts from the upper tuffaceous zone give a westward direction of stream transport between N65°W and N108°W (Fig. 6). Imbrication directions also give a dominantly westward transport direction.

Chamita Formation

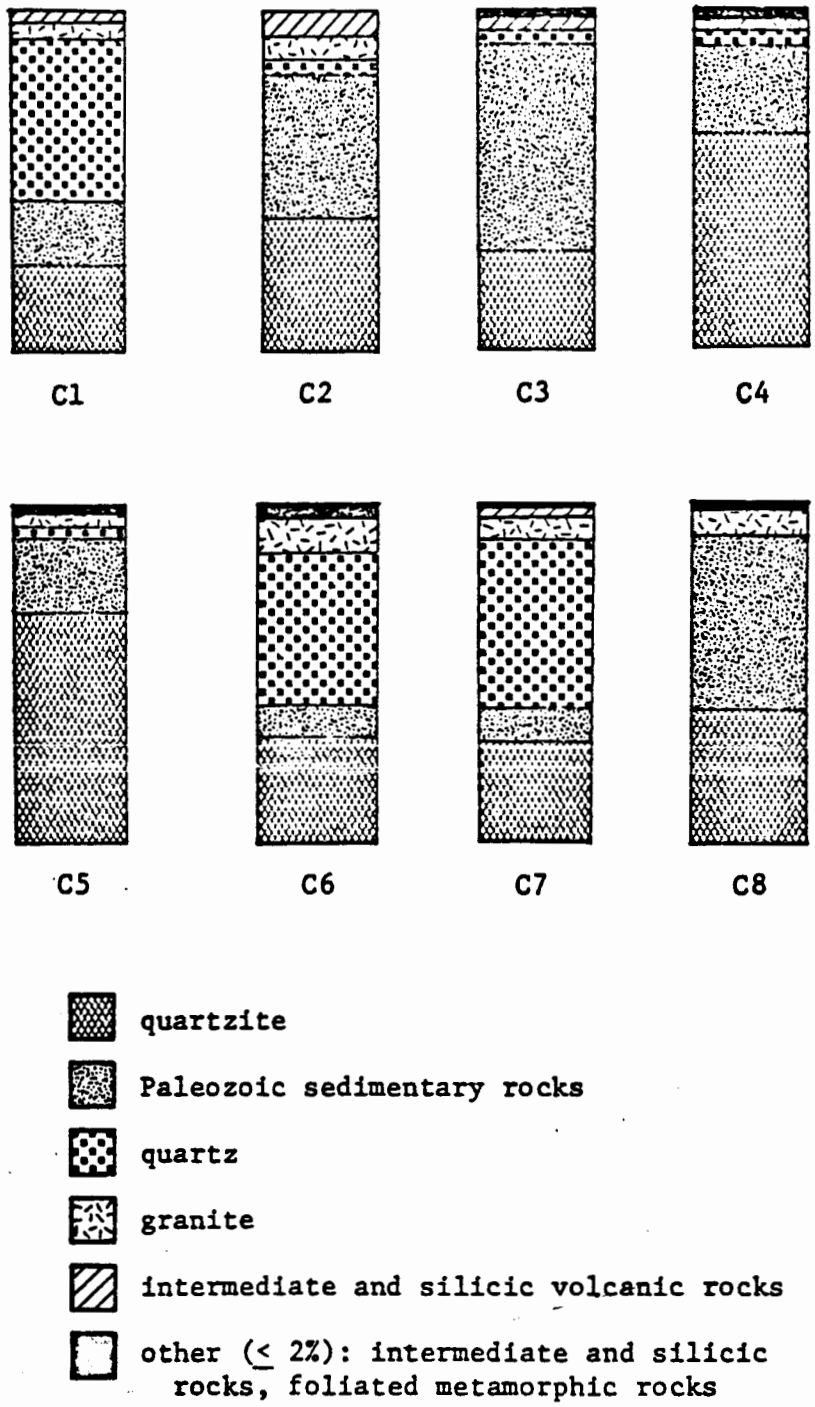


Figure 5. Composition of gravel clasts from the Chamita Formation. See Fig. 6 for locations and Appendix D for percentages and methods.

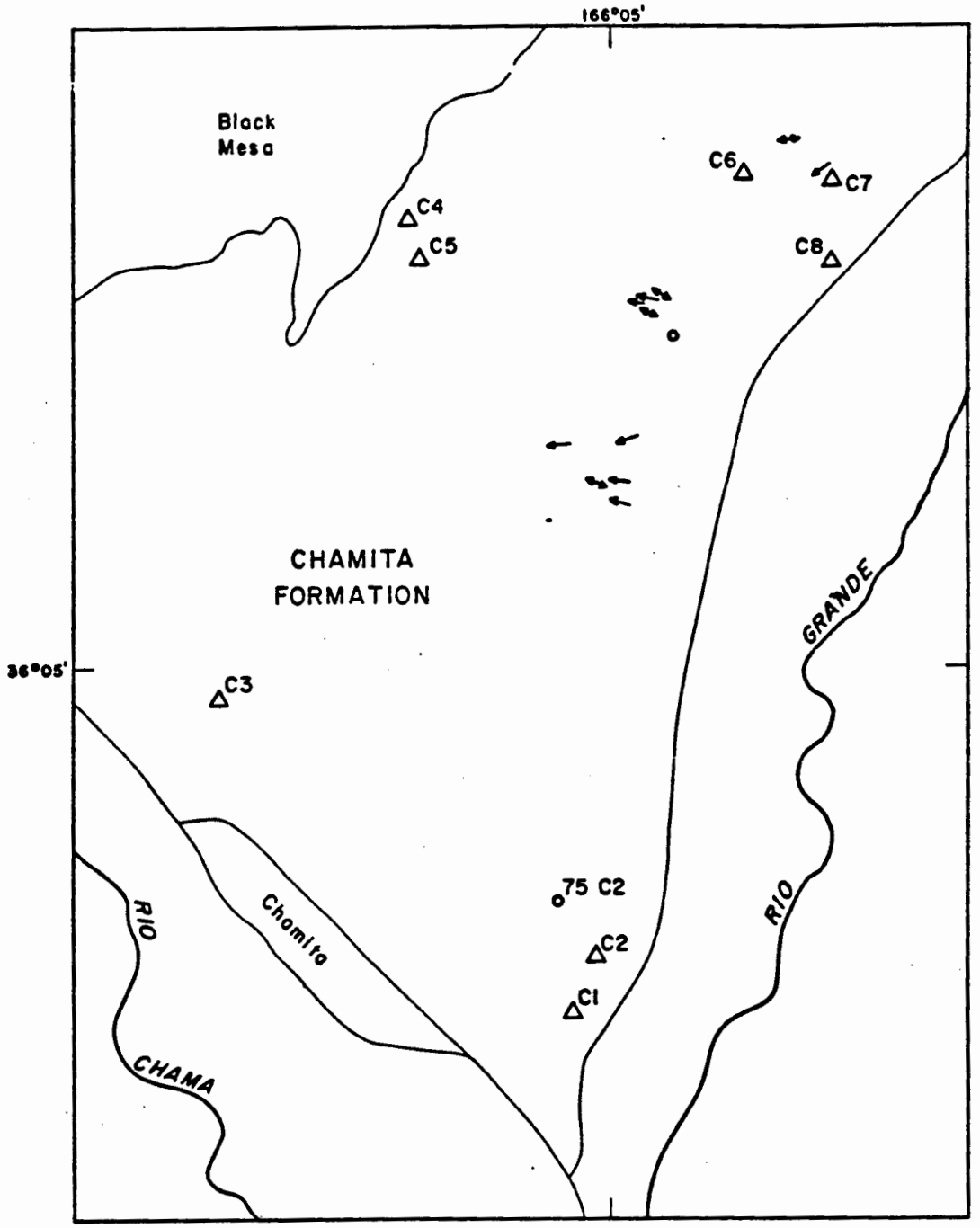


Figure 6. Inferred flow directions (arrows) in the Chamita Formation based on flute casts and pebble imbrication. Triangles indicate clast count sites described in Fig. 5. Circles indicate location of dated pumices.

The age of the Chamita Formation is middle Pliocene. Within the upper tuffaceous zone is a particularly important fossil horizon including the San Juan and Rak Camel quarries. Vertebrate fossils from these quarries are assigned to the Hemphillian (middle Pliocene) by Galusha and Blick (1971). Fossil collections from the quarries are presently available for study at the American Museum of Natural History. Two lapillistones from the Chamita Formation have been dated by fission-track methods (MacFadden and Manley, 1976). (Sample locations are given in Table 3, Appendix A.) A lapillistone from near the middle of the lower tuffaceous zone was dated at 5.2±1.0 m.y. The uppermost lapillistone from the upper tuffaceous zone was dated at 5.6±0.9 m.y. (See Appendix B for procedures.) These dates, although apparently inconsistent with the stratigraphy, are separated by only 76 m of section (Galusha and Blick, 1971) and are within the limitations of the dating technique.

The Ancha Formation

Sedimentary deposits overlying the Tesuque Formation with angular unconformity at the southern margin of the Española Basin have been given the name Ancha Formation and included in the Santa Fe Group by Spiegel and Baldwin (1963, p. 45). However, Galusha and Blick (1971) considered the formation to be post Santa Fe Group. The Ancha Formation is overlain by surface gravels or by basalt flows from the Cerros del Rio field. Near the type locality in the Santa Fe area, the Ancha Formation is

30 m to 90 m thick and consists of granitic sand and gravel deposits containing two pumice beds (Spiegel and Baldwin, 1963). I have located five pumices at this site; four of them have been reworked by fluvial processes (Fig. 8).

The lowest pumice deposit is a thin (0-30 cm) bed of cemented, reworked pumice. Pumice fragments are scarce but appear to contain biotite phenocrysts. Higher in the section are three sedimentary layers each containing pumice in a matrix of small, angular granitic pebbles and sand. The highest of these layers is 14 m below a phreatomagmatic deposit that directly underlies a Cerros del Rio basalt flow. The three upper pumice layers and the lower layer are probably equivalent to the two pumice beds described by Spiegel and Baldwin (1963, p. 47).

On the next ridge to the west is a fifth pumice bed. It is an undisturbed, 2 meter-thick pumice with a maximum clast size of 33 mm. This pumice, sample 73A2, has been examined petrographically (tables 1 and 2, Appendix A) and it is not related to the air-fall deposits of the Bandelier Tuff nor to the Puye or Tesuque Formation pumices studied in this dissertation.

Pumices are also present on terraces cut into the Ancha Formation. Several sites were described by Spiegel and Baldwin (1963, p. 63-64). One of these, 72DS1, has been examined petrologically and chemically. It is not related to any other described pumice and its age is unknown. Zircons are absent or exceedingly sparse, therefore fission track dating was not attempted.

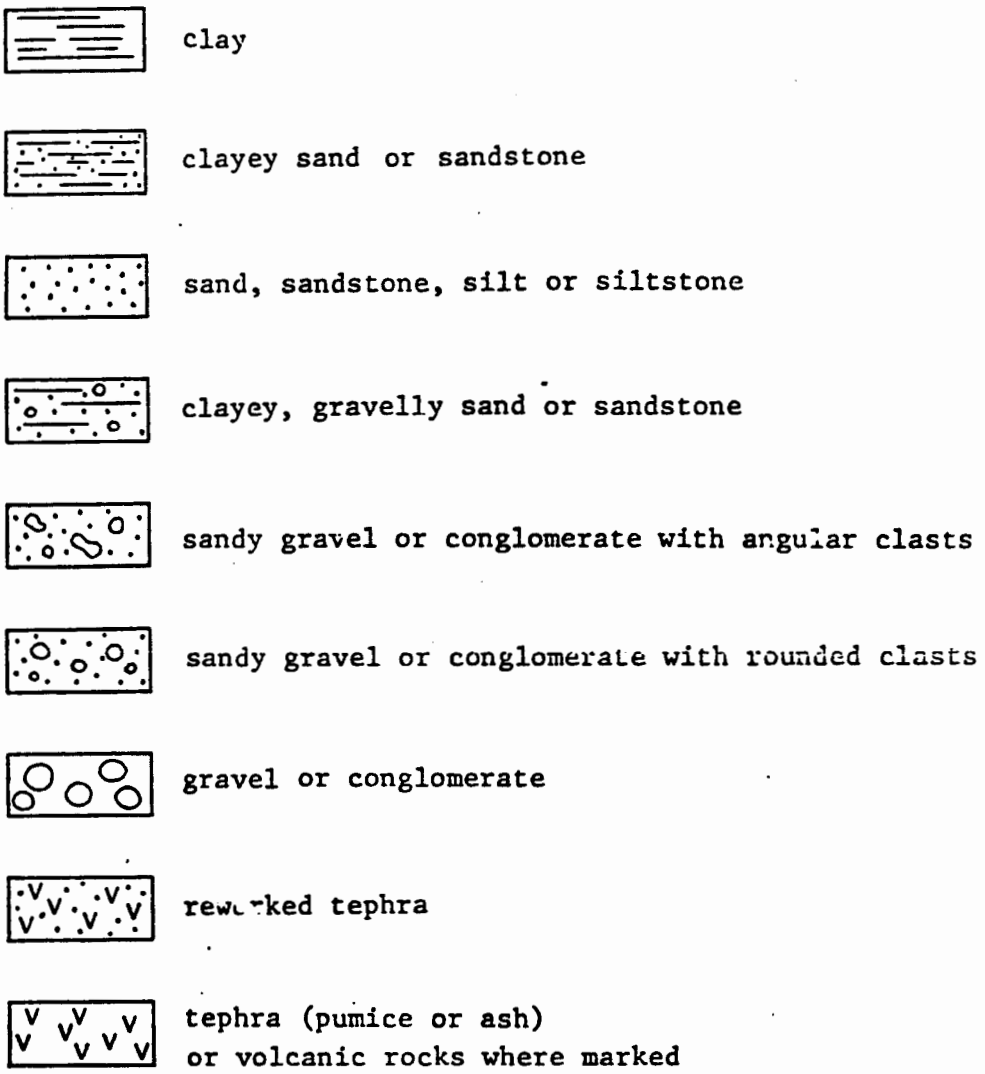


Figure 7. Key to symbols used on Figures 8, 14, 25, 41, 47 and 56.

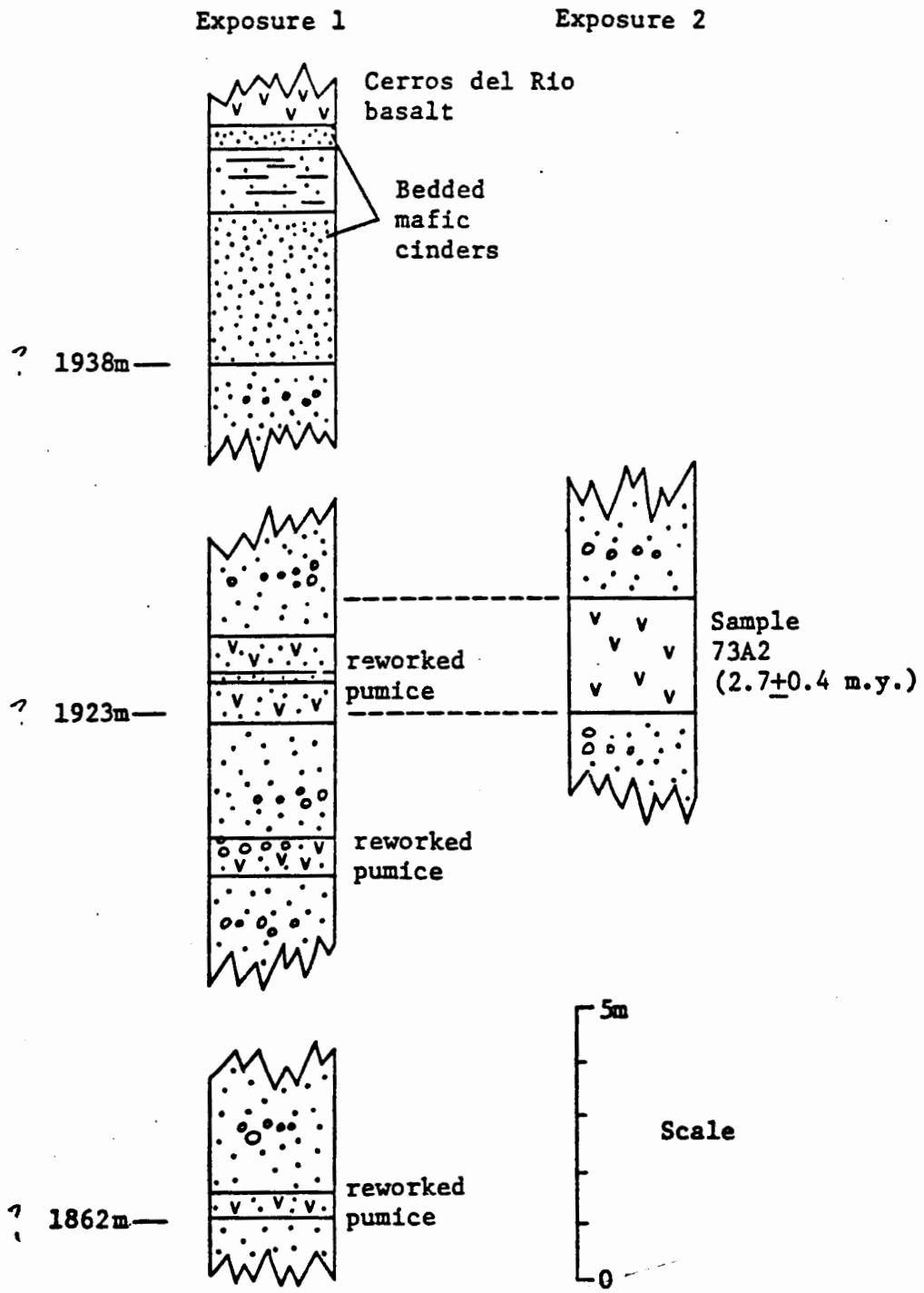


Figure 8. Position of pumice deposits near the type locality of the Ancha Formation. Locations: Exposure 1 - 106°6'25"W, 35°45'4"N; Exposure 2 - 106°06'30"W, 35°45'10"N; Horcado Ranch Quadrangle. See Fig. 10 for location of sample 73A2. See Fig. 7 for key to symbols.

The age of the Ancha Formation was unknown prior to this study. It was assumed by Galusha and Blick (1971, p. 78) to be Pleistocene and nearly equivalent to, or younger than, the Bandelier Tuff. Spiegel and Baldwin (1963) suggested a late Pliocene to early Pleistocene age (1963, p. 58). Fission-track dating of zircons from pumice sample 73A2 has given an age of 2.7±0.4 m.y. (Manley, 1976a) (Appendix B). The Cerros del Rio flow overlying the type Ancha Formation has a K-Ar age of 1.97±0.06 m.y. (Manley, 1976b) (Appendix C). These radiometric ages establish a late Pliocene age for the Ancha Formation.

The Ancha Formation is correlative with the Puye Formation. Spiegel and Baldwin (1963, p. 59) suggested an intertonguing relationship; I concur. These two formations, with source areas on opposite sides of the Española Basin, interfinger near the present position of the Rio Grande. Griggs (1964, p. 31) mentioned an exposure south of Mesa de los Ortizes and east of the Rio Grande where arkosic sediments overlie a portion of the Puye Formation.

Miller (1963) used the term "Ancha Formation" for extensive gravel deposits underlying the northeast plateau. On the basis of a "Pearlette-like" ash he assigned these gravels a Pleistocene age and correlated them with the Ancha Formation of Spiegel and Baldwin (1963). My work indicates that the Ancha Formation of Miller includes: 1) a Miocene unit equivalent to the Tesuque Formation; and 2) a series of discontinuous pediment and terrace gravels of late Pliocene to Pleistocene age. The Miocene unit is further discussed in the section on the late Tertiary

stratigraphy of the northeast plateau. The younger gravels are briefly described in two sections entitled high surface gravels and Quaternary gravels. Owing to the new classification of the deposits of the northeast plateau, I propose that the "Ancha Formation" as used by Miller (1963) be discarded.

The Puye Formation

The name Puye Gravel was first used by Smith (1938) in the northwest part of the Española Basin. Griggs (1964), who mapped near Los Alamos, published the first description and type locality of the Puye Conglomerate. Bailey and others (1969) changed the name to Puye Formation because of the abundance of nonconglomeratic beds within the unit. The Puye Formation is exposed along the eastern margin of the Pajarito Plateau from the southern end of White Rock Canyon northward to the confluence of the Rio Chama and Rio Grande, and again on the northeastern flank of the Valles caldera (Smith and others, 1970). The Puye Formation overlies the Chamita Formation with angular unconformity and is unconformably overlain by the Bandelier Tuff. At the type locality (NW 1/4 NE 1/4 SW 1/4 sec. 11, T19N, R7E) the Puye Formation is 71 m thick but ranges elsewhere in thickness from 18 to 221 m (Griggs, 1964).

The formation is divided by Griggs (1964) into two members:

1) The Totavi Lentil (0-24 m thick): a well-rounded, pebble to cobble gravel, rich in quartzite that unconformably overlies the Chamita Formation (Galusha and Blick, 1971, p. 77).

2) A fanglomerate (maximum thickness 194 m). a mixture of sand and gravel lenses with poor sorting and rounding, and boulders up to 1.5 m long. The gravel is composed of latite clasts. Pumice beds are intermixed. The volcanic rocks are derived from the Tschicoma Formation which is related to the Toledo caldera of the Jemez Mountains. In the type section, the fanglomerate conformably rests on the Totavi Lentil and is overlain by the Bandelier Tuff, the Culebra lake clay of Kelley (1952) or flows from the Cerros del Rio field.

These two members are characteristic of the Puye Formation north of White Rock Canyon.

Several geologists (Bryan, 1938; Denny, 1940a; Kelley, 1956) have concluded that the Totavi Lentil is a Rio Grande gravel. The Totavi Lentil contains 40 to 60 percent quartzite, 30 to 40 percent intermediate volcanic rocks, and small percentages of several other lithologies (Figs. 9 and 10). The roundness, sorting, heterogeneity and presence of diagnostic lithologies support the conclusion that this deposit represents a large axial stream with an extensive drainage basin. Diagnostic lithologies include chert from the Rio Chama drainage basin, basalts from the northern Española Basin, and Paleozoic rocks from the Sangre de Cristo Mountains.

Field work in White Rock Canyon has shown that these well-rounded, Totavi Lentil stream gravels are present to the southern

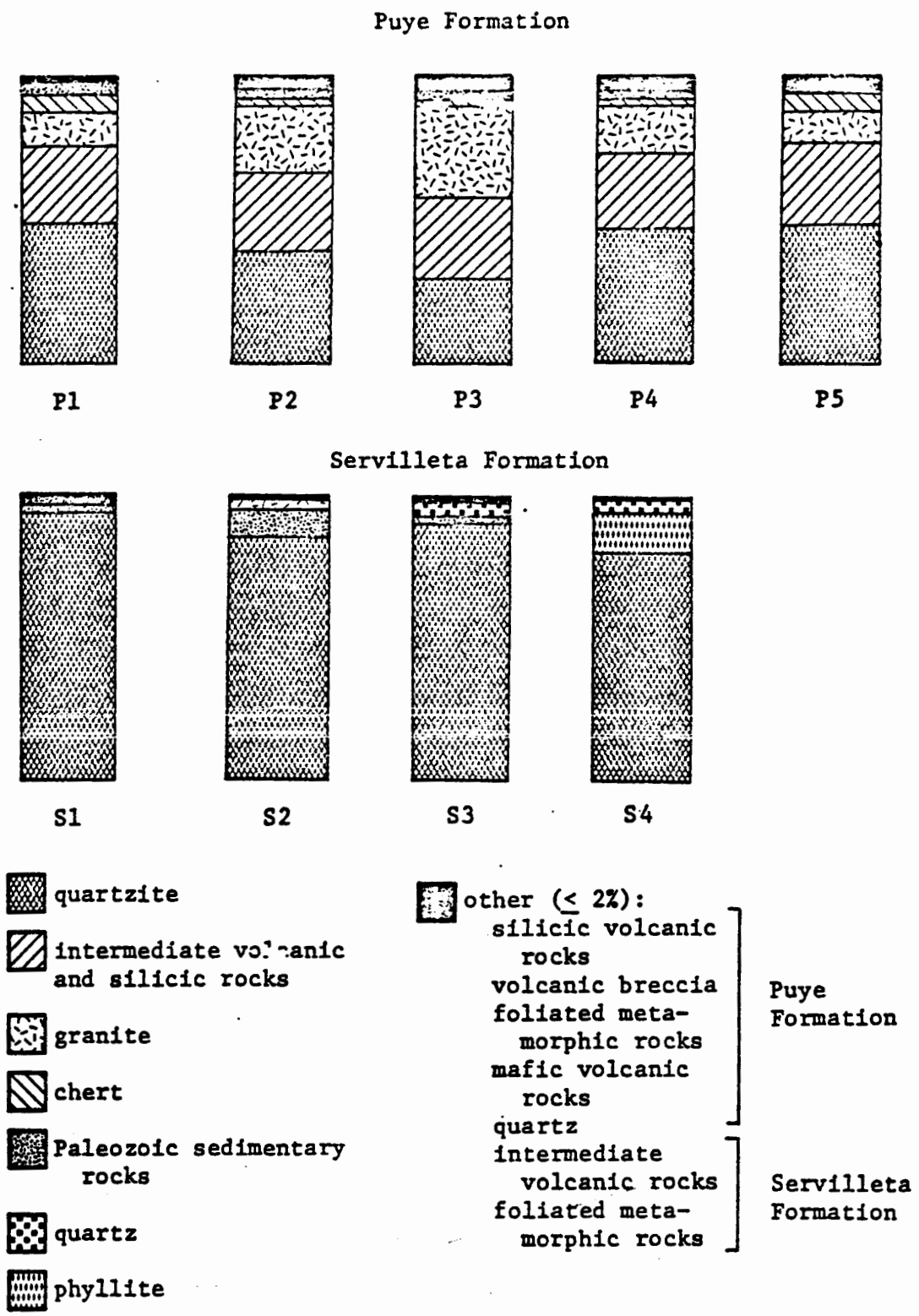


Figure 9. Composition of gravel clasts from the Puye and Servilleta Formations. See Fig. 8 for sample locations and Appendix D for percentages and methods.

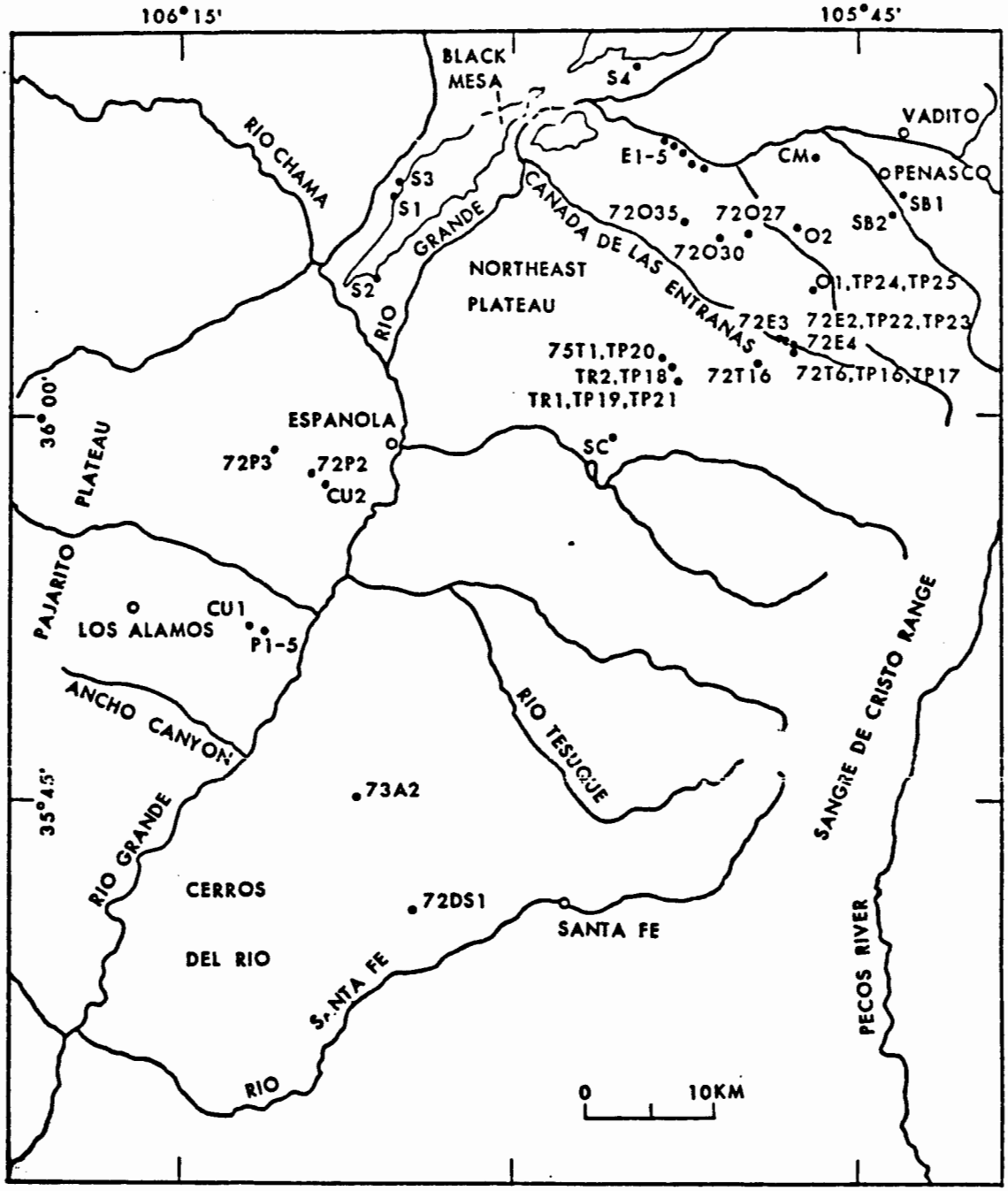


Figure 10. Location map for: (1) Clast counts from the Puye (P) and Servilleta (S) Formations, and several surface and terrace gravels; (2) Measured sections from the Culebra lake clay (Cu) (Kelley, 1952); and (3) Tephra sites.

end of the canyon. They are frequently interbedded with flows and volcaniclastic deposits from the Cerros del Rio field. Some exposures show rounded gravels incorporated in mud flow deposits. Rounded clasts that have been broken may indicate stream gravel fractured by violent eruptions (Fig. 11).

Field work also indicates that the fanglomerate member represents water-laid deposits mixed with lahars, as was suggested by Bailey and others (1969). In addition, the deposit contains numerous reworked tephra layers and two air-fall pumice beds whose stratigraphic relationship to each other is indeterminate in the field. These two pumice layers, located with the assistance of R. L. Smith, have been analyzed to determine if they are similar to those from other deposits in the basin. The samples are: 1) the Santa Clara pumice, a prominent white pumice bed on the north side of the Santa Clara Canyon road, 8.7 km up the canyon from the Santa Clara Pueblo; and 2) the Puye Cliffs pumice from a cliff-face close to the south side of the road to the Puye Cliffs Ruin, State Highway 5 (Fig. 12). Neither of these pumices could be correlated with any others examined from the Española Basin.

The interfingering of several deposits in White Rock Canyon complicates the description of the Puye Formation. The Totavi Lentil can be seen overlying the fanglomerate in places. Both members interfinger with volcaniclastic deposits and flows from the Cerros del Rio field, and with lake sediments. Because of these relationships, I suggest that the Totavi Lentil and fanglomerate members be considered facies and that the Puye

Figure 11. Fractured stream pebbles in a mud-flow deposit in the Puye Formation, White Rock Canyon.

Figure 12. The Puye Cliffs pumice (72P2) overlying the Totavi Lentil. See Appendix A and Fig. 10 for location.

Formation consists of at least four facies:

1) Axial stream gravel (i.e., the Totavi Lentil) consisting of well-rounded clasts some of whose provenance is outside the Española Basin.

2) Fanglomerate including mud-flow deposits and tephra layers derived principally from the Jemez Mountains.

3) Volcaniclastic layers and cinder-rich mud-flows derived from volcanism in the Cerros del Rio field.

4) Lake sediments.

The latter two facies are described below.

The volcaniclastic facies includes mud-flows related to volcanism and phreatomagmatic units. An example of the latter deposit may be seen exposed directly beneath a Cerros del Rio flow on the west side of Mesa de los Ortizes (Fig. 13). This is a 17 meter-thick deposit of thin-bedded clastic material. The beds are 13 mm to 76 mm thick and consist of alternating layers of:

1) granule gravels containing over 70 percent angular basalt clasts mixed with subangular clasts of basalt, granite, chert, quartz and quartzite; and

2) fine sands of similar composition but less basalt.

Scattered randomly throughout the layers are pebbles of angular basalt, well-rounded basalt, chert and silicic volcanic

Figure 13. Interbedded dark-colored phraeatomagmatic layers and light-colored sands of the Puye Formation exposed beneath the western edge of Mesa de los Ortizes.

rocks. The thin layering shows deformation beneath some of these isolated pebbles.

Similar thin-bedded layers have been observed elsewhere. At the top of the Ancha Formation near the type section are two phreatomagmatic deposits. The lower 2.7-meter-thick deposit is separated from the upper, 0.5-meter-thick deposit, by a 1.2-meter-thick silt layer. These deposits are overlain by a Cerros del Rio basalt flow (Spiegel and Baldwin, 1963, p. 51-52). Basaltic tuffs that may be in part phreatomagmatic were included in the Cerros del Rio flow units as mapped by Griggs (1964, p. 37-39). Galusha and Blick (1971, p. 82) mentioned a laminated deposit overlying a varve deposit in White Rock Canyon. This laminated deposit may also be phreatomagmatic in origin. The varves are part of the lake sediments facies and not related to glaciation.

The lake sediments facies of the Puye Formation includes deposits of several minor and two major lakes. The major deposits include the Culebra lake clay of Kelley (1952) and the diatomite beds in White Rock Canyon. Neither of these units has been adequately described in the literature. Additional description is given here.

The Culebra lake clay (Kelley, 1952), mapped by Griggs (1964) as an "old alluvium" unit, is exposed along the edge of the Pajarito Plateau from White Rock Canyon north to State Highway 5. It unconformably overlies the Puye Formation, as described by Griggs (1964), and ranges in thickness from 0 to 40 m. Along State Highway 4, the lake clay interfingers with, and is overlain by, pillow-textured basalts from the Cerros del Rio field. This

exposure and one immediately south of State Highway 5 have been measured and described (Fig. 14). The gravels present within the section along State Highway 4 are rounded pebble gravels composed of quartzites, intermediate volcanic rocks, granites, quartz, chert and traces of foliated metamorphic rocks.

Kelley (1952) considered the Culebra lake clay was formed when the ancestral Rio Grande was dammed by a Cerros del Rio flow. The interfingering relationship with Cerros del Rio basalts and the presence of basaltic glass cinders in the clays support this conclusion. The lake formed was large: eight kilometres separate the sections observed along the edge of the Pajarito Plateau (cf. Fig. 9). These two sections begin at elevations of 1,829 and 1,932 m. If one assumes minimal vertical displacement of these outcrops since their deposition, the lake in which they were deposited must have covered most of the Española Basin.

The diatomite beds in White Rock Canyon have not been reported prior to this study. The beds are on the east side of the Rio Grande across from the mouth of Alamo Canyon. They are 21 metres thick, are thin-bedded and may include fine silt (Fig. 15). Some layers contain basaltic cinders and angular pebbles. Many layers contain small concretions and show penecontemporaneous deformation. A parallel alignment of small channels gives a strike of N14^{o}W with a probable flow direction southeastward.

The age of the Puye Formation has been uncertain. Both Smith (1938) and Denny (1940a) considered it primarily a

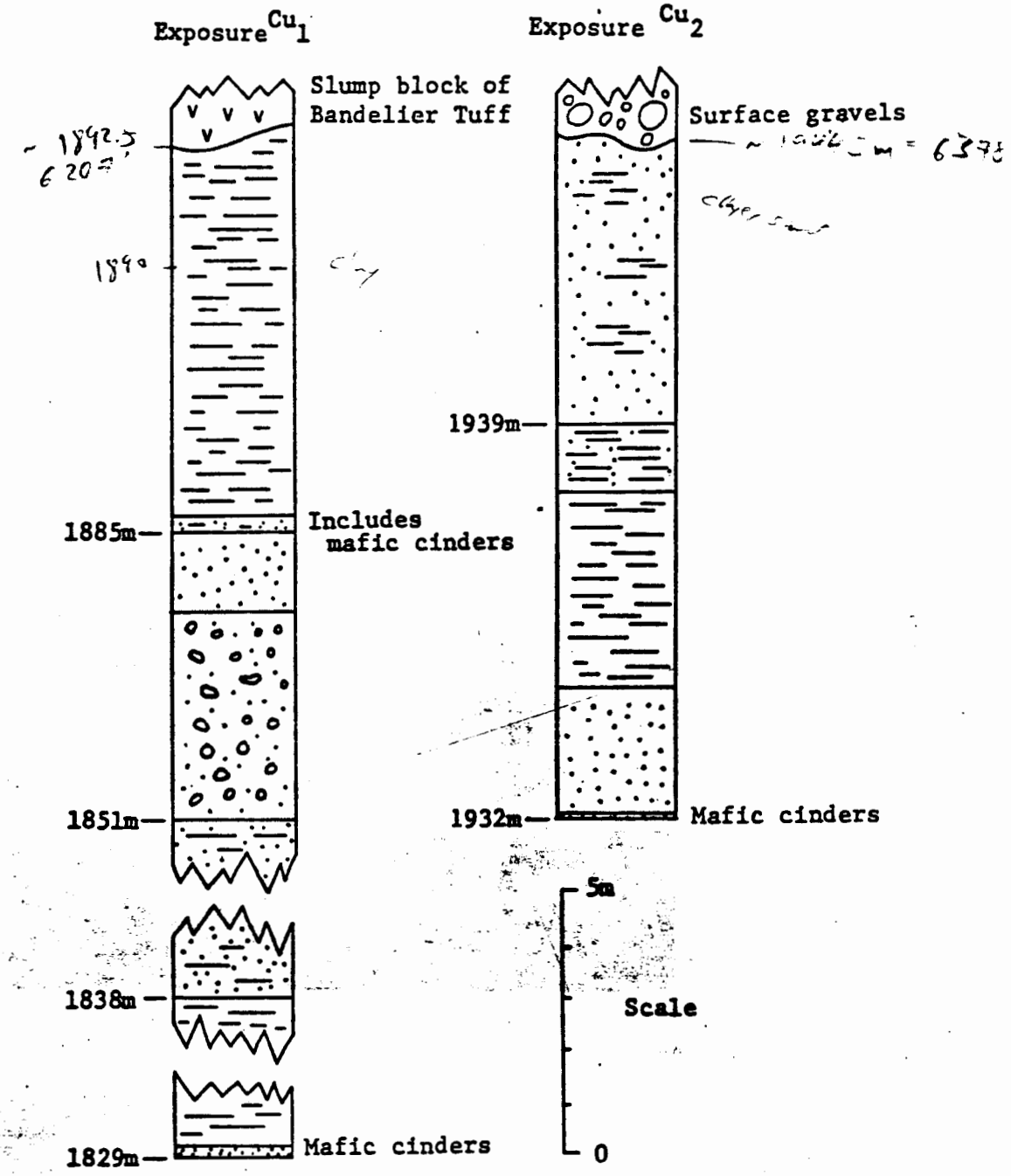


Figure 14. Measured sections of the Culebra lake clay of Kelley (1952). Locations: Exposure 1 - 106°11'27"W, 35°52'20"N, White Rock Quadrangle. Exposure 2 - 106°08'33"W, 35°57'07"N, Puye Quadrangle. See Fig. 10 for map locations. See Fig. 7 for key to symbols.

Figure 15. Diatomite beds in the Puye Formation, White Rock Canyon.

Pleistocene unit. Griggs (1964) believed the Puye Formation to be late Pliocene, and the Culebra lake clay, of Pleistocene age. Near the Jemez Mountains, the Puye Formation is interbedded with the Tschicoma Formation and is therefore at least partially contemporaneous with it. Flows from the Tschicoma Formation have been radiometrically dated at 6.7 to 3.7 m.y. (Bailey and others, 1969). The basalt overlying the Culebra lake clay of Kelley (1952) has been dated at 2.08±0.3 m.y. by Miles Silberman of the U.S. Geological Survey (Smith, R.L., written commun., 1974). Fission-track dating of zircons from the Puye Cliffs pumice provided an age of 2.9±0.5 m.y. (Manley, 1976a) (Appendix B). This pumice directly overlies a 4.6-meter-thick basal Totavi Lentil gravel. A Cerros del Rio basalt overlying Totavi Lentil gravel in Ancho Canyon (Fig. 16) has yielded a K-Ar age of 2.6±0.4 m.y. (Manley, 1976c) (Appendix C). In conclusion, the Puye Formation, including the Culebra lake clay of Kelley (1952), along the eastern margin of the Pajarito Plateau, is late Pliocene in age; closer to the Jemez Mountains it may be middle to late Pliocene.

Cerros del Rio Volcanic Rocks

An area of basaltic to andesitic volcanism along the Rio Grande at the southern end of the Española Basin has been referred to as the Cerros del Rio (Smith and others, 1970) or the "basaltic rocks of Chino Mesa" (Griggs, 1964, p. 37). These flows overlie the Santa Fe Group and, in places, portions of the Puye and Ancha Formations. They are exposed on both sides of the

Figure 16. Relationship of the Ancho Canyon basalt to Totavi Lentil gravels of the Puye Formation. See Appendix C for location.

Rio Grande throughout the length of White Rock Canyon and over an area of 181 square kilometres east of the river. Several small cones can be seen and flow directions appear to be outward from these local eruptive centers. The sequence, including interlayered sediments, is greater than 396 m near Chino Mesa (Griggs, 1964, p. 37).

Griggs divided the Cerros del Rio volcanic rocks into five map units and briefly described each unit. However, detailed mapping of the entire field has not been done and complete petrographic studies of the flows are not available. The oldest units (1 and 2) interfinger with the Puye Formation. Units 3 and 4 overlie the Puye Formation and are overlain by the Bandelier Tuff. According to Smith and others (1970), at least part of the youngest unit overlies the Otowi Member of the Bandelier Tuff.

The age of the Cerros del Rio flows is late Pliocene to early Pleistocene. Unit 1, in Ancho Canyon, has yielded K-Ar dates of 1.17±0.09 m.y. and 2.6±0.4 m.y. (Appendix C). The latter age is accepted as the more reasonable in relationship to the stratigraphy and other ages. The former age appears to be too young perhaps due to argon loss. A sample collected from Unit 3 where State Highway 4 crosses it (Sec. 21, R7E, T19N) has been dated by Miles Silberman and yielded a K-Ar age of 2.08±0.30 m.y. (Smith, R.L., written commun., 1974). East of the portion of the Cerros del Rio flows mapped by Griggs (1964), a basalt overlies the type area for the Ancha Formation (Spiegel and Baldwin, 1963). That basalt, probably equivalent to Unit 3,

has a K-Ar age of 1.97±0.06 m.y. The flow overlying the Otowi Member of the Bandelier Tuff must be less than 1.4 m.y. (Doell and others, 1968).

Eruption of the Cerros del Rio volcanic rocks was in part synchronous with the deposition of the Puye and Ancha Formations. Additional commentary is located in the sections discussing these formations.

The Servilleta Formation

All the post-Santa Fe Group basalt flows and interlayered sediments in the northern part of the Española Basin are considered part of the Pliocene Servilleta Formation (Miller and others, 1963). This formation was introduced by Butler (1946, 1971) and used by Montgomery (1953) to include the basalts and interlayered alluvium north and west of the Picuris Range. Although no type locality nor total extent are given by previous authors, the formation in common usage is extended to include basalts in the Rio Grande rift from the Española Basin northward to Taos.

The Servilleta Formation unconformably overlies the Tesuque and Chamita Formations. It is overlain by eolian sands of undetermined age. Close to the Picuris Range the flows are typically 15 metres thick (Montgomery, 1953, p. 53). The southernmost extension of these flows, capping Black Mesa, is commonly 9 metres thick and thins to 30 cm in places on the southwest edge.

The Servilleta basalts in the center of the rift were described by Lipman (1969) as coarse-grained, porous olivine tholeiites. The feldspar is usually labradorite (Miller, 1956). The basalt near the town of Vadito (Fig. 18) differs from the other Servilleta basalts; it is a fine-grained, sparsely vesicular basanite with olivine, pyroxene, plagioclase, alkali feldspar, opaque oxides and analcite (Appendix C).

The Servilleta basalts have been dated by the K-Ar method in three areas. Near Taos, the sequence of flows ranges in age from 3.6 to 4.5 m.y. (Ozima and others, 1967). The Black Mesa flow has been dated at 2.78±0.22 m.y. and the flow near Vadito at 5.11±0.42 m.y. (Appendix C). Further K-Ar dating has been done north of the Española Basin by Lipman and Mehnert (1975).

The difference in composition and age between the flow at Vadito and the other Servilleta basalts leads me to conclude that the Vadito flow is not a part of the Servilleta Formation but belongs to the pretholeiitic, feldspathoidal eruptive series of Pliocene to Holocene age on the High Plains (Lipman and Mehnert, 1975; Manley, 1976b).

Gravels at the base of the lowest Servilleta Formation basalt have been observed by several geologists including Lambert (1966), Galusha and Blick (1971), Miller (1956), Montgomery (1953) and myself (Fig. 17). Beneath the southern portion of the Black Mesa flow the gravel exposures are predominantly well-rounded quartzites, but also contain intermediate and silicic volcanic rocks (Fig. 9). Exposures show gravels and interfingering sands in sections as much as 9 m thick.

Figure 17. The Servilleta Formation near Vallito Peak on Black Mesa. Basal gravels are approximately 1.5 m thick and overlie the Chamita Formation.

Maximum clast size observed was 51 cm. Imbrication of clasts indicates a direction of transport towards the south or southeast. At some of these exposures, pillow structures give evidence that water was present at the time of eruption. Both the gravels and the basalt unconformably overlie the Chamita Formation at the southern end of Black Mesa.

Beneath the Servilleta basalt on the mesa northeast of Velarde, is a 4.6-metre-thick gravel bed composed of quartz, quartzite, granite, sandstone, phyllite and some volcanic clasts. These gravels unconformably overlie the Ojo Caliente Sandstone of the Tesuque Formation according to Galusha and Blick (1971). (See discussion p. 104).

The composition, imbrication, and rounding of the gravels beneath the Servilleta Formation on Black Mesa indicate the presence of an axial river with source areas in the Sangre de Cristo Mountains and north of the Española Basin. These axial river gravels are contemporaneous with axial gravels of the Puye Formation and both are considered to be deposits of the ancestral Rio Grande. The higher percentage of intermediate volcanic rocks and presence of basalt in the Puye Formation axial gravels imply that these clasts were contributed to the ancestral Rio Grande downstream (southwest) from Black Mesa. Perhaps an ancestral Rio Chama brought volcanic clasts from the Brazos uplift and Jemez Mountains into the Rio Grande close to the present-day confluence.

High Surface Gravels on the Northeast Pleateau

The Embudo Complex and Tesuque Formation are cut by three major geomorphic surfaces extending northwestward from the Sangre de Cristo Mountains toward the northern margin of the Española Basin (Fig. 18). The gravels on these surfaces were included in the Ancha Formation by Miller (1963). The existence of these surfaces and their deposits helped create the illusion that all the sedimentary rocks of the northeast plateau were young fan or pediment gravels (Cabot, 1938; Miller, 1963).

Each surface has been named for the drainage to the north of it. The surfaces from north to south are the Oso, the Entrañas, and the Truchas (Figs. 19, 20, and 21). The Oso is the highest in altitude, the Truchas is the lowest. The differences in altitude between the surfaces are on the order of 30 metres. Unfortunately, only one good exposure was found of the contact between these surface gravels and the underlying Tesuque Formation. The exposure shows Oso surface gravels overlying the Tesuque Formation with angular unconformity (Fig. 22). Here the gravel is less than 3 metres thick.

The scarcity of exposures has presented difficulties in mapping the extent of the surface gravels. The hillsides are gravel-mantled with a mixture of surface and Tesuque Formation or Embudo Complex clasts. A contact was approximated where the lithologic percentages and size of clasts changed.

The gravels on the geomorphic surfaces are distinct from the underlying Tesuque Formation. The clasts are quartzites

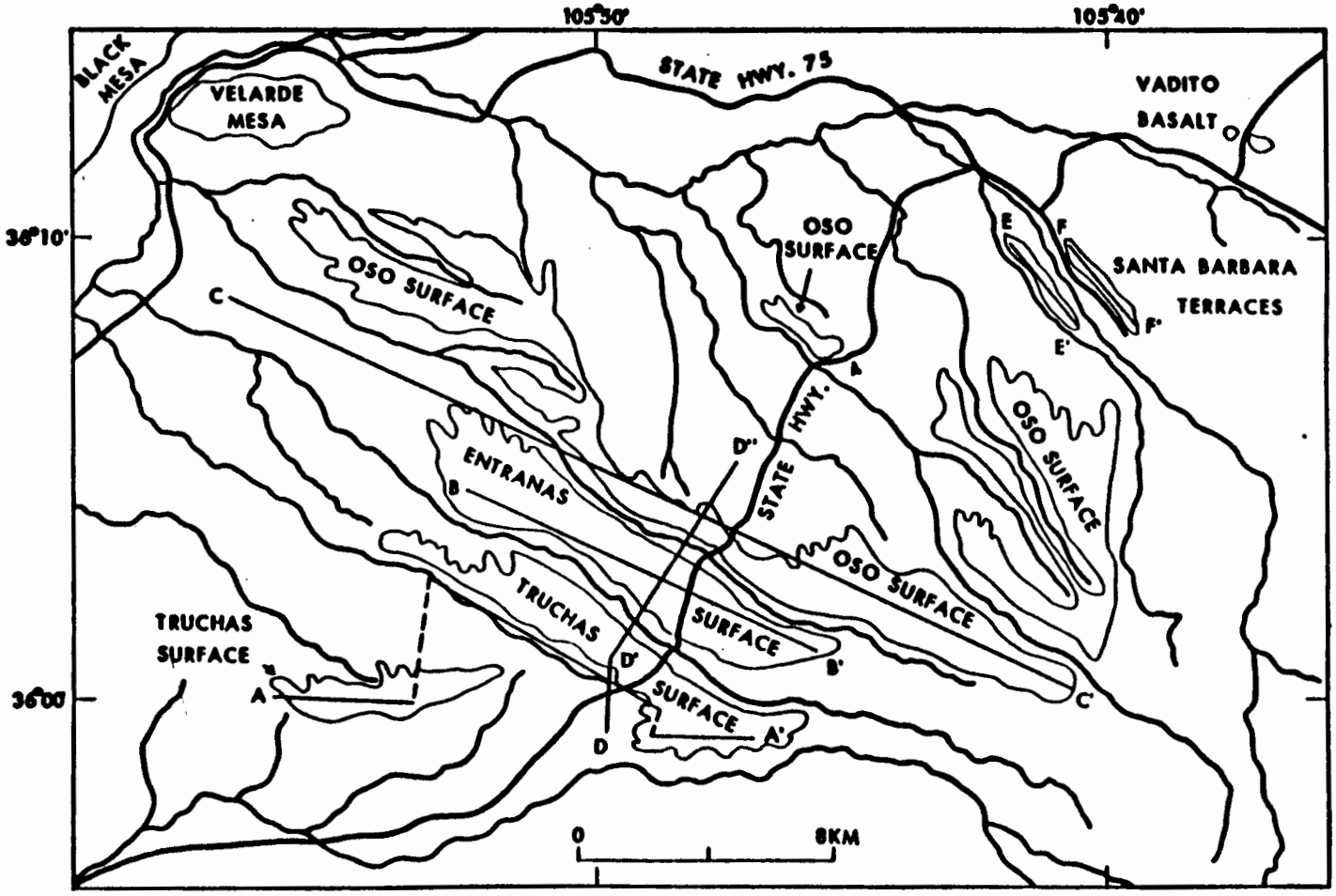


Figure 18. High surfaces on the northeast plateau. The profiles indicated by A-A', B-B', and C-C' are shown in Fig. 24. Cross section D-D'-D" is shown in Fig. 21. Profiles for the Santa Barbara terraces, E-E' and F-F', are compared to the profile for the Oso surface in Fig. 29.

Figure 19. Surfaces of the northeast plateau. Entrañas surface to left; Truchas surface and town of Truchas to right; Sangre de Cristo Mountains in the background.

Figure 20. Two of the high surfaces on the northeast plateau. Oso surface left of Cañada de las Entrañas; Entrañas surface on the right; Sangre de Cristo Mountains in the background. Photo taken near the windmill pumice site. See Fig. 58 for location.

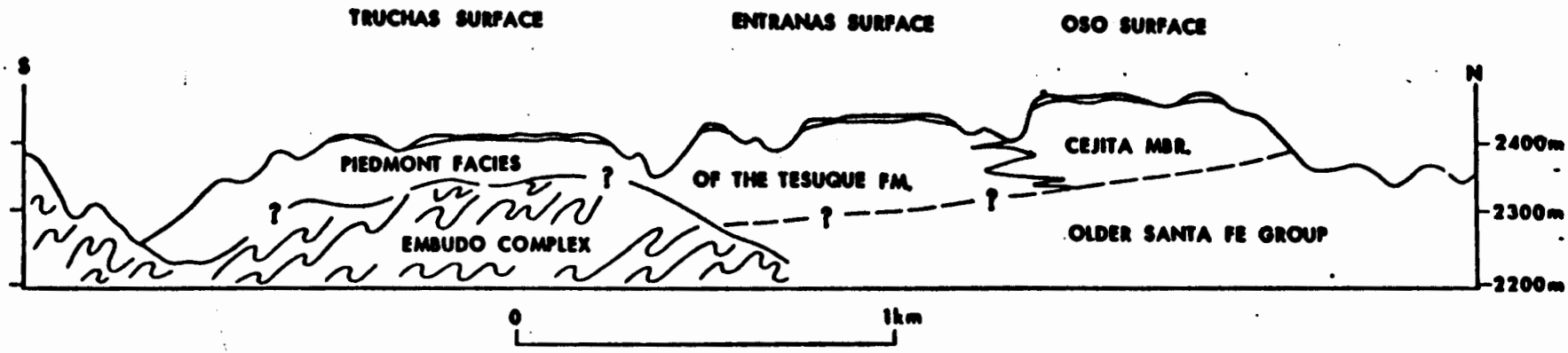


Figure 21. Cross section of the northeast plateau. Location of section shown on Fig. 18 as D-D-D".

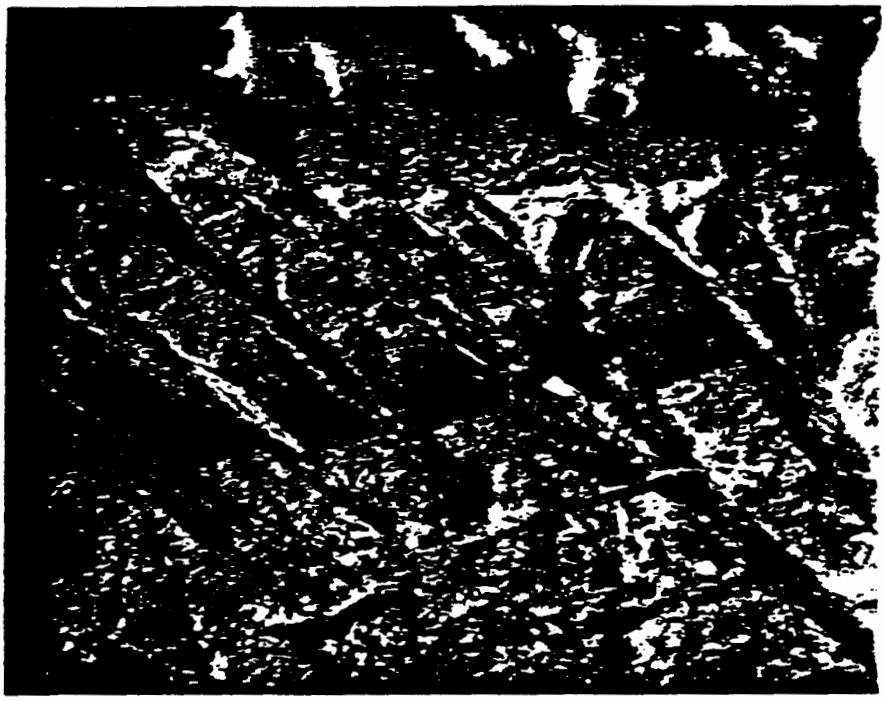


Figure 22. Angular unconformity between Oso surface gravels and Tesuque Formation north of Las Trampas.

with only traces of other metamorphic rocks and granite (Fig. 23). The surface gravels are coarse: boulders are commonly 100 to 130 cm in length and better rounded (0.6) than pebbles and cobbles. Boulders as large as 139 to 76 cm in length were found on the Oso and Entrañas surfaces, respectively, 20 kilometres from the mountain front.

Each of the surfaces has a well-developed soil developed in the gravels and overlying eolian sand where the latter is present. Relict soils consist of cambic and argillic B horizons underlain by indurated calcium carbonate and silica enriched horizons (hardpans). Near the margins of the surfaces the B horizons have commonly been stripped. In other places the B horizon is as much as 0.3 to 1 metre thick. The hardpans are 0.6 to 1.2 metres thick and the upper part of the horizon shows laminar structure. Foliated metamorphic clasts have been wedged apart by calcium carbonate crystallization. An in-depth study of the soils was beyond the scope of the present work.

Longitudinal profiles for the Oso, Entrañas and Truchas surfaces show gentle gradients (Fig. 24). Extension of these profiles suggests former base levels of the Rio Grande.

There are two possible origins for the geomorphic surfaces. They may represent a stair-stepped sequence of down-cutting and valley broadening cycles--the drainage had shifted southward prior to each rejuvenation. The possibility also exists that these surfaces originated by the faulting of a single surface. No clear evidence supports or refutes either

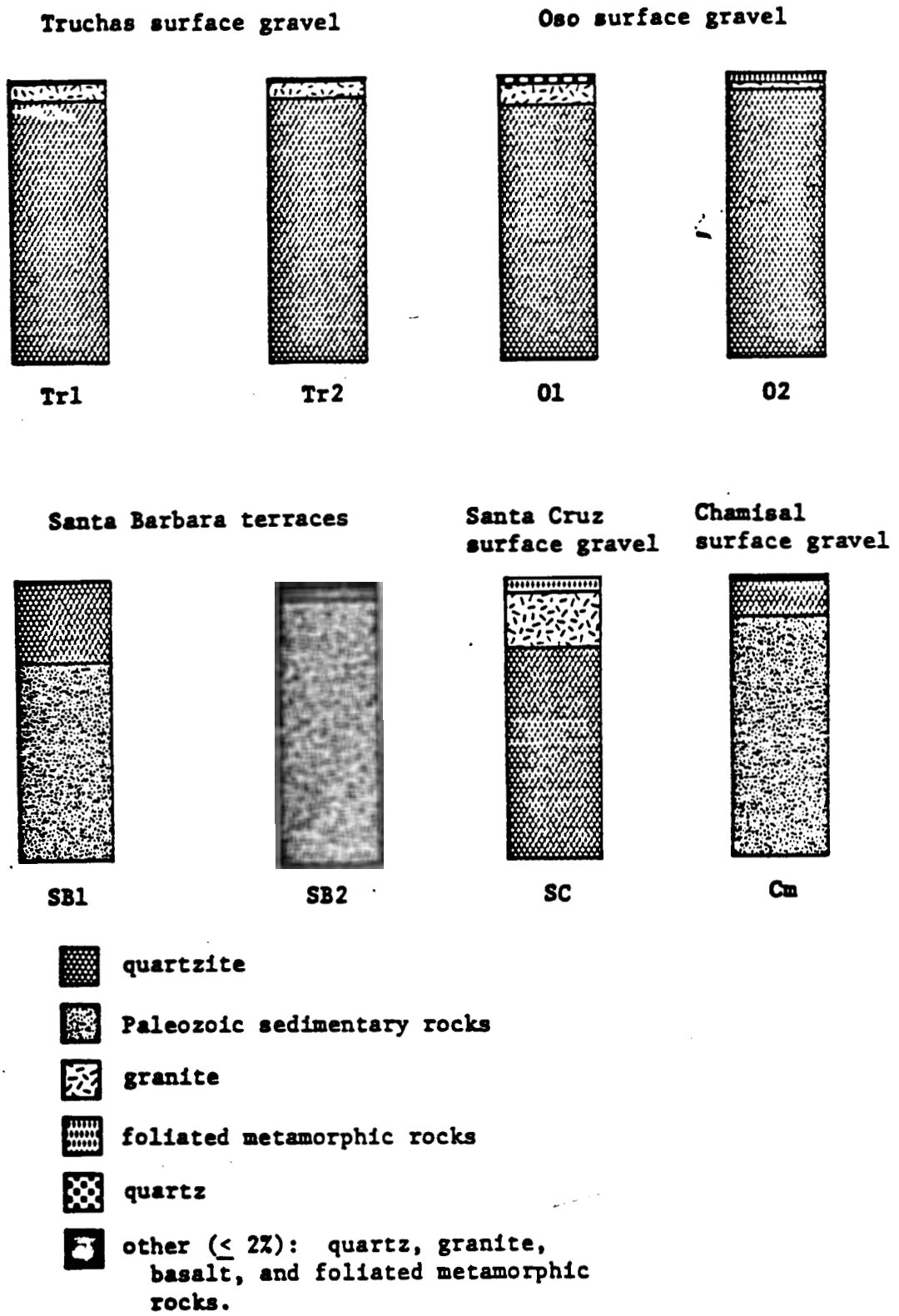


Figure 23. Composition of gravel clasts from the high surfaces, Santa Barbara terraces, Santa Cruz surface and Chamisal surface. See Fig. 10 for locations and Appendix D for percentages and methods.

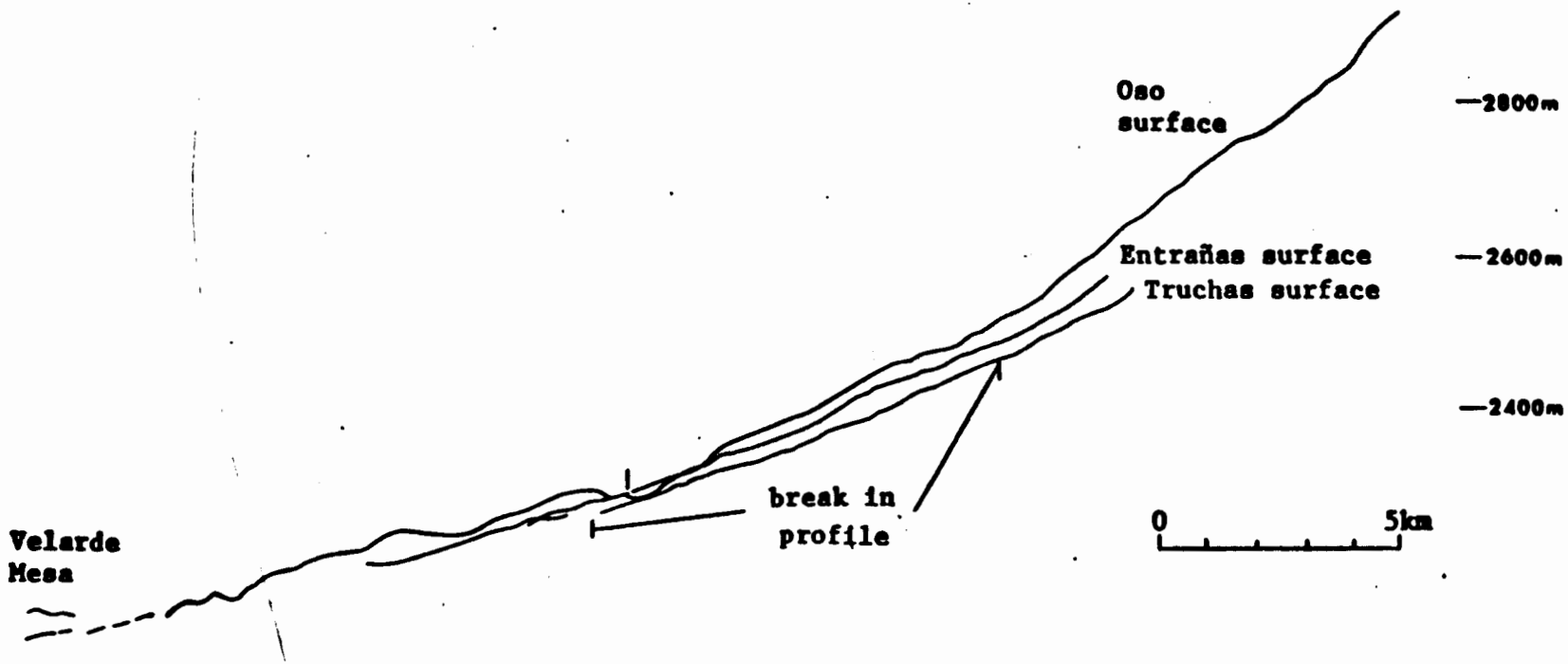


Figure 24. Profiles of the high surfaces. The Oso surface extends beneath the basalt-capped Velarde Mesa. See A-A', B-B', C-C' on Fig. 18 for locations.

hypothesis; however, the former hypothesis is preferred for the following reasons:

1) The Tesuque Formation shows no offset of strata on opposite sides of the dividing valleys, as would be expected if faulting had occurred.

2) The surfaces are fan-shaped in plan view and each diverges slightly from the others. Faulting is less likely to produce this radial pattern.

3) No examples of major east-west faults are known in the Española Basin.

The age of the surface gravels has been approximately determined by K-Ar dating and correlation of pumice. The highest and oldest surface, the Oso, extends to within 2 kilometres of Velarde Mesa (Fig. 23). By extending the profile of the surface, it appears that it is graded to the one upon which the Servilleta basalt was extruded (Cabot, 1938). In addition, the gravel composition at the base of the Servilleta Formation is similar to the Oso surface with the exception of the intermediate volcanic clasts found in the former. The basalt on Velarde Mesa was once continous with the basalt capping Black Mesa on the west side of the Rio Grande (Miller, 1956), which has yielded a K-Ar age of 2.78±0.22 m.y. (Appendix C). This basalt overlies the Chamita Formation which has two zircon fission-track ages of near 5 m.y. Therefore, the Oso surface gravels are as old or older than 2.78±0.22 m.y. but younger than 5 m.y.

A minimum age for the youngest of the surface gravels can only be estimated. The Truchas pumice quarry (Fig. 25) occurs in an erosional saddle cut 37 metres below the Truchas surface. Underlying the pumice are gravels related to the cutting of the northwestward trending Cañada Ancha (Fig. 30). The pumice could not be traced for any distance away from the quarry and could not be located on the west side of State Highway 4. It appears that the pumice is not a continuous bed but only a lens. Such lenses are common of air-fall deposits (Smith, R.L., personal commun., 1972). The base of the pumice deposit is not exposed in the quarry. To the east however, the gravels associated with the pumice can be observed overlying older, more weathered gravels that presumably belong to the Tesuque Formation. These relationships indicate an air-fall pumice younger than the formation of the Truchas surface.

The Truchas quarry pumice (72T16) is correlated with the Guaje Pumice of the Bandelier Tuff (Izett and others, 1972; Izett and Wilcox, 1968), for the following reasons:

1) Refractive indices of glass shards are similar.

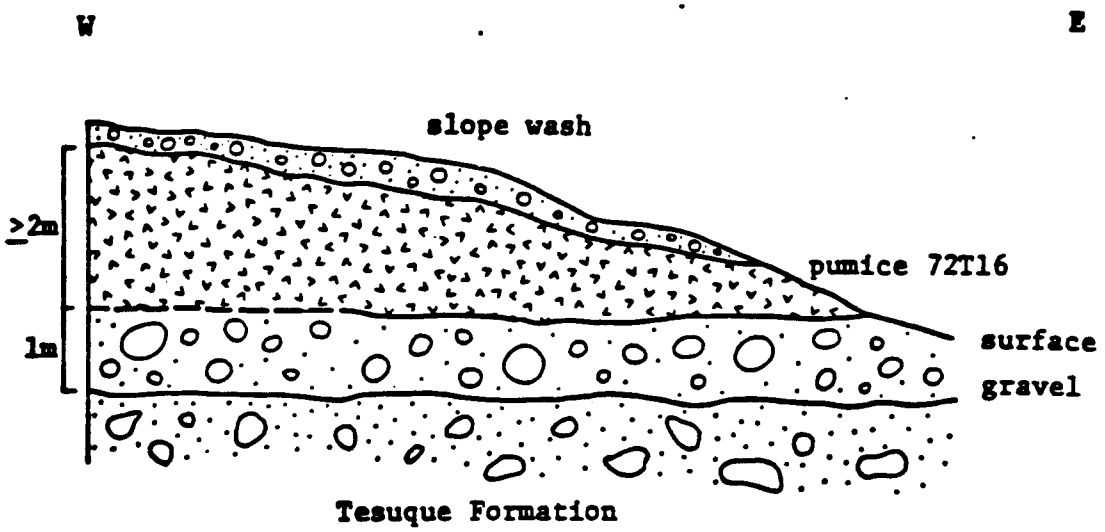
2) Tephras are both pumiceous in nature.

3) Phenocryst suites match.

4) Refractive indices of the clinopyroxenes overlap.

5) Similarity exists in the microprobe analyses of glass chemistries.

The petrology and chemistry of both the Guaje and Truchas pumices are given in Appendix A. Unfortunately it was not possible to



Characteristics:

surface gravel	Tesuque Formation	
56cm	25.5cm	maximum clast size
10cm	5.0cm	average clast size
round to subround	round to angular	
moderately sorted	poorly sorted	
amphibolites-fresh	amphibolites-altered	

Figure 25. Stratigraphic relationships at the Truchas pumice quarry. See Fig. 10 for map location of sample 72T16. See Fig. 7 for key to symbols.

obtain reliable indices of refraction for the orthopyroxene in the Truchas pumice. The orthopyroxenes are sparse, altered, and often lack glass mantles. Large clast size of the Truchas pumice indicates a close source (Walker, 1971). No other known Late Pliocene to Pleistocene source area would have been close enough. The Guaje Pumice bed has been K-Ar dated at 1.4 m.y. (Doell and others, 1968).

In summary, the age of the high surface gravels can be bracketed between 5 and 1.4 m.y. and were probably deposited between 3 and 2 m.y.

Bandelier Tuff and Cerro Toledo Rhyolite

The Bandelier Tuff caps much of the Pajarito Plateau; it overlies the Puye Formation and basalts from the Cerros del Rio field. Smith (1938) introduced the term but the tuff was first described by Griggs (1964), and later redefined by Bailey and others (1969). On the western side of the Pajarito Plateau the tuff is as much as 320 metres thick (Griggs, 1964, p. 47).

The Bandelier Tuff is composed of two members, the Otowi and Tsirege. Each is a multiple-flow, compound cooling unit of welded tuffs with a basal air-fall unit. The basal units are the Guaje and Tsankawi Pumices (Bailey and others, 1969). Eruption of the Bandelier Tuff was genetically related to the Toledo and Valles calderas of the Jemez Mountains.

For many years the Valles caldera was considered the source for all local pumice beds and the Great Plains "Pearlette"

ashes (Miller, 1963, p. 51; Swineford, 1949). More recently it has been recognized that rhyolitic Pleistocene ash deposits might be derived from any of three major centers:

1) the Yellowstone caldera in Wyoming (Pearlette type B, about 2.0 m.y.; type S, about 1.2 m.y.; and type O, about 0.6 m.y.) (Wilcox and others, 1970; Izett and others, 1971; Naeser and others, 1971);

2) the Long Valley area of California (Bishop ashes of 0.73 m.y. average age) (Dalrymple and others, 1965); and

3) the Valles caldera of New Mexico (Otowi Member, about 1.4 m.y.; and Tsirege Member, about 1.1 m.y.) (Doell and others, 1968).

Tephra from sedimentary deposits in the Española Basin have been compared with published information on these ashes and pumices. The Truchas pumice quarry sample (72T16) is the only correlative located to date. It correlates with the Guaje Pumice of the Bandelier Tuff.

The air-fall member of the Cerro Toledo Rhyolite may include as many as a dozen individual beds and is related to the post-collapse history of the Toledo caldera (R.L. Smith, written commun., 1974). These beds are phenocryst-poor rhyolites that occur stratigraphically between the two members of the Bandelier Tuff. A complete study of these air-fall beds was beyond the scope of this dissertation; however, one pumice (72B2)

was partially analyzed for comparative purposes. The analyses show this Cerro Toledo Rhyolite air-fall bed to be lower in iron and manganese, and higher in calcium, than the Guaje and Tsankawi pumices (Appendix A). Correlative tephra layers in the Española Basin have not been identified.

Quaternary Gravel Deposits

Along the eastern margin of the Española Basin are a number of Quaternary surface and terrace gravels. Many of the gravel deposits were included in Miller's (1963) Ancha Formation. Near the northeast plateau, three areas of gravel deposits were examined to establish their distinctiveness and thereby separate them from the high surface gravels and Tesuque Formation. Brief descriptions of these units are given below.

Santa Barbara Gravels

Two prominent terraces parallel the Rio Santa Barbara from the mountain front to the town of Peñasco (Figs. 18, 26 and 27). The terrace on the northeast side of the river is the higher of the two, approximately 50 metres above the valley floor, and is underlain by 24 metres of gravel. The lower terrace gravels, 24 metres above the present floodplain, are 4.6 metres thick. Both gravel deposits are composed of predominantly well-rounded cobbles of Paleozoic lithologies (Fig. 23) overlying the more quartzite-rich, pebble gravels and sands of the Santa Fe Group (Fig. 28). Both of these terraces are cut into the Sante Fe

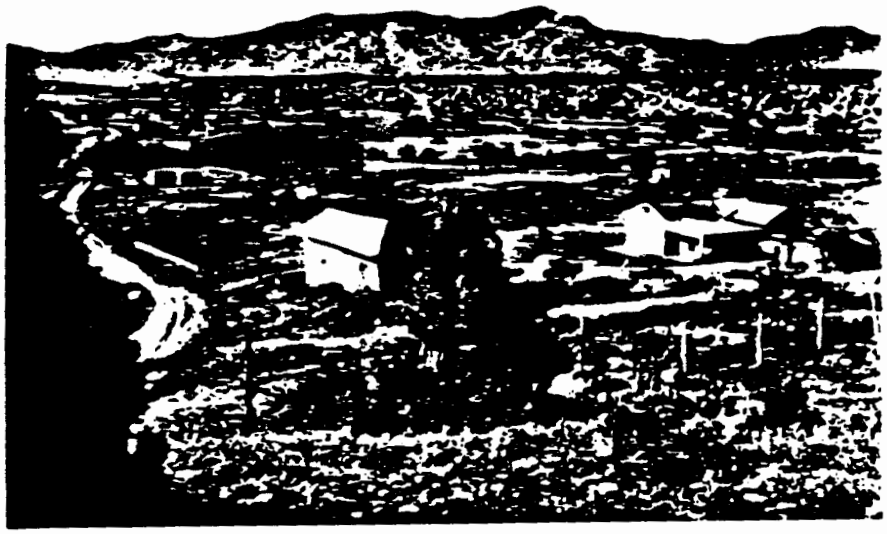


Figure 26. View north showing the terrace on the northeast side of the Rio Santa Barbara. Cultivated land in the middle distance is on the southwest terrace; Picuris Range in the background.

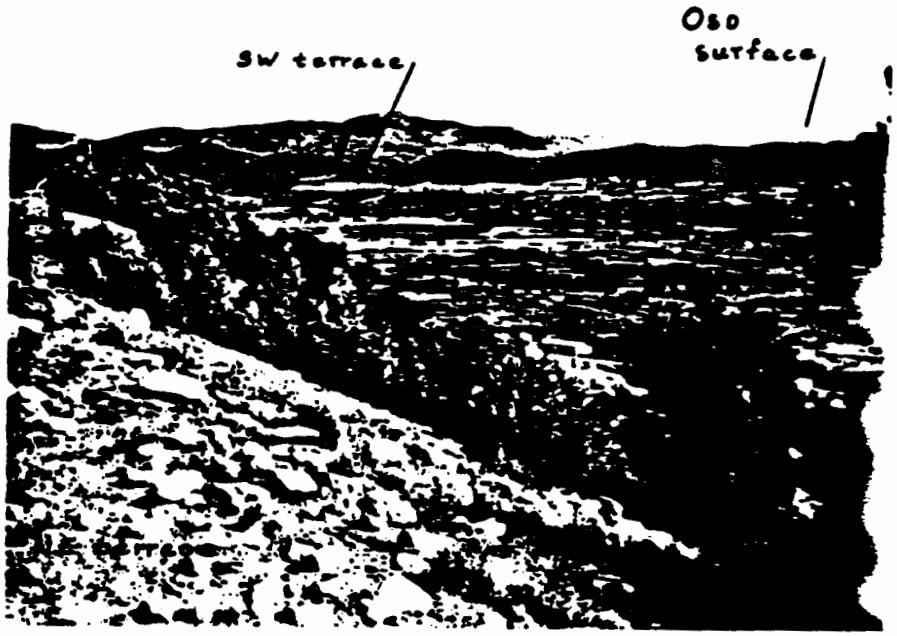


Figure 27. Terrace on the southwest side of the Rio Santa Barbara in the middle distance. View to the south from the northeast terrace. Sangre de Cristo Mountains in the background.

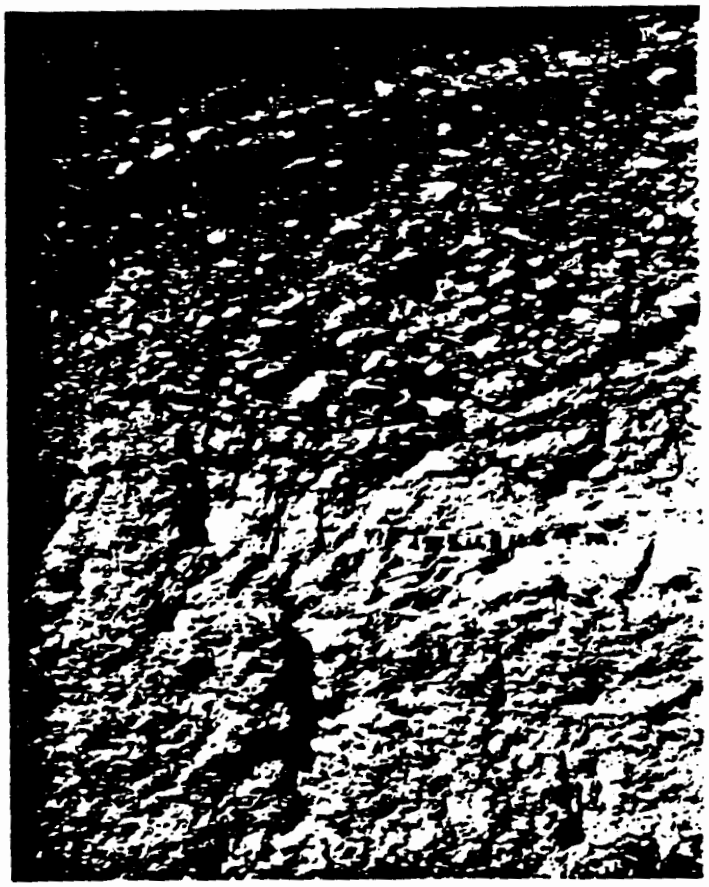


Figure 28. Exposure showing contact of the northeast terrace gravels, Rio Santa Barbara, overlying the Tesuque Formation of the Santa Fe Group.

Group below the elevation of the Oso surface gravels to the south. The terraces have more gentle gradients at equivalent distances from the mountains than the high surfaces (Fig. 29).

It is probable that these are glacial outwash terraces although neither of them can be physically correlated with glacial deposits in the Sangre de Cristo Mountains. On the basis of their altitude and proximity to present drainage, they are most likely correlative with moraines of Wisconsin age (Richmond, 1963).

Santa Cruz Gravels

The gravels beneath the prominent surface northeast of Santa Cruz Reservoir (Fig. 2) do not belong to the high surface gravel sequence because they are coarser and lie on a surface cut into the Santa Fe Group below the base of the lowest high-surface gravel (the Truchas surface gravel). The gravels are 17 metres thick and consist mainly of cobbles and small boulders (76 cm maximum size observed) of quartzite (Fig. 23); they overlie the Santa Fe Group with angular unconformity. Imbrication of clasts indicates a westward direction of transport for the gravels. Similar gravels were noted on divides west and southwest of the Santa Cruz Reservoir. They are considered part of the same deposit because of their similarities in composition and altitude. Reworked volcanic ash is associated with these gravels, but it has not been possible to identify this ash.

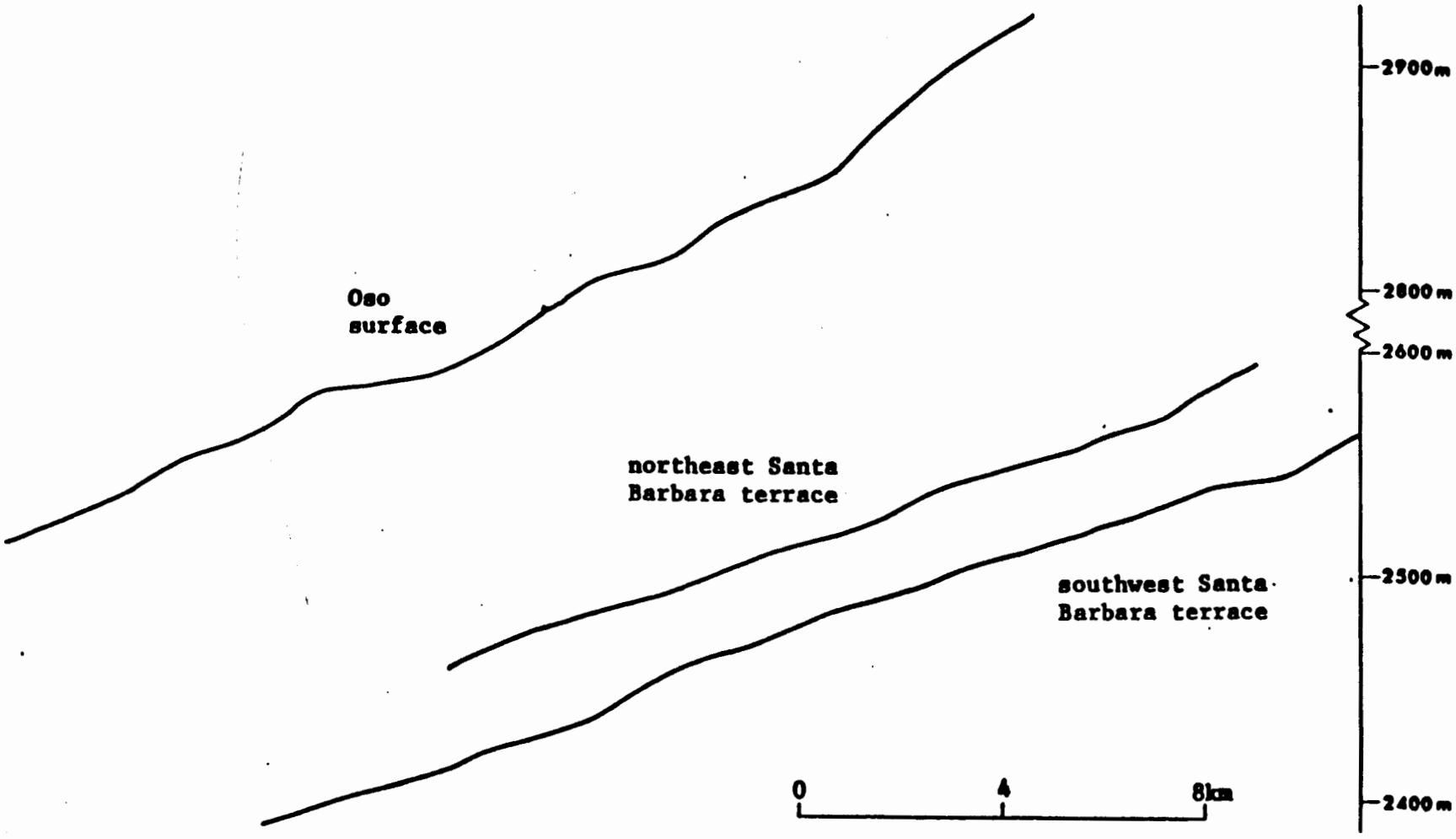


Figure 29. Surface profiles for the terraces along the Rio Santa Barbara compared to the profile for the Oso surface.

Chamisal Gravels

The flat-topped hills north of the town of Chamisal (Fig. 30) are underlain by well-rounded cobble gravel and silty sands. The gravel is 3 metres thick, overlies the Santa Fe Group, and is overlain by 4.6 to 9 metres of silty sands with small angular pebbles. The gravel clasts are predominantly Paleozoic sandstones with some basalt, quartzite and Paleozoic limestone (Fig. 23); the angular pebbles above are quartzites with, on the top surface, granite and limestone clasts. The origin of these gravels is unknown but they do not resemble either the Cejita Member or the piedmont facies of the Tesuque Formation. The presence of basalt and abundant Paleozoic clasts suggests the Sangre de Cristo Mountains and Vadito flow as source areas. If this assumption is correct, the gravels post-date the 5.11 m.y, Vadito flow and are therefore late Pliocene or Pleistocene in age.

Other Quaternary Gravels

Additional isolated deposits of gravels were mapped by Miller (1963) as part of the Ancha Formation. The area north of the Santa Barbara terraces was not studied; nor were the outcrops that extend southward from the Santa Cruz Reservoir to Santa Fe. These gravels appear to be relatively thin (less than 30 metres) and related to surface cutting episodes paralleling present drainages.

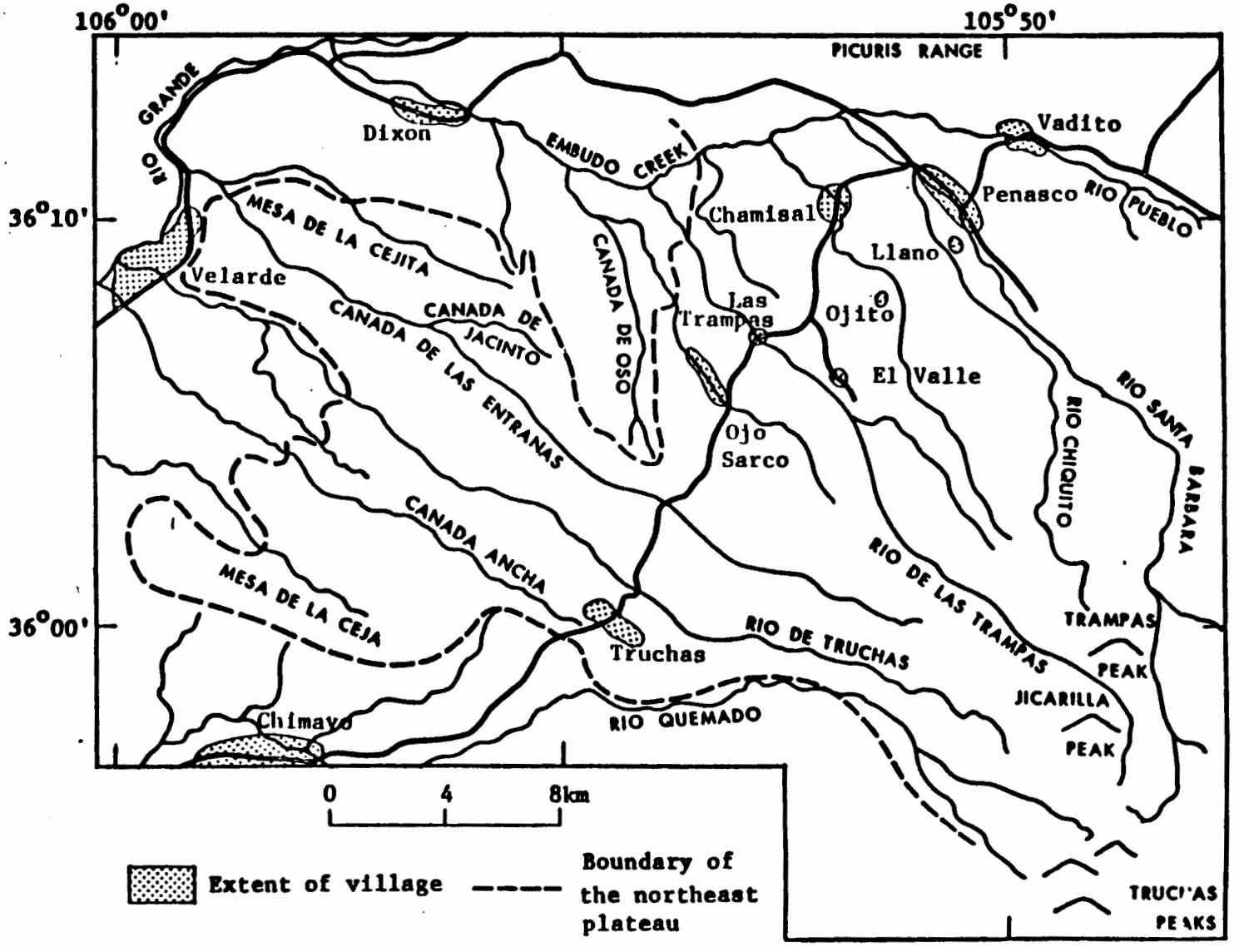


Figure 30. Place names on the northeast plateau.

Terraces exist along the present Rio Grande. Their composition is similar to that of the present river. These gravels were observed west and northwest of Española and on hills south of State Highway 5.

CHAPTER V

LATE TERTIARY STRATIGRAPHY OF THE NORTHEAST PLATEAU

This section will describe two facies of the Tesuque Formation that have been recognized as a result of detailed mapping: the Cejita Member and the piedmont facies.

New Unit: Cejita Member of the Tesuque Formation

Terminology

The northeast plateau is a tableland in the northeast portion of the Española Basin. It is 370 to 1160 metres higher in altitude than the Rio Grande floodplain, is fan-shaped with the apex near Jicarilla Peak, and dissected by northwestward flowing drainages (Fig. 30). The plateau extends from the Sangre de Cristo Mountains to the Rio Grande. It is bounded on the south by the Rio Quemado and Santa Cruz valley; on the northeast the plateau abuts against the Picuris Range; and to the northwest an erosional basin, the Dixon sub-basin, separates the northeast plateau from the Picuris Range.

The northeast plateau has received little study prior to this dissertation. Galusha and Blick (1971) referred to the area as the Picuris re-entrant fan but did not map it. Sedimentary rocks in the western Dixon sub-basin were assigned to the Ojo Caliente Sandstone; the overlying gravels, now recognized as part of the

Cejita Member, were termed the Truchas pediment gravel (Galusha and Blick, 1971, p. 67 and 70). Miller (1963) mapped the sedimentary rocks in this area and assigned them to three formations: Picuris, Tesuque, and Ancha. The Ancha Formation was described as "remnants of a once-continuous sheet of unconsolidated gravel" that is locally more than 90 metres thick (Miller, 1963, p. 51). Little additional description of these sediments was given; however, it is understood that this work was a reconnaissance study uncompleted because of his untimely death.

To better understand the stratigraphy of the northeast plateau, and thereby the history of the Española Basin as a whole, it was necessary to map in detail the area of Miller's Ancha Formation and differentiate deposits where possible. As a result of this remapping, the sedimentary rocks shown as Ancha Formation and part of the underlying Tesuque Formation have been reassigned to:

1) the Cejita Member of the Tesuque Formation
2) a piedmont facies of the Tesuque Formation
3) high surface gravels
4) Quaternary gravels (including the Santa Barbara, Santa Cruz, and Chamisal gravels)

The term Ancha Formation for these deposits is inappropriate and has been abandoned. (See discussion under Ancha Formation.)

Description

The Cejita Member of the Tesuque Formation is exposed beneath Mesa de la Cejita at the northwest edge of the northeast plateau (Fig. 58). The extent of exposure throughout the mapped area varies considerably. Vertical cliffs and steep gullies predominate in places; elsewhere hillsides are mantled with gravel and outcrops are nonexistent.

The Cejita Member overlies the Ojo Caliente Sandstone of Galusha and Blick (1971) and a little known older unit of the Santa Fe Group in the Dixon sub-basin; it is overlain in turn by gravels of the Oso surface. To the south, the Cejita Member interfingers with the piedmont facies of the Tesuque Formation. The Cejita Member varies in thickness from 1.5 to 120 metres. It is thickest to the northwest and thins to the southeast. The original thickness is not known because the upper surface has been eroded during the formation of the Oso surface.

The Cejita is a well-rounded, pebble to cobble gravel with interbedded sand units (Figs. 31 and 32). Boulders are present in many outcrops; the largest observed was 1.2 metres in length. Individual gravel beds may be as much as 37 metres thick and continuous for distances up to 1.6 kilometres. Large scale crossbedding can occasionally be observed in the gravel beds. The number of sand units increases toward the base and southern margin of the Cejita Member. Channeling and flute casts are

Figure 31. Exposure of the Cejita Member of the Tesuque Formation. Location west of windmill pumice site.

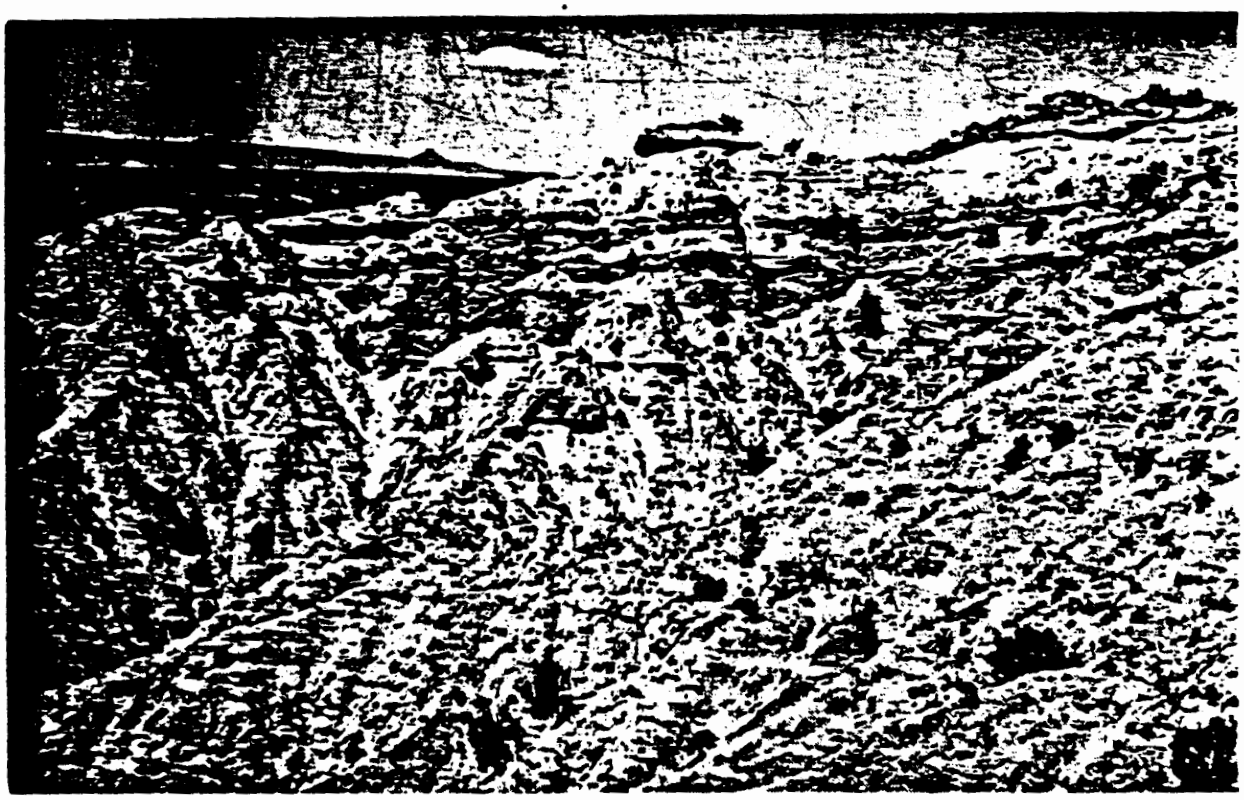


Figure 32. View of sands and gravels of the Cejita Member of the Tesuque Formation. Location north of the Rio Truchas, about 3 km southeast of Velarde.

occasionally seen in the sand units. Transport directions indicated by flute casts and pebble imbrication are generally westward (Fig. 58).

Clast counts show that the two major lithologies, quartzite and Paleozoic rocks, vary in percentage from 5 to 65 percent and 30 to 95 percent respectively. Other lithologies include granite, quartz, and intermediate to silicic volcanic rocks; together they constitute less than 10 percent of the clasts (Fig. 33). The volcanic clasts are found mainly in exposures along the north end of Mesa de la Cejita and are seldom observed to the south (Appendix D). The gravels are slightly to well-cemented by noncrystalline and crystalline calcium carbonate.

The source area for the Cejita Member was the Sangre de Cristo Mountains and Picuris Range. This statement is based on the following evidence:

1) The Paleozoic clasts in the Cejita gravels include Pennsylvanian lithologies with typical Pennsylvanian fauna including corals, bryozoa, brachiopods and crinoids (Fig. 34). Similar rocks are exposed in the Sangre de Cristo Mountains directly east of the Cejita Member.

2) Quartzites similar to those of the Cejita are present in the Precambrian rocks of the Sangre de Cristo Mountains and Picuris Range (Fig. 35). Included in these quartzites are sillimanite-bearing rocks not observed in other Precambrian source areas.

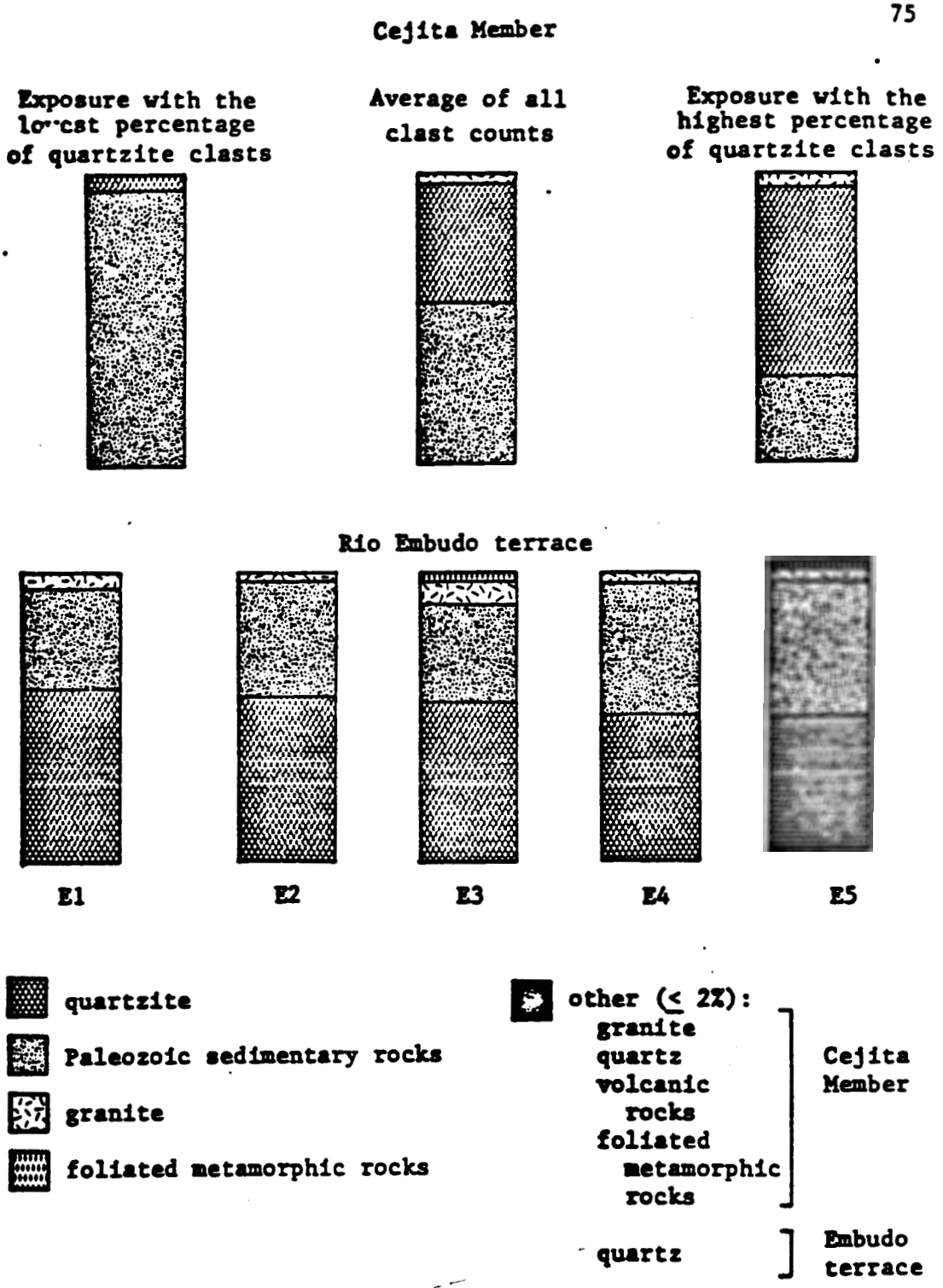
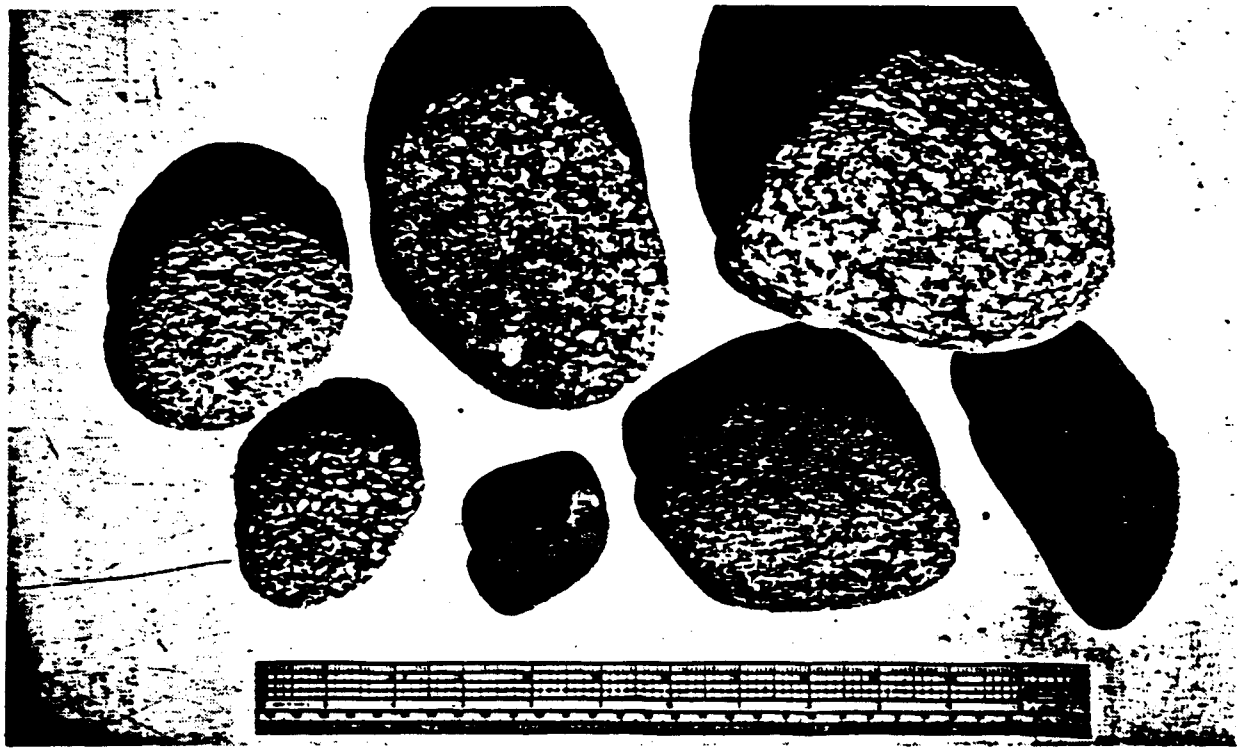


Figure 33. Composition of gravel clasts from the Cejita Member of the Tesuque Formation and a stream terrace along the south side of the Rio Embudo. The average composition for the Cejita Member is taken from information given in Appendix D. See Fig. 10 for locations.



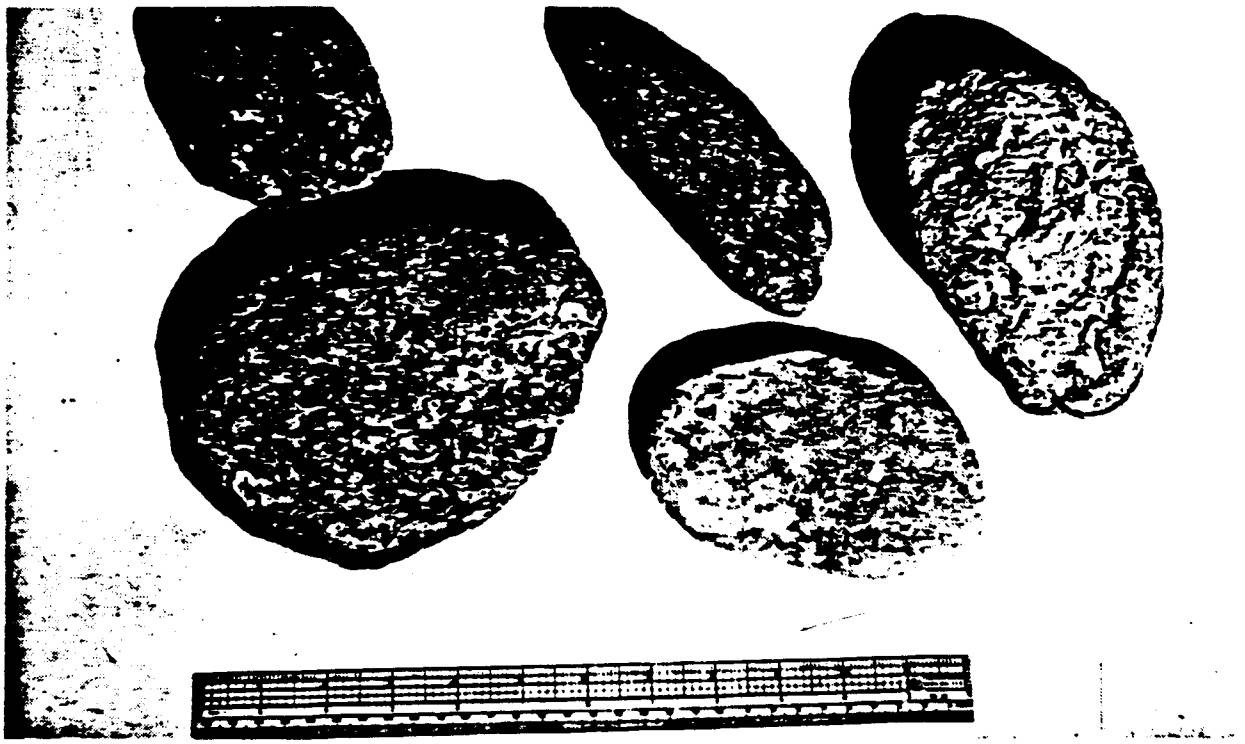


Figure 34. Paleozoic clasts from the Cejita Member of the Tesuque Formation.
View 1: Sandstone and conglomerates.
View 2: Limestones.

Figure 35. Precambrian clasts from the Cejita Member of the Tesuque Formation. Granite (1), schist (2), and quartzites (all others).

3) The intermediate and silicic volcanic rocks seen in the Cejita appear to be derived from reworking older sedimentary rocks. Rocks rich in volcanic clasts are presently exposed flanking, and steeply dipping away from, the Picuris Range. The volcanic clasts in the Cejita are not like those of the Jemez Mountains.

4) Pebble imbrication and flute directions indicate a source area to the east.

5) Terrace gravels along the Rio Embudo are composed of the same major lithologies as the Cejita (Fig. 33). The Rio Embudo has a provenance in the Picuris Range and Sangre de Cristo Mountains.

The Cejita Member was deposited by a major river flowing westward from the Sangre de Cristo Mountains into or through what is presently the Española Basin. Direction of flow and provenance mitigate against this river being an ancestral Rio Grande. The river that deposited the Cejita gravel was aggrading and shifted across a valley floor at least 5.6 kilometres wide. Along the southern margin of that floodplain, the river gravels interfingered with piedmont sands and gravels. The piedmont deposits are described below.

The type section for the Cejita Member is designated as the location for clast count Cj 12 (Fig. 58 and Appendix D) (105°53'19" W, 36°08'18" N; T. 22 N., R. 10 E., unsurveyed land grant; Velarde 7.5' Quadrangle). At this site the Cejita Member

is a single, 4-metre-thick gravel bed overlain and underlain by sands and gravels of the piedmont facies.

Piedmont Facies of the Tesuque Formation

Terminology

These deposits were previously mapped by Miller and others (1963) as part of the Ancha and Tesuque Formations. My work shows no basis for a contact between these units as shown by Miller and others (1963); however, a contact does exist, higher in the section, between a piedmont facies and the thin, high surface gravels. The piedmont facies is continuous with the Tesuque Formation as mapped by Galusha and Blick (1971) south of the northeast plateau.

Description

The piedmont facies of the Tesuque Formation underlies the northeast plateau from its southern margin north to Mesa de la Cejita. The western and southern margins of the plateau have good exposures; the eastern and central parts of the plateau contain isolated gullies, road cuts, and irrigation ditches in which the piedmont facies can be observed. The piedmont facies overlies older sedimentary rocks, such as the Picuris Tuff, and the unmapped older Santa Fe Group rocks of the eastern Dixon sub-basin; it is unconformably overlain by the high surface gravels.

The piedmont facies varies considerably in thickness. It is 310 metres thick at the southern margin of the plateau and may be considerably thicker toward the center of the basin where accurate measurements are not feasible due to numerous high angle faults. East of State Highway 4, the piedmont facies thickens and thins as it fills pre-Santa Fe Group valleys cut into the Embudo Complex. In several places the piedmont facies has been stripped from the Embudo Complex. The original thickness of the piedmont facies cannot be determined because its upper surface has been cut by the formation of the three high surfaces of the northeast plateau. Gravel-capped hills of Embudo Complex protrude 60 metres above the Oso surface near the mountains which implies that the piedmont facies was once at least that much thicker.

The piedmont facies consists of poorly defined beds of sandy pebble gravels with some gravely sand, gravel, and sand beds (Figs. 36, 37 and 38). Clay content is generally low although occasional dark red, clay-rich zones were found. Cross-bedding can occasionally be seen in the sand and gravely sand beds; slightly more common are channel cuts at the base of gravel beds. Beds are discontinuous lenses broken by rapid changes in texture and numerous small unconformities (Fig. 39). Individual beds are as much as 12 metres thick and clasts are angular to subround (Fig. 40). Sorting varies from poor in the sandy gravels to moderately well in the sands. Sand samples were compared visually to sized standards and averaged 3.5ϕ (Folk, 1968). Three representative sections, measured near

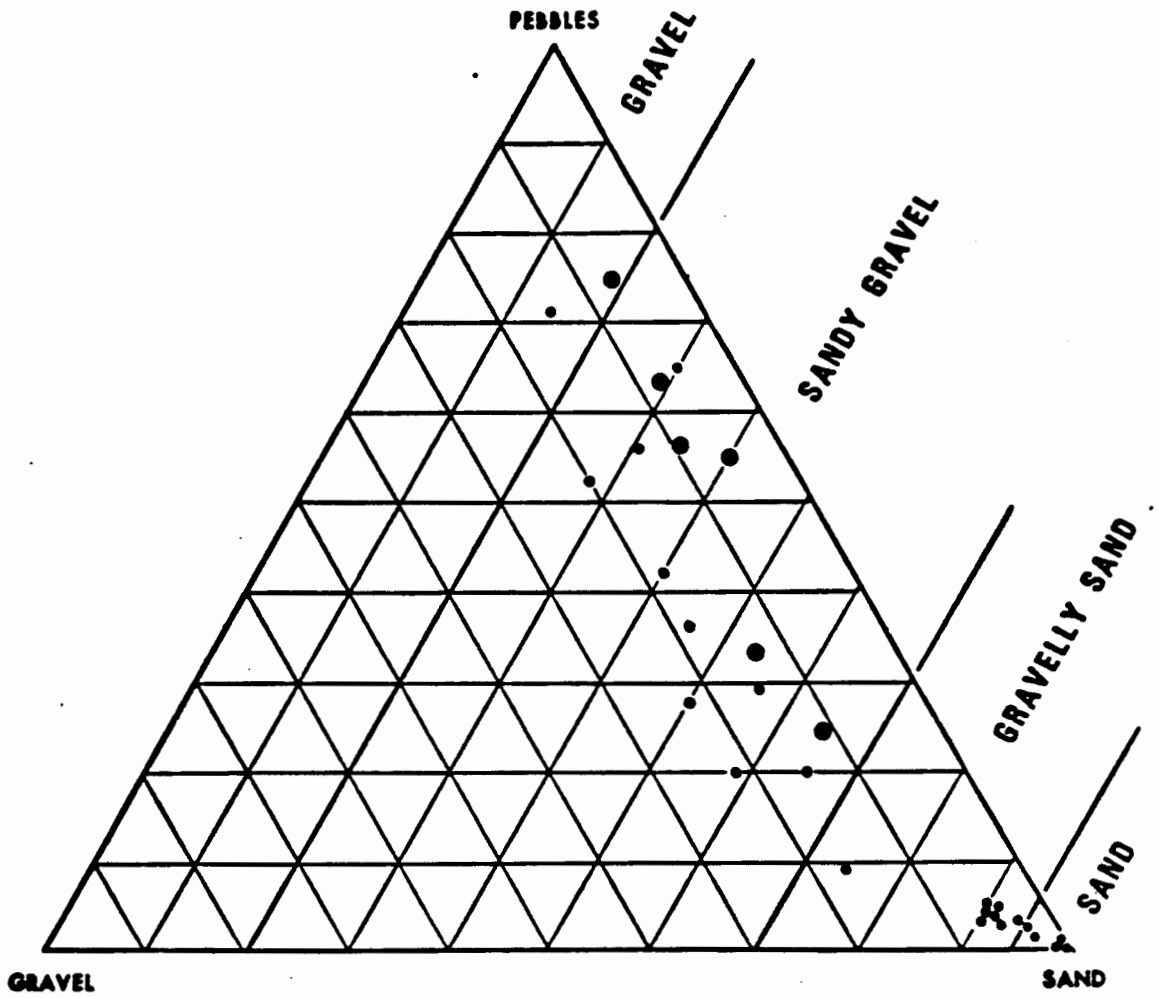


Figure 36. Grain-size analysis of the piedmont facies underlying the Truchas surface. Calculated by weight percent. Samples were collected at 1.5 m intervals in a stratigraphic section 44 m thick (Section 2313 m to 2344 m elevation). Classification is that of Folk (1968). See T1, Fig. 43 for map location and Appendix D for procedures. Encircled points indicate samples with cobbles present.

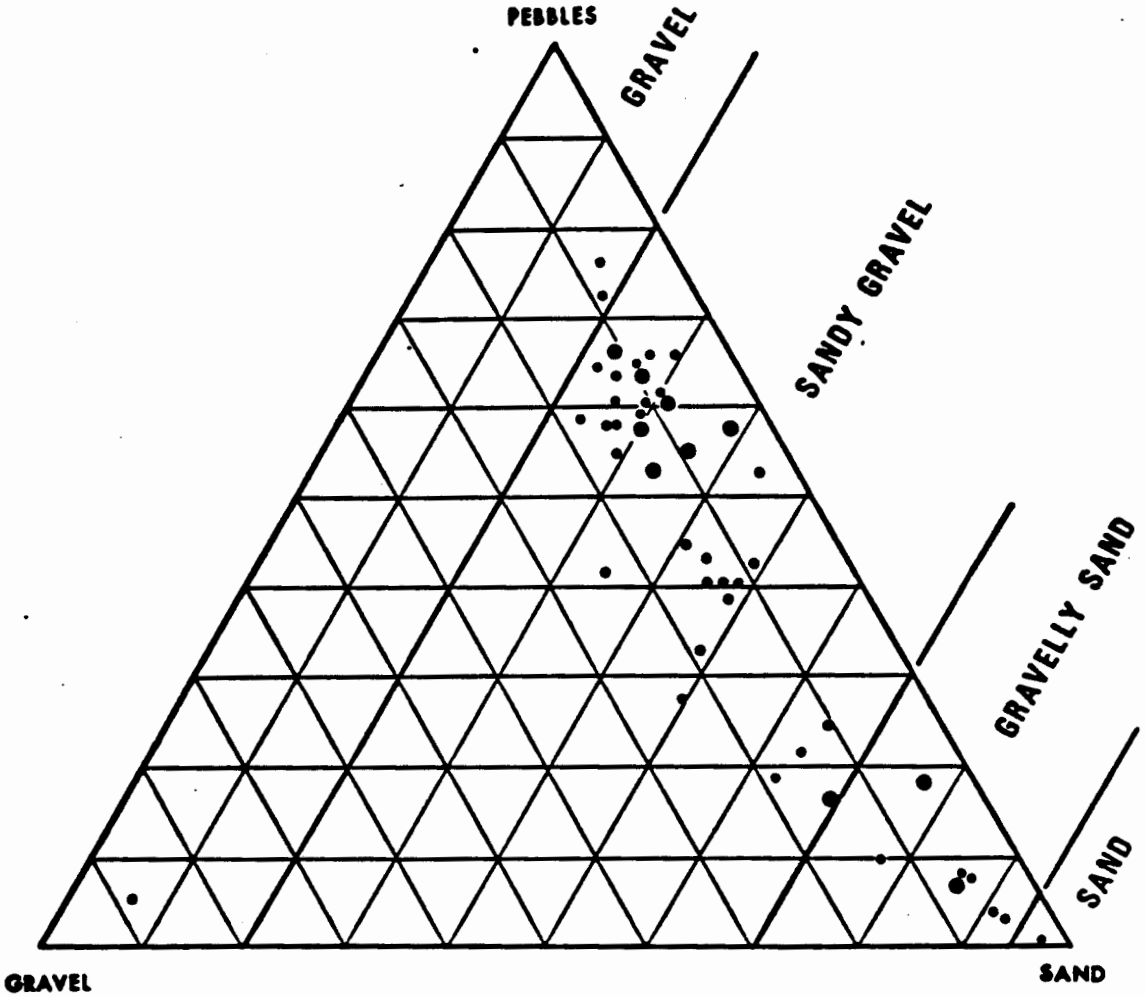


Figure 37. Grain-size analysis of the piedmont facies underlying the Entrañas surface. Calculated by weight percent. Samples were taken at 1.5 m intervals in a stratigraphic section 58 m thick (Section 2402 m to 2432 m elevation). Classification is that of Folk (1968). See T2, Fig. 43 for map location and Appendix D for procedures. Encircled points indicate samples with cobbles present.

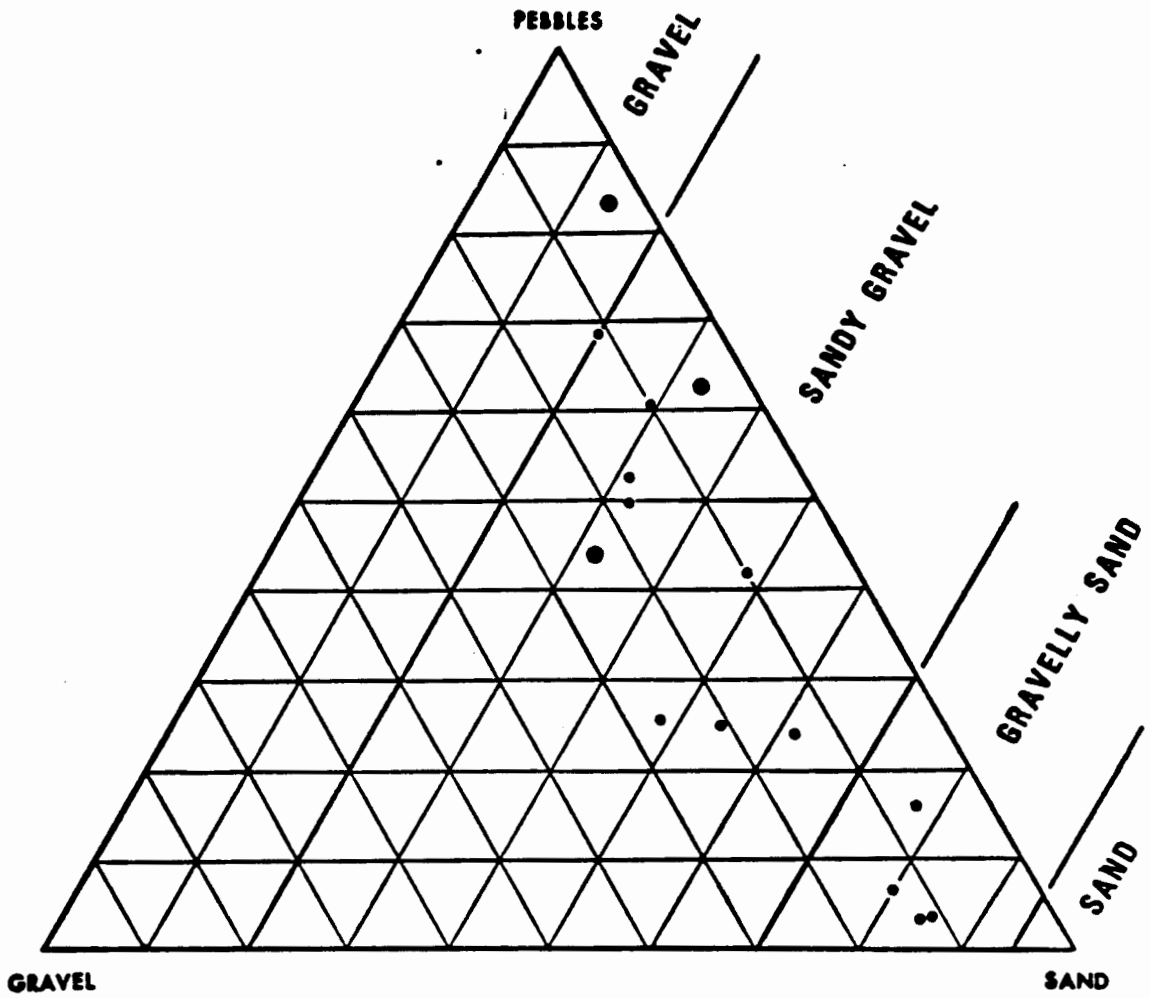


Figure 38. Grain-size analysis of the piedmont facies underlying the Oso surface. Calculated by weight percent. Samples were taken at 1.5 m intervals in a stratigraphic section 24 m thick (Section 2420 m to 2451 m elevation). Classification is that of Folk (1968). See T3, Fig. 43 for map location and Appendix D for procedures. Encircled points indicate samples with cobbles present.

Figure 39. Exposure of the piedmont facies of the Tesuque Formation. Location on a south-facing escarpment 1.7 km west of Truchas (T1 on Fig. 43). Chimayo and Santa Cruz valleys in the middle distance; Pajarito Plateau and Jemez Mountains in the background.

State Highway 4 (Fig. 43), are given in Figure 41. The piedmont facies includes several tephra layers and tuffaceous sediments, especially toward the northern part of the plateau. These are discussed in detail below.

The composition of gravels in the piedmont facies is predominantly quartzite, which often contains sillimanite, and granite. Lesser amounts of muscovite or biotite schist, gneiss, amphibolite, and quartz may also be present (Fig. 42). The sand and granule fractions commonly contain abundant quartz and feldspar grains because of the disintegration of the granite into mineral grains of those sizes.

Some units in the piedmont facies are cemented with noncrystalline calcium carbonate cement. Microscope examination showed that in most cases weakly-cemented sands contain a high percentage of alterred shards and pumice fragments, and/or phenocrysts. Alteration of volcanic glass may facilitate the formation of cement. (Ash beds replaced by calcium carbonate have been observed within the Nambe Member of the Tesuque Formation.) The cemented sands weather to resistent ledges or rounded, steep slopes. Gravel beds are better cemented than sands and also weather to ledges. Cementation is more prevalent towards the center of the basin than near the mountain front.

The piedmont facies was deposited as coalescing alluvial fans which were built westward from the Sangre de Cristo Mountains. The source rocks were the Precambrian granites of the Embudo Complex and quartzites of the Ortega and Vadito Formations.

Figure 40. Sandy gravel in the piedmont facies of the Tesuque Formation. Location 2.3 km west of site shown in Fig. 39.

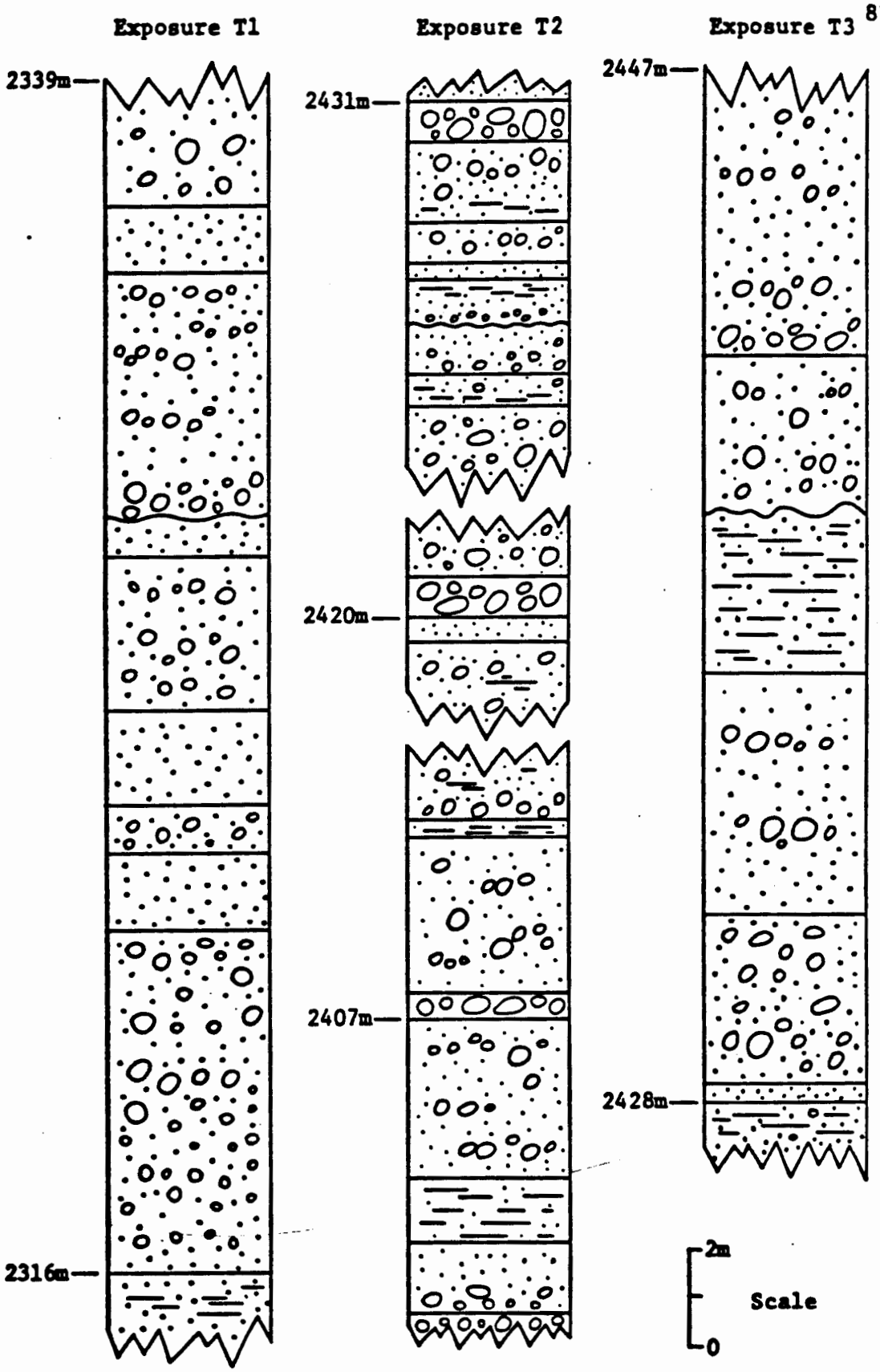


Figure 41. Three representative sections of the piedmont facies of the Tesuque Formation. See Fig. 43 for locations. See Fig. 7 for key to symbols.

Piedmont facies of the Tesuque Formation

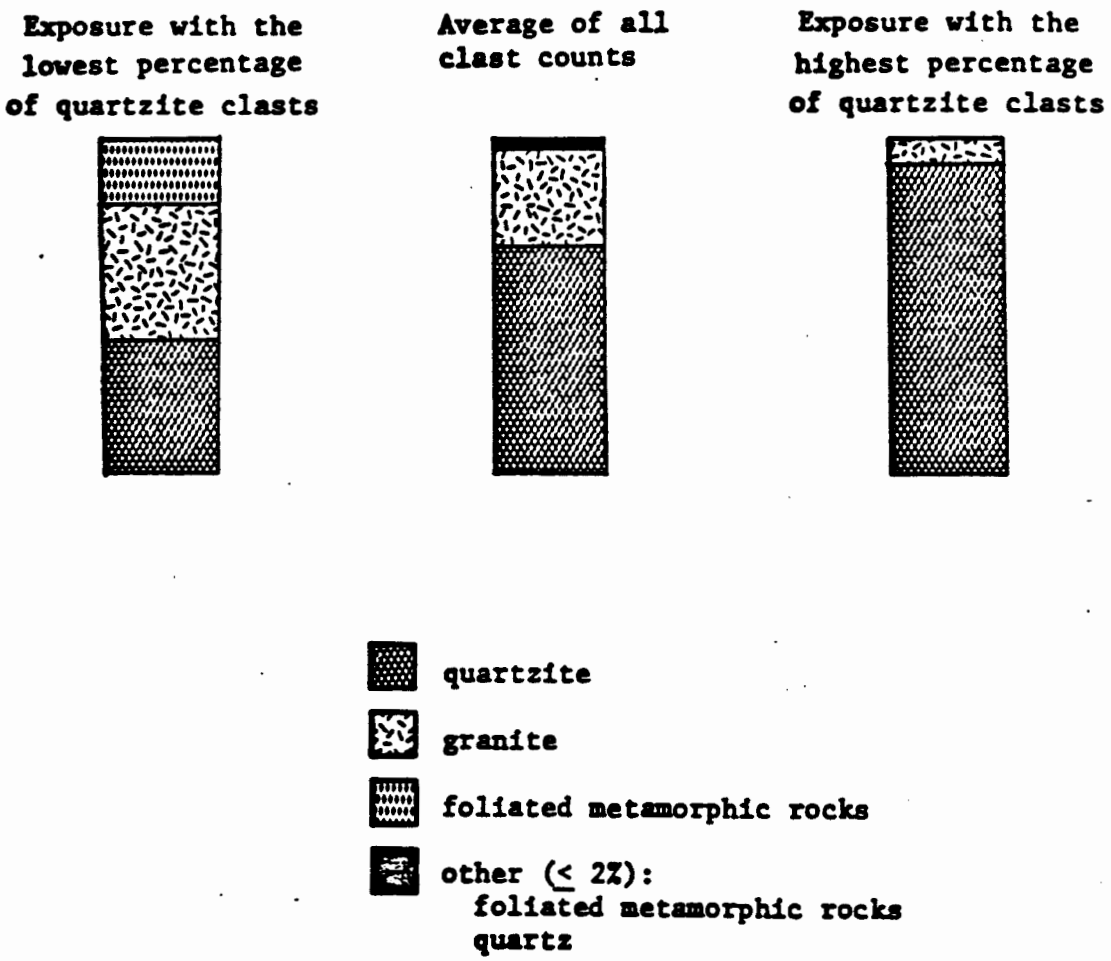


Figure 42. Composition of gravel clasts from the piedmont facies of the Tesuque Formation. The average composition is taken from the information given in Appendix D. See Figs. 10 and 58 for locations.

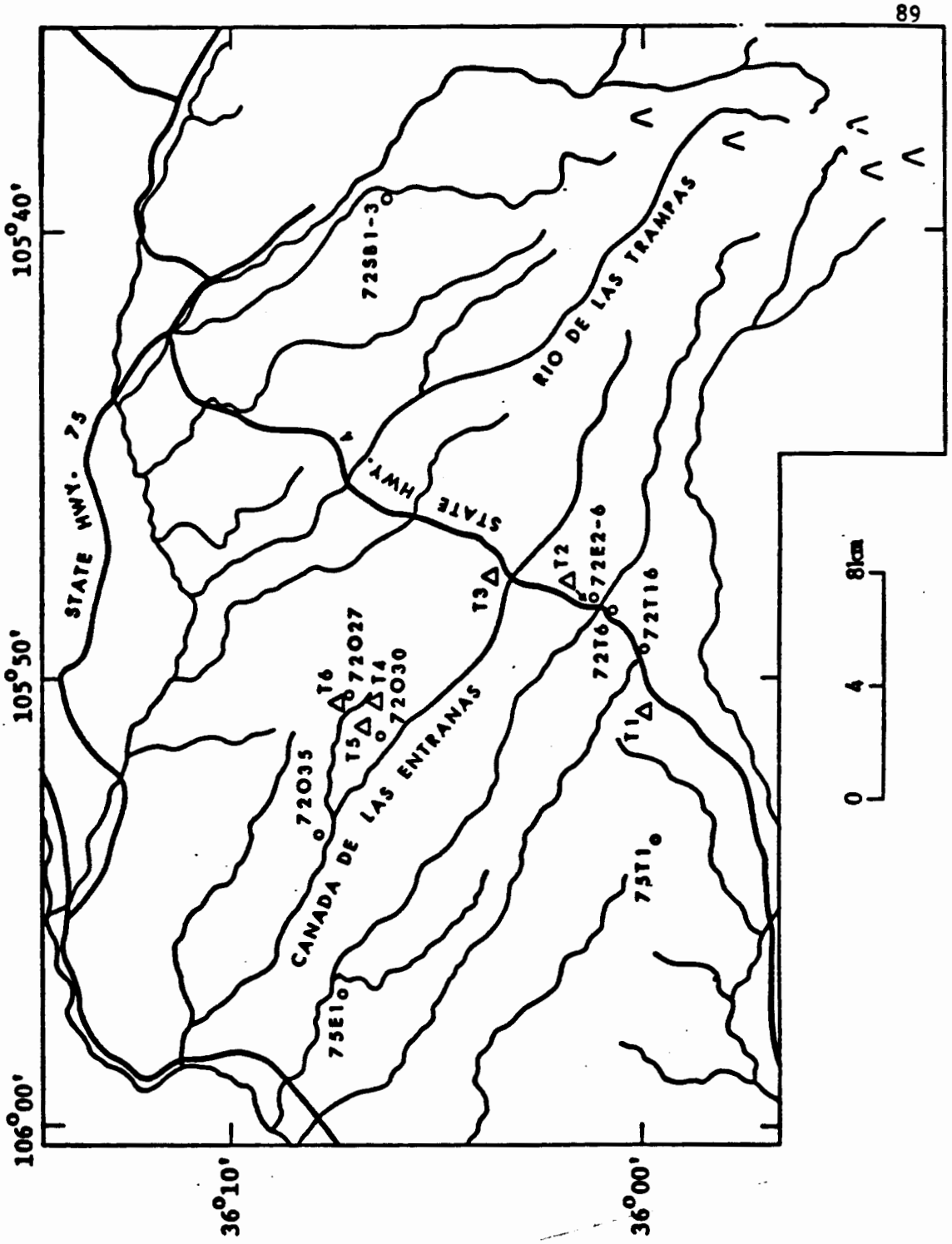


Figure 43. Location map for representative sections of the piedmont facies, Tesuque Formation, and tephra sites on the northeast plateau. The sections are shown in Fig. 41. Tephra are described in Appendix A.

Deposits of the piedmont facies resemble the sheetfood and sieve deposits described by Bull (1972) as characteristic of alluvial fans.

Tephra Deposits

Both ash and pumice beds occur in the piedmont facies of the Tesuque Formation. They have been found in several localities (Fig. 43). Miller (1963, p. 51) mentioned one locality north of the town of Truchas and suggested its source to be the Valle Grande (Valles) caldera in the Jemez Mountains. No other ash locations are reported in the literature. An additional seventeen pyroclastic deposits were located during the course of my field work (Appendix A). Most deposits could be traced for only short distances (1.5 metres or less) due to either limited exposures or lensing of the deposits themselves. For these reasons, as well as the lack of well developed bedding in the piedmont facies as a whole, the stratigraphic relationship of one deposit to the others could seldom be determined.

Detailed petrographic studies were done on four pumices which were stratigraphically well located, and had little alteration or detrital contamination (Appendix A). It was possible to date two of these pumices (Orilla-72027, 12.7±1.8 m.y., and Cueva-75T1, 10.8±1.6 m.y.) by the fission-track method (Appendix B). Of the pumices studied in detail, one is located near the town of Truchas (Cueva-75T1); the other three are exposed near the edges of the Oso surface just southeast of Mesa

de la Cejita (Orilla-72027, Sebastian-72030, and windmill-72035) (Figs. 44, 45, and 46). (See also Fig. 43 and Appendix A for locations.)

Two pumice deposits, Sebastian-72030 and Cueva-75T1, located on opposite sides of the northeast plateau, appear to be equivalent on the basis of the phenocryst suite and refractive indices of glass and hornblende phenocrysts. None of the pumices near Mesa de la Cejita correlate with each other and their stratigraphic relationships are indeterminate. However, they appear to be part of the same sequence of tephra and tuffaceous sands. This sequence was observed in isolated outcrops beneath the Oso surface from the Cañada de las Entrañas windmill southeastward for a distance of about 7 kilometres. Sections showing the characteristics of this sequence are given in Figure 47.

Chemical analyses (Appendix A) for six elements were run on the glasses of the piedmont facies tephra except for Cueva-75T1 which was too altered to yield reliable results. The chemical analyses show that Orilla-72027 and Sebastian-72030, with over 70 percent SiO_2, are rhyolites, whereas windmill-72035 (65 percent SiO_2) is a dacite.

None of the piedmont facies tephra examined in detail are equivalent to tephra from the Chamita, Ancha or Puye Formations, or the Bandelier Tuff or air-fall member of the Cerro Toledo Rhyolite (tables 1 and 2). Each of the eight tephra units fully described in this dissertation constitutes a new time-stratigraphic marker for sedimentary rocks in northern New Mexico.

Additional new markers, partially described, include the air-fall member of the Cerro Toledo Rhyolite (72B2), the tephra from the Chamita Formation (75C1, 75C2), the Entrañas surface ash (75E1), and the Divide surface pumice (72DS1). These tephra have been partially analyzed for the chemical composition of the glasses. None of them has been described previously in the literature.

Figure 44. Orilla pumice (72027) site. Deposit is 25 cm thick and is overlain by a partially cemented shard-rich sand. This pumice gave a fission-track age of 10.8±1.6 m.y. See Fig. 43 for location.

Figure 45. Sebastian pumice (72030) site. Deposit is 8 cm thick. It forms a cemented ledge below the rock hammer. This pumice appears correlative with the Cueva pumice (75T1) whose age is 12.7±1.8 m.y. See Fig. 43 for location.

Figure 46. Windmill pumice (72035) site. Deposit is 30 cm thick. It is cut by a channel of the Cejita Member. See Fig. 43 for location.

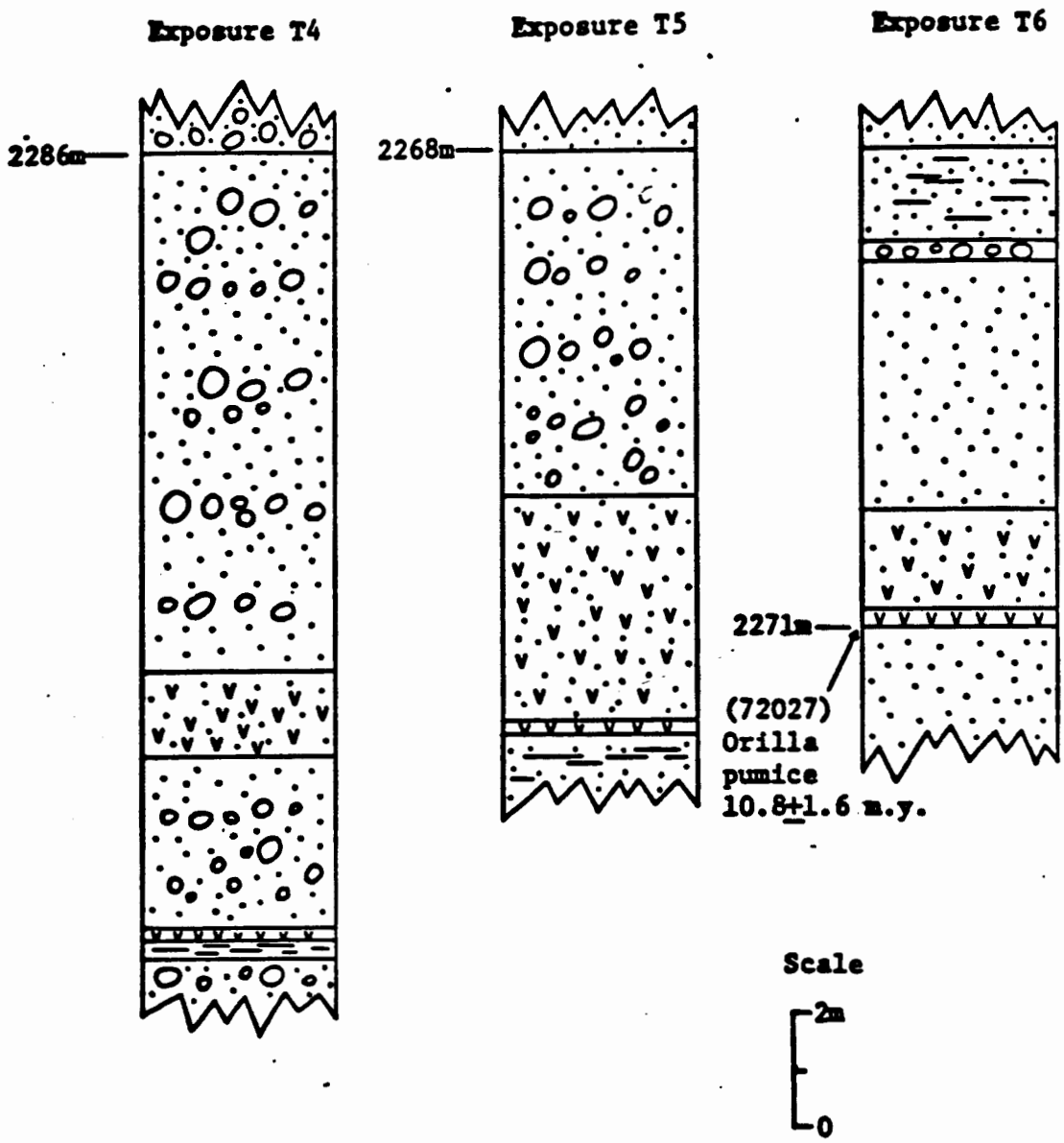


Figure 47. Representative sections of the tuffaceous portion of the piedmont facies, Tesuque Formation. See Fig. 43 for locations. See Fig. 7 for key to symbols.

Table 1. Phenocryst suites and refractive indices of glass fractions from tephra in the Española Basin. q=quartz, s=sanidine, p=plagioclase, m=magnetite, b=biotite, a=apatite, h=hornblende, c=clinopyroxene, o=orthopyroxene, z=zircon, ol=olivine (site locations given in Appendix A).

Sample	Phenocrysts	Refractive Index of Glass (Mode + Range)
Truchas Quarry		
(72T16)	q,s,m,a,c,o,z,ol	1.499 (1.497-1.500)
Cueva		
(75T1)	m,a,b,h,z	----
Orilla		
(72027)	p,m,a,h,z	1.501 (1.498-1.502)
Sebastian		
(72030)	p,m,b,a,h,z	1.498 (1.493-1.501)
Windmill		
(72035)	p,m,a,c,o,z	1.520 (1.517-1.523)
Puye Cliffs		
(72P2)	p,m,b,a,h,o,z	1.500 (1.499-1.501)
Santa Clara		
(72P3)	p,m,b,a,ol	1.509 (1.507-1.511)
Ancha Fm.		
(73A2)	p,m,a,h,c,z	1.518 (1.517-1.520)
Guaje*	q,s,m,c,o,z,ol	1.498 (1.497-1.499)
Tsankawi*	q,s,p,m,h,c,o,z,ol	1.498 (1.497-1.498)

*Data from Izett and others, 1972.

Table 2. Optical properties of selected phenocrysts from tephra in the Española Basin. (Site locations given in Appendix A.)

Sample	Hornblende	Clinopyroxene	Orthopyroxene
Truchas Quarry		x=1.730-1.736	
(72T16)		y=1.734-1.742	
		z=1.745-1.754	
Cueva	x=1.644-1.650		
(75T1)	y=1.663-1.666		
	z=1.666-1.672		
Orilla	x=1.642-1.648		
(72027)	y=1.658-1.666		
	z=1.667-1.670		
Sebastian	x=1.642-1.646		
(72030)	y=1.658-1.664		
	z=1.666-1.670		
Windmill pumice		x=1.683-1.687	x=1.680-1.684
(72035)		y=1.690-1.693	y=1.689-1.692
		z=1.712-1.713	z=1.692-1.697
Puye Cliffs	x=1.649-1.654		x=1.678-1.679
(72P2)	y=1.664-1.669		y=1.684-1.686
	z=1.672-1.678		z-1.689
Santa Clara	x=1.658-1.664		x-1.686-1.689
(72P3)	y=1.667-1.674		y=1.691-1.697
	z=1.682-1.684		z-1.696-1.700
Ancha Fm.	x=1.680-1.684	x-1.682-1.685	
(73A2)	y=1.691-1.695	y=1.686-1.690	
	z=1.694-1.696	z=1.712-1.715	
Guaje*		Nx=1.727-1.730	Nx=1.682-1.692
		Ny=1.733-1.736	Ny=1.692-1.697
		Nz=1.753	Nz=1.694-1.700
Tsankawi*	Nx=1.660-1.665	Nx=1.730-1.734	Nx=1.680-1.689
	Ny=1.674-1.676	Ny=1.733-1.736	Ny=1.688-1.696
	Nz=1.682-1.686	Nz=1.751-1.754	Nz=1.64-1.698

*Data from Izett and others, 1972.

Relationship and Age of the Cejita Member and the Piedmont Facies

The Cejita Member of the Tesuque Formation interfingers with, overlies, and is overlain by the piedmont facies of the Tesuque Formation. The interfingering relationship is best observed along the north side of Cañada de las Entrañas. Just west of the windmill, at 2152 metres altitude, a single bed of Cejita gravel separates nontuffaceous piedmont deposits below from overlying piedmont deposits containing some tuffaceous layers (Fig. 48). Here a southeastern swing of the river depositing the Cejita gravel laterally truncated the piedmont facies deposits including the windmill pumice layer (72035) (Fig. 46). Further east, within a zone of small faults, the section includes several Cejita gravel beds separated by sands and piedmont gravel beds (Figs. 49 and 50). The differences in clast composition, size and angularity allow for easy separation of these two facies.

The tephra and tuffaceous sand sequence of the piedmont facies overlies a portion of the Cejita gravel along the southeast end of Mesa de la Cejita. The Orilla pumice (72027) is part of this sequence although the Cejita gravel has pinched out at that location.

The age of the Tertiary rocks of the northeast plateau has not been previously known. Galusha and Blick (1971) assigned the uppermost sediments along the southern margin of the plateau

Figure 48. Single bed of Cejita Member gravel separating nontuffaceous piedmont deposits from overlying partly tuffaceous piedmont deposits of the Tesuque Formation. View is northwest from windmill pumice site.

Figure 49. Panorama of the north side of Canada de las Entranas. At this site the Cejita Member and the piedmont facies interfinger and are offset by three small faults.

Figure 50. Interfingering of the Cejita Member and piedmont facies of the Tesuque Formation. Close view of hillside shown in Fig. 49.

to the Pojoaque Member; therefore a late Barstovian (Valentinian) to Clarendonian age was implied. The western margin of the plateau was partially mapped as the Hemphillian Chamita Formation. Only one fossil locality is known from the Tertiary deposits of the northeast plateau. This is the Osbornoceros Quarry located above a channel deposit on an isolated upthrown fault block (Galusha and Blick, 1971, p. 76 and Fig. 38). As previously mentioned, a portion of these sedimentary rocks were given a Pleistocene age by Miller (1963).

Fission-track dating of zircons from tephra in the piedmont facies establishes a Miocene age. The Orilla pumice (72027), originally mapped as part of the Ancha Formation, has a radiometric age of 10.8±1.6 m.y. The Cueva pumice (75T1) mapped as Pojoaque Member by Galusha and Blick (1971), and as Ancha Formation by Miller (1963) yielded an age of 12.7±1.8 m.y. The Sebastian pumice (72030) appears to be correlative with the Cueva pumice.

In light of this radiometric dating and remapping, the piedmont facies and the Cejita Member are considered contemporaneous. The piedmont facies is a part of the Tesuque Formation as described by Galusha and Blick (1971). The Cejita Member is set aside as a separate member of the Tesuque Formation because of its great difference in sedimentary characteristics and origin.

Relationships With Other Tertiary Units

The Miocene age for the Cejita Member and piedmont facies make them a part of the Tesuque Formation. Their relationship to the members of the Tesuque Formation as mapped by Galusha and Blick (1971) is complicated. One problem arises from the present dearth of radiometric ages that establish the limits for the American land-mammal ages. Another, always present difficulty in paleontology, is the question of geographic synchroneity of faunal zone changes. The radiometric age for the Cueva pumice (75T1, 12.7±1.8 m.y.) proves that the sedimentary rocks near the top of the Tertiary section along the southern margin of the plateau are Miocene and should correlate with rocks containing late Barstovian or early Clarendonian fauna (Everden and others, 1964). The piedmont facies is, therefore, equivalent in age to the lower part of the Pojoaque Member of the Tesuque Formation (Fig. 3).

The relationship of the Cejita Member to the Ojo Caliente Sandstone is unclear. The Ojo Caliente Sandstone, where it underlies the Cejita Member in the Dixon sub-basin, must be older than the Orilla pumice (72027, 10.8±1.6 m.y.) age. This is inconsistent with the position given the Ojo Caliente Sandstone by Galusha and Blick (1971) who suggested that it is a late Clarendonian, post-Pojoaque Member deposit. It appears that either the sands mapped in the Dixon sub-basin as Ojo Caliente Sandstone are a similar, but older, unit, or the age and

stratigraphic relationships of the Ojo Caliente Sandstone are as yet imperfectly known. The first possibility is supported by the discovery of previously unrecognized deformation in the Dixon sub-basin. The outcrops of Cejita Member beneath Velarde Mesa and Black Mesa west of Velarde prove the Cejita Member is present in these areas and the unit cannot be Ojo Caliente Sandstone as originally mapped by Galusha and Blick (1971). (Sands north of Velarde along the Rio Grande and east of Black Mesa have not been studied and can therefore not be related to either the pre-Cejita sands or Ojo Caliente Sandstone.)

It is also possible that the stratigraphic relationships of the Ojo Caliente Sandstone and the Pojoaque Formation and Chamita Formation are misunderstood. The faulting beneath Black Mesa could be of sufficient magnitude to have downdropped the Chamita Formation against much older deposits on the west (Fig. 3). If such were the case, the Ojo Caliente Sandstone and volcanic-clast-rich Chama-el rito Member become possible correlatives with the pre-Cejita sands and volcanic-clast-rich sedimentary rock of the Dixon sub-basin (described below).

The pre-Cejita sands are exposed in several places along the western and northern margins of the map area (Fig. 58). These sands are generally disconformably overlain by Cejita gravels but may also be observed interfingering with the Cejita at the base of the section. Eolian crossbedding is common in the sands; they are light-brown, well-sorted and weakly indurated in places (Fig. 51).

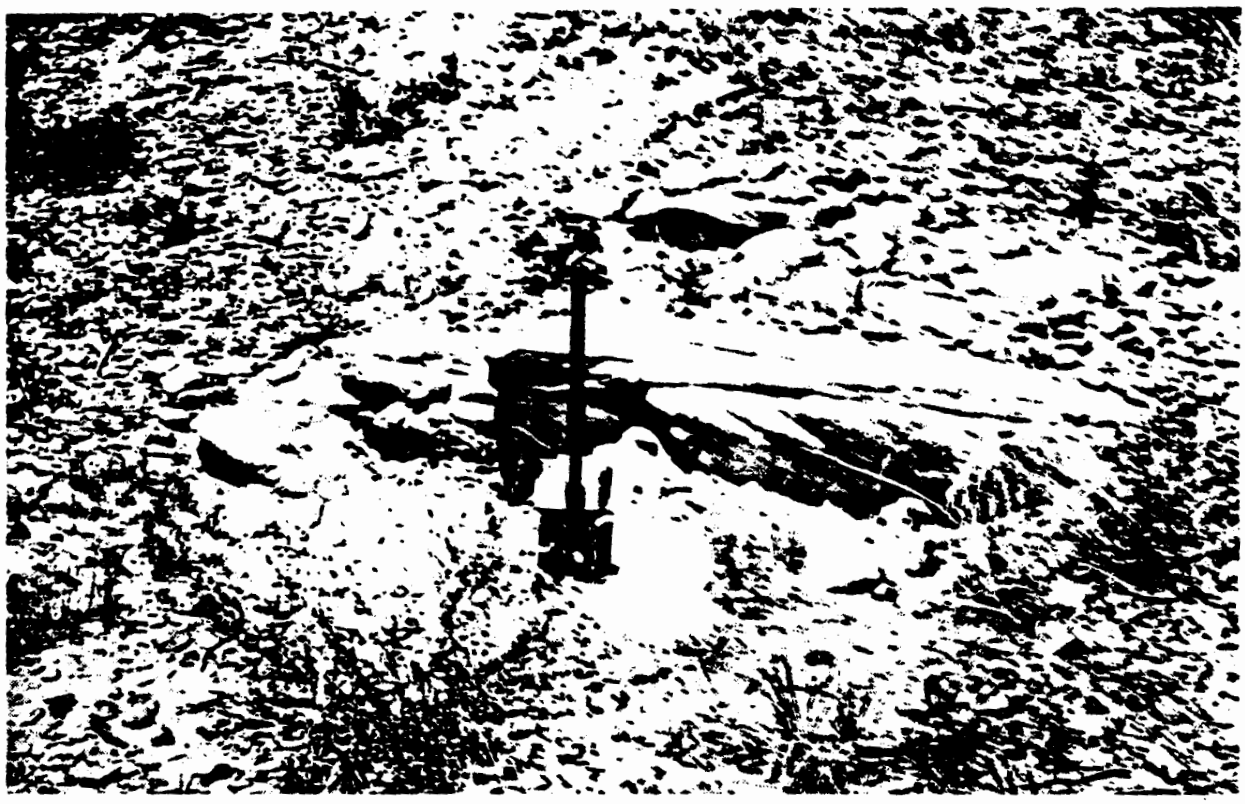


Figure 51. Eolian cross-bedding in sands underlying the Cejita Member. Site is 1.6 km east of the Velarde School.

The Cejita Member overlies volcanic-clast-rich sedimentary rocks in the Dixon sub-basin that are not a part of the pre-Cejita sands (Figs. 52 and 53). These rocks crop out east of the pre-Cejita sands and comprise the majority of rocks exposed in the Dixon sub-basin. They underlie the Cejita Member with erosional, and in places, angular unconformity. They consist of sands and pebble to cobble gravels that contain subrounded clasts, are very poorly sorted and are discontinuous. The composition is similar to the Cejita Member; it includes Paleozoic litholgies, quartzites and volcanic rocks. However, the volcanic rocks are more abundant than in the Cejita Member and are often altered. Numerous small faults have offset and tilted these sedimentary rocks in a variety of directions. The composition and amount of deformation serve to distinguish this older unit from the Cejita Member in most cases. Where distinction is difficult the contact has been taken to be the base of the lowest massive cliff of gravel with a Cejita Member composition. These older sedimentary rocks in the Dixon sub-basin have not been studied. They are mapped as Tesuque Formation by Miller and others (1963) but their age and relationship to early members of the Tesuque Formation is unknown. Their relationship to the Picuris Tuff is also poorly understood.

The Cejita Member is older than the Chamita Formation. A fault zone separates them and has allowed the displacement of the Chamita Formation to a lower elevation. Radiometric age determinations support a Pliocene age for the Chamita. Although

Figure 52. Older rock of the Santa Fe Group underlying the Cejita Member in the Dixon sub-basin. Photograph taken in Cañada de Lorenzo, Sec. 34, T23N, R 10 E.

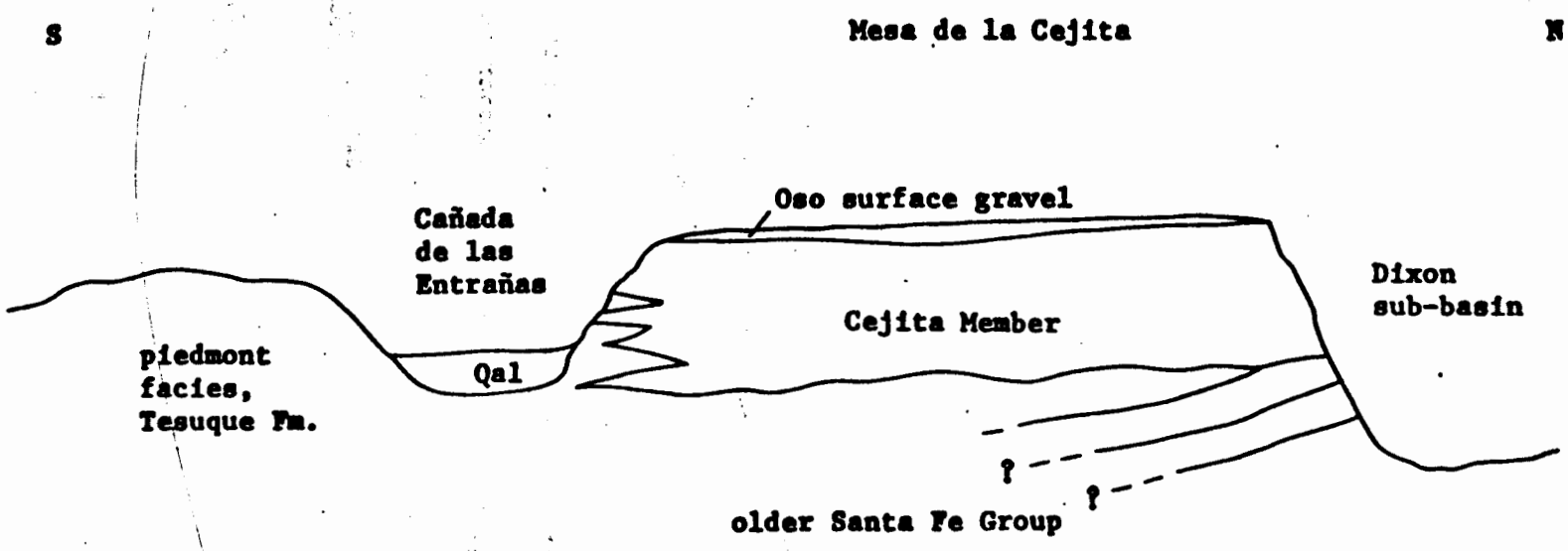


Figure 53. Diagram of the stratigraphy beneath Mesa de la Cejita.

the Cejita Member of the Tesuque Formation and the Chamita Formation are known to be distinct units in time and space, they have several similarities and may be related genetically. Both contain Paleozoic lithologies, Precambrian quartzites, and minor amounts of similar intermediate to silicic volcanic rocks. Both show a predominant westward transport direction. It is probable that the Chamita Formation represents the continued deposition by a drainage system whose source area was the Sangre de Cristo Mountains east of Velarde. Throughout Chamita time this drainage was interrupted, as evidenced by the shift to quartzite-rich gravels with few Paleozoic clasts, abundant sand and silt beds, and an increase in tuffaceous sediments.

The Chamita Formation may be the facies equivalent of the upper part of the Pojoaque Member west of the Rio Grande. On the northeast plateau, exposures show a narrow zone of interfingering between the Cejita floodplain, rich in Pennsylvanian rocks, and the quartzitic piedmont gravels. Had this zone been covered, the age equivalency of the Cejita Member and the piedmont facies would have been uncertain. The Chamita Formation appears to represent a similar floodplain deposit with an east-west trend. South of the Chamita Formation should be piedmont deposits that interfinger with it. Thus part of the upper Pojoaque may represent these piedmont deposits and be younger than previously realized. Unfortunately, the type area for the Chamita Formation is bounded on the south by the floodplains of the Rio Chama and Rio Grande.

The Cejita Member may correlate with sedimentary rocks exposed near the towns of Las Trampas, Ojito, Ojo Sarco and El Valle on the northeast plateau (Fig. 30), which are compositionally similar but have more angular clasts (table 10). Their angularity could be due to their closeness to the source area. Unfortunately these exposures are discontinuous and their relationships to each other are difficult to discern.

CHAPTER VI

STRUCTURE

There are numerous faults cutting the Santa Fe Group. Most of them are of limited lateral exposure (less than 3.2 kilometres) and are high-angle, normal faults with displacements of less than 91 metres (Galusha and Blick, 1971, p. 101). "The faults with east side down are more numerous, but those with west side down are usually larger" (Galusha and Blick, 1971, p. 101). The faults occur across the entire Española Basin; their strike is northward, subparallel to the strike of the Sante Fe Group. Dips in the Santa Fe Group are usually westward and less than 5°, except on rotated fault blocks where they are as much as 30°.

Several new faults were mapped in the Tertiary rocks of the northeast plateau. These faults are similar to those observed by Galusha and Blick (1971) in the central part of the basin. All of them have nearly vertical fault planes. One prominent fault extends along the western margin of the northeast plateau parallel to the Rio Grande floodplain; another probable fault parallels this one (Figs. 54, 55 and 58). These faults indicate a west-side down displacement of possibly 300 metres. A fault crossing (La Mesita) Velarde Mesa extends southward to an area of large slump blocks on the west side of the Rio Grande below Black Mesa. These three faults indicate that the course of the Rio Grande in this area, and the occurrence of numerous slump blocks, may be fault controlled. This zone of faulting is an extension of

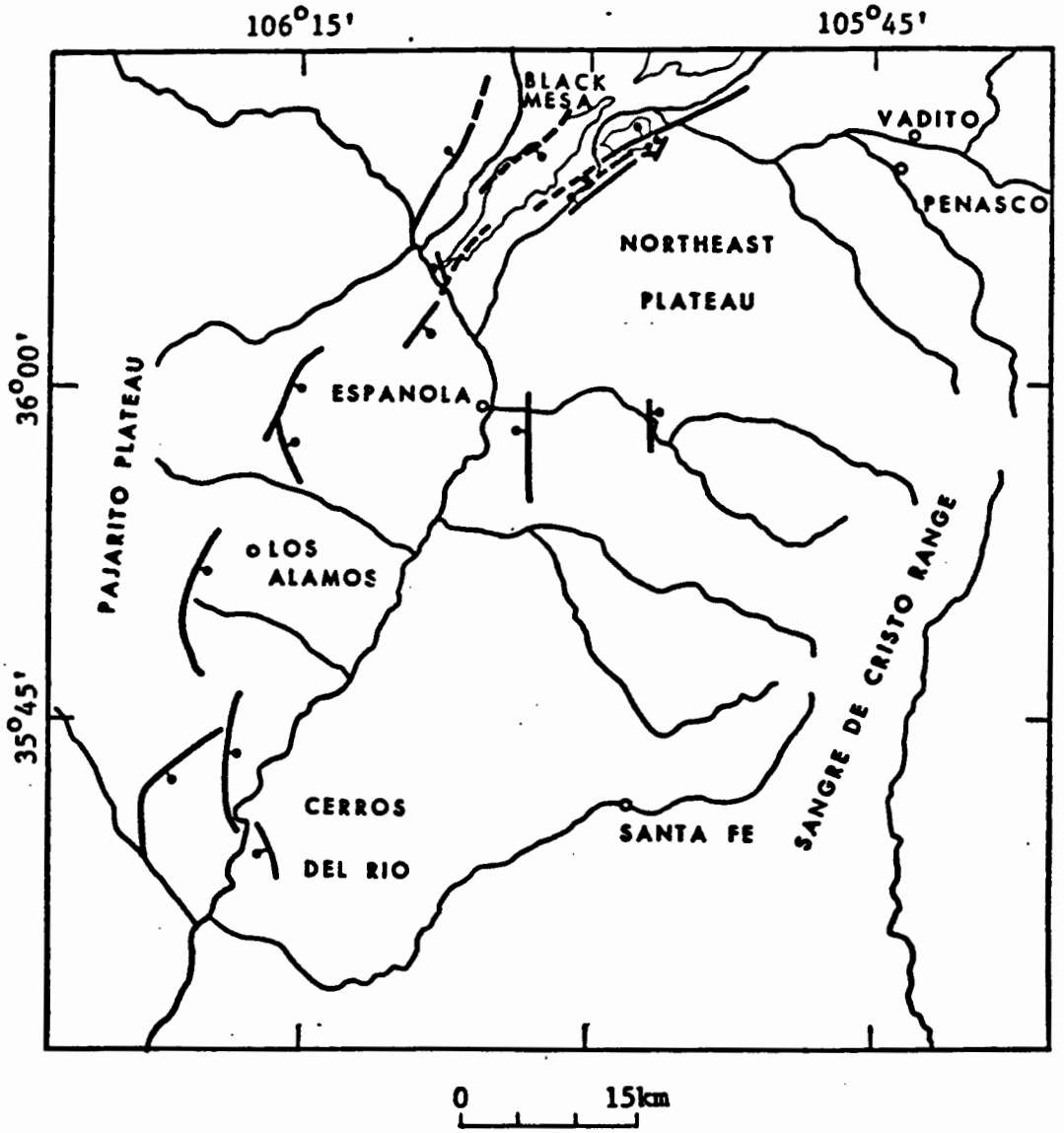


Figure 54. Prominant faults in Late Cenozoic rocks of the Española Basin.

Figure 55. The Velarde fault. This west-side down fault extends along the northwestern end of the northeast plateau and offsets the Cejita Member.

the faulting shown by Miller and others (1963) along the northwest side of the Picuris Range.

There appear to be two east-side down faults beneath Black Mesa. One offsets the basalt flow capping Black Mesa. This fault parallels the mesa along the northwest edge. Faulting is suspected rather than one flow draped over two levels because basal gravels are found in the colluvium along the offset. The second fault is beneath the southern end of the mesa, north of the Chamita Formation type area. This fault has not offset the Servilleta across the top of Black Mesa but slump blocks and a downwarped tongue of basalt appear to be the result of sliding along the fault plane. The Pliocene Chamita Formation has been considerably downwarped relative to the Miocene rocks of the northeast plateau, which implies activity along this fault in post-Chamita, pre-Servilleta time.

The faulting near Velarde (La Villita) and beneath Black Mesa serves to link the Picuris Range faulting with faulting shown by Galusha and Blick (1971) and Smith and others (1970) northwest of Española and southward across the Pajarito Plateau. This zone was active in late Pliocene to Pleistocene time.

Faulting across, and possibly along, the edge of the Pajarito Plateau has differentially lowered that area with respect to the eastern side of the basin, especially the northeast plateau (Fig. 56). The Rio Grande appears to be fault controlled in White Rock Canyon. Throughout the canyon a lack of stratigraphic correlation across the canyon is apparent.

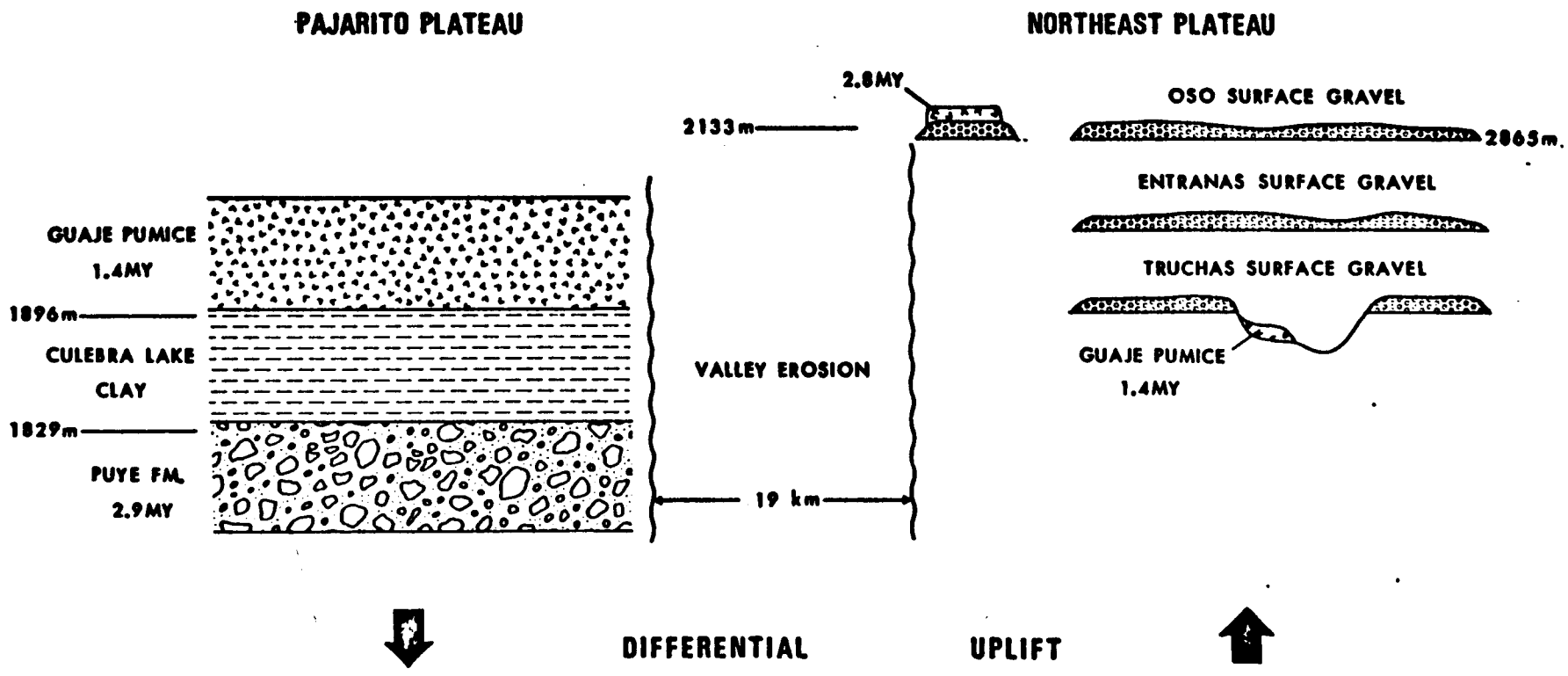


Figure 56. Relative positions of sedimentary and igneous rock units on east and west sides of the Española Basin. See Fig. 7 for key to symbols.

In few places is the Bandelier Tuff preserved on the east side of the river, yet deeply incised tributary canyons on the west are filled with ash-flow tuffs. Until detailed mapping has been done in White Rock Canyon, the amount and direction of faulting cannot be definitively stated.

The structural history of the eastern boundary of the Española Basin is not clear. Faults are recognized but their time of motion is difficult to establish. According to Sutherland (1972, p. 140) a right-lateral, strike-slip fault with 37 kilometres of displacement in Precambrian time is present along the western margin of the Sangre de Cristo Mountains. This fault formed the east margin of the Uncompahgre highland in late Paleozoic time. Perhaps the unusual north-south orientation of the Rio Chiquito valley supports the existence of a major mountain front fault in that area. Galusha and Blick (1971, p. 104) suggested that this border fault and those mapped north of Santa Fe by Cabot (1938) and Spiegel and Baldwin (1963) do not involve the Santa Fe Group and are pre-Santa Fe Group in age. Therefore, there may be no major late Tertiary eastern border fault for the Española Basin.

Few folds are present in the Santa Fe Group but small drag folds exist along faults. Galusha and Blick (1971) describe a broad syncline in the area of the type Chamita Formation. Steep dips of 40° to 50° southward, beneath the southeast edge of Black Mesa, may represent drag on a fault (Fig. 54). Near Velarde Mesa, at the western end of the Dixon sub-basin, are

the largest, tightest folds observed in the Española Basin. These folds occur in pre-Cejita Member rocks and are related to faulting.

The ages of deformation in the Española Basin are not well known. Deformation occurred during and after deposition of the Santa Fe Group and is continuing today. Only one radiometric date is available for the rocks of the basal Santa Fe Group. It is a lead-alpha date of 18 m.y. (Jaffe and others, 1959) on a dacitic ash in the Nambe Member. However, lead-alpha dates on rocks of Tertiary age are generally not reliable. The Hemingfordian fauna of the Nambe Member imply a maximum age of 21 m.y. (Turner, 1970). Formations of Pliocene and Pleistocene ages (the Servilleta, Puye, and Bandelier Tuff) have been faulted but less extensively than the pre-Pliocene rocks. Major periods of deformation appear to have been related to a pre-Cejita interval and a post-Chamita/pre-Servilleta interval. The latter interval would be a short one between approximately 4.5 and 3 m.y.

CHAPTER VII

THE LATE CENOZOIC HISTORY OF THE ESPAÑOLA BASIN

There are no radiometric ages for the earliest Tertiary sedimentary rocks in the Española Basin; however, rifting had probably begun by the early Miocene. Both north and south along the rift studies support this time of rifting: regional extension began about 29 m.y. ago in the Socorro-Magdalena area (Chapin and Seager, 1975); rifting was in progress by 26 m.y. in southern New Mexico (Seager and Clemons, 1975) and in southern Colorado (Lipman and Mehnert, 1975). Large fanglomerate deposits were spread from the highlands into the newly-formed basins. The Los Pinos Formation was built from the San Juan and Tusas (Brazos uplift) Mountains into the San Luis Valley (Butler, 1971). Potassium-argon ages on interbedded volcanic rocks of the Hinsdale Formation range between 26.8 m.y. and 15.0 m.y. (Lipman and Mehnert, 1975). Intrusions at Questa, near Taos, have been dated at 23.5 to 22.3 m.y. (Laughlin and others, 1969). The Picuris and Abiquiu Tuffs probably represent deposition related to this early Miocene period of volcanism. The configuration of the basin into which these tuffs were deposited is not known. If the postulated source areas in the southern San Juan Mountains and northern Sangre de Cristo Mountains is correct, the drainage directions were south and southwestward.

There followed a period of lessened volcanism but continued rifting and fanglomerate deposition. From the northeast plateau to Santa Fe, the Precambrian rocks of the Sangre de Cristo Mountains were being eroded and redeposited as the lower Tesuque Formation. North of the northeast plateau, in the Dixon sub-basin, volcanic detritus was still entering the Española Basin from the north, and Paleozoic detritus from north and east, was mixed with it.

The margins of the basin at this time are unknown. The eastern margin may have been further east; fine-grained sedimentary rocks near the present mountain front imply a source further east. The western margin may not have existed as such; deposition may have continued across the present Nacimiento uplift into the San Juan Basin. The lower Tesuque Formation could represent a broad piedmont slope open to the west.

Several changes occurred in the late Miocene: the Picuris Range was uplifted, the Cejita drainage was established, and volcanism began in the Jemez Mountains. The Picuris Range must have been uplifted before the deposition of the Cejita Member. By its uplift the southward movement of volcanic debris into the Española Basin was deflected westward. The volcanic-clast-rich lower Tesuque Formation was largely removed from the uplift by Cejita time and contributed few clasts to the Cejita Member.

The Cejita drainage had become established prior to 11 m.y. This drainage flowed westward from an area of Paleozoic and Precambrian rocks in the Sangre de Cristo Mountains into the

subsiding Española Basin or across the area into the San Juan Basin. Where the Cejita drainage went is an important question for the tectonic history of the Española Basin. There are no known playa deposits in the basin that would imply it was a topographic entity at that time. On the other hand, no Cejita-like gravels are known for the western margin of the basin. The answer may arise from future field work although most of the Miocene section on the west is not exposed because of downwarping, faulting, and burial beneath the volcanic rocks of the Jemez Mountains.

Volcanism began in the Jemez Mountains at about 12 m.y. ago (Smith and Bailey, 1968). Eruptions from this center began contributing air-fall material to the piedmont sedimentation along the east side of the basin. Tephra deposits in the Tesuque Formation increased. The west side of the basin was slowly covered with volcanic rocks and a topographic western margin for the basin was thereby enhanced, or possibly developed for the first time.

Deposition and volcanism continued in the Pliocene with some changes in pattern. By middle Pliocene more intense deformation and volcanism had begun. The major site of volcanism in the Jemez Mountains shifted northward. The Lobato basalt (7.4 m.y.) and the Tschicoma Formation (6.7 to 3.7 m.y.) were extruded during this period (Bailey and others, 1969).

The Pliocene depositional system in the basin slowly changed. The Chamita Formation gives evidence that the

Paleozoic-rock-bearing drainage from the Sangre de Cristo Mountains became smaller, was less well-defined as an axial stram, and was frequently interrupted by local volcanism. The possibly correlative piedmont deposits in the Pojoaque Formation contain Paleozoic clasts in some gravel beds. The Española Basin was now developing as a topographic basin and the previously westward flowing piedmont and axial stream system was progressively shifted and blocked by the accumulating volcanic rocks of Jemez Mountains. Some streams shifted southward; channels braided; and compentency dropped.

The lack of early Jemez Mountains volcanic rocks in the Chamita and upper Pojoaque Formations implies that either their presence is not yet recognized or the Jemez volcanic field was developing on a piedmont slope which extended toward the San Juan Basin. The latter possibility is supported by the westward transport directions in the Chamita Formation.

In late Pliocene the depositional system was completely interrupted. The Chamita Formation was being deposited from about 6 or 7 m.y. to 4 m.y. By 3 m.y. it was downfaulted near the present confluence of the Rio Chama and Rio Grande by movement along the Velarde and Black Mesa faults. The sedimentary rocks to the south, along the Rio Grande, were also downwarped. Most of the deformation of the Santa Fe Group near the center of the basin took place during this 4 to 3 m.y. interval.

A drainage system with a stream entering the basin from the north, the ancestral Rio Grande, was integrated after

deformation ceased and erosion resulted in a basin-wide unconformity. The drainage system for the basin had reestablished itself along the downwarp into the present north to south flowing system. The Totavi Lentil of the Puye Formation, the basal gravels of the Servilleta Formation on Black Mesa, and the Oso surface gravels represent deposits of the ancestral Rio Grande and its tributaries. The minimum age of the ancestral Rio Grande is now well established. Basalts overlying Rio Grande gravels include the Servilleta Formation flow on Black Mesa (2.8 m.y.) and a Cerros del Rio flow in Ancho Canyon (2.6 m.y.). The Puye Cliffs pumice (2.9 m.y.) also overlies ancestral Rio Grande gravels.

A period of increased volcanic activity followed the formation of the 3 m.y. old unconformity. Basaltic volcanism occurred at both ends of the basin: the Servilleta flows extended down from the north; and the Cerros del Rio field began in the south. Volcanic detritus, lahars and tephra built eastward from the Jemez Mountains to form the Puye Formation.

The volcanic activity in the Cerros del Rio field was causal or closely related to three other events.

1. Deformation accompanied extrusion: the 3 m.y. old surface was downwarped and downfaulted.
2. This lowered area permitted accumulation of piedmont deposits from the Sangre de Cristo Mountains to the east. The result was the Ancha Formation. Deposition of the Ancha

Formation ceased by 2 m.y., the age of the overlying Ancha Canyon basalt.

3. Periodic damming of the Rio Grande by basalt flows caused changes in the river course and, at least once, created a large lake (Culebra) that filled much of the Española Basin. A basalt flow that entered the lake yielded an age of 2.1 m.y. (Smith, R.L., written commun., 1974).

The combined deformation and volcanism controlled the depositional-erosional balance of the Rio Grande. Periods of equilibrium existed during which the unconformities within the Ancha Formation and the Entrañas and Truchas surfaces were created.

The early Pleistocene was not marked by major changes. Volcanism continued in the Cerros del Rio field and Jemez Mountains. The basin was quite probably still filled with the Culebra lake. White Rock Canyon was partially excavated following the draining of the Culebra lake.

Eruption of the Bandelier Tuff members and the Cerro Toledo Rhyolite occurred between 1.4 and 1.1 m.y. (Doell and others, 1968). A great volume of debris entered the Española Basin from the west but was rapidly eroded as White Rock Canyon was cut. The history of the basin since the eruption of the last of the Bandelier Tuff has been one of erosion. The basin was excavated to its present configuration with only a few standstills that allowed for the formation of minor surfaces (Santa Cruz surface)

and terrace deposits (Santa Barbara terraces). Faults on the Pajarito Plateau which offset the Bandelier Tuff give evidence that deformation continues.

CHAPTER VIII

REGIONAL RELATIONSHIPS

The late Cenozoic history of the Española Basin may be compared to the history of the rest of the Rio Grande rift. In many cases ages of individual units are not yet well known; in some cases individual units are not even recognized—the term Santa Fe Group has been used to describe the entire Tertiary and Quaternary section.

The Rio Grande presently heads in the San Juan Mountains of southwest Colorado. These mountains began to develop as a major volcanic field about 35 m.y. ago (Lipman and others, 1970). Establishment of the upper Rio Grande across the San Juan Mountains was related to volcano-tectonic collapse structures, especially east-trending synclines and grabens, associated with the Creede Caldera. After filling the caldera with the Oligocene Creede Formation (Stevens and Van Loenen, 1972), the Rio Grande overflowed to the San Luis Valley (Stevens, 1968). The San Luis Valley began to form structurally in the Miocene (Lipman and Mehnert, 1969). There is no evidence that the Rio Grande left the San Luis Valley until the late Pliocene. For a time the Rio Grande may have either terminated in the San Luis Valley or continued eastward beyond the Sangre de Cristo Mountains by a route as yet unrecognized. Lipman and Mehnert (1969) suggested that the eastern margin of the San Luis Valley

dropped relative to the west about 5 m.y. ago. Accelerated uplift of the northern Sangre de Cristo Mountains occurred in the Pliocene after about 7 m.y. (Scott, 1975). This period of deformation may be correlative with the post-Chamita Formation deformation in the Española Basin which occurred between about 5 m.y. and 3 m.y. ago. Following this downdropping of the San Luis Valley, the Rio Grande shifted to a southward course and entered the Española Basin.

When did the Rio Grande reach the Albuquerque area and southern New Mexico? The basins to the south, the Santo Domingo and Albuquerque-Belen basins, were being formed by late Miocene (Wright, 1946). Rio Grande stream gravels are present in the Upper Buff (Bryan and McCann, 1937), also known as the Peña Blanca Member, of the Tesuque Formation (Wright, 1946; Hoge, 1970). These deposits are considered late Pliocene or early Pleistocene in age. Therefore the Rio Grande was integrated at least to Albuquerque by early Pleistocene. The 3 m.y. old erosion surface that developed in the Española Basin probably extended into the Albuquerque area or occurred there contemporaneously. The Ortiz surface and the surfaces beneath the basalt flows on Santa Ana and Chivato Mesas may represent parts of this same surface. The Santa Ana Mesa flow has a K-Ar age of 2.5±0.3 m.y.; the Chivato flow is 2.8±0.15 m.y.; and a Cerros del Rio flow that possibly overlies the Ortiz surface is 2.8±0.12 (Bachman, G.O., and Mehnert, H.H., written commun., 1975).

In the Socorro area, the lower unit of the Santa Fe Group, the Popotosa Formation (Denny, 1940b) is highly deformed by normal faulting. In several areas the Popotosa Formation is exposed on intrarift horsts (Chapin, 1971). The formation contains fanglomerate and playa deposits, and interbedded volcanic rocks. Andesites near the base of the formation have ages of 24 m.y. (Chapin, 1971) and 26 m.y. (Machette, M.N., oral commun., 1976). In the upper part of the Popotosa Formation volcanic rocks have ages of 10.7 m.y. (Weber, 1971). The playa deposits imply an arid climate in an area of internal drainage. The ages for the Popotosa Formation establish it as correlative of the Tesuque Formation, and in part, of the Cejita Member. There is no evidence that a major south-flowing river existed in the Socorro area at this time.

Prior to integration, individual basins in the southern part of the state had internal drainage and were filled with lakes (Strain, 1971). The Rio Grande came into existence as these lakes overflowed from one to another and rock barriers were eroded. The Rio Grande connected a series of basins following the rift zone into northern Mexico (Kottlowski, 1953). These basins included the Mesilla Bolson, Bolson de los Muertos and the Hueco Bolson. In the lower parts of these basins a large lake formed, Lake Cabeza de Vaca. This lake served as an end point for the Rio Grande drainage until middle Pleistocene time (Strain, 1966, 1971) when the river became integrated with the

lower Rio Grande-Conchos System draining to the Gulf of Mexico (Hawley and Kottlowski, 1969; Strain, 1971; Hawley, 1975).

In summary, the integration of basins along the Rio Grande rift from the Española Basin to the southern border of New Mexico occurred rapidly between about 4 and 3 m.y. ago. At the end of this interval deposition of axial river deposits began. Then, following integration to the Gulf of Mexico, in middle Pleistocene time, the Rio Grande entrenched into its earlier deposits.

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Appendix A

Tephra of the Española Basin

1. Sample Locations and Descriptions
2. Chemistry and Petrology of Selected Tephra
   a. Refractive indices of pyroxene and amphibole phenocrysts
   b. Chemical analyses of glasses

Table 3. Location of tephra s/ from the Española Basin

ormation	Sample # and Name	Location Quad: Lat. & Long.	Maximum Thickness	Clast Size*	Comments
esuque(?)	72SB1-3 Santa Barbara	El Valle: 36°06'34" N 105°39'16" W	1m	Ash	Reworked; highly altered. Two ashes with gravel between.
esuque	75T1 Cueva	Chimayo: 36°2'21" N 105°53'17" W	45.7cm	Pumice	Highly altered.
hamita	72035 Windmill	Velarde: 36°08'17" N 105°53'06" W	30.5cm	Pumice 3.8cm	Reworked; abundant lithic fragments (av. size .64cm).
hamita	72030 Sebastian	Truchas: 36°07'03" N 105°51'01" W	7.6cm	Pumice .64cm	Contains lithic fragments (<64cm); highly altered.
hamita	72027 Orilla	Truchas: 36°07'18" N 105°50'08" W	25.4cm	Pumice .64cm	Overlain by shard layer which grades upward into ash-rich sand.
hamita	75C1 Upper Tuffaceous	San Juan Pueblo: 36°5'57" N 106°4'50" W	12.7cm	Pumice .64cm	Upper Tuffaceous Zone (Galusha and Blick, 1971).
hamita	75C2 Lower Tuffaceous	San Juan Pueblo: 36°4'20" N 106°5'08" W	45.7cm	Pumice	Lower Tuffaceous Zone (Galusha and Blick, 1971)
—	72T6 Miller	Truchas: 06°3'05" N 105°48'02" W	2.9m	Ash	Reworked; altered. Mentioned by Miller (1963).
—	72E2-6 Entrañas	Truchas: 36°3'13-18" N 105°48'07-17" W	45.7cm	Ash	Highly altered and contaminated. Three exposures of a single layer.
'uye	72P2 Puye Cliffs	Puye: 35°57'36" N 106°9'02" W	~ 1.2m	Pumice 7.6cm	Pumice clasts occurring as a lahar.
'uye	72P3 Santa Clara	Puye: 35°58'52" N 106°10'52" W	25.4cm	Pumice 1.9cm	
ncha	73A2 Ancha	Horcado Ranch: 35°45'10" N 106°06'26" W	2.1m	Pumice .33cm	Located in the Ancha Formation type section.
—	75E1 Ojito	Velarde: 36°07'34" N 105°56'51" W	20.3cm	Ash	Related to Entrañas surface gravels.
Bandelier	72T16 Truchas	Truchas: 36°2'26" N 105°49'32" W	>1.8m	Pumice .8cm	Overlain by 1m ash layer.
Toledo Rhyolite	72B2 Toledo	White Rock: 35°52'29" N 106°14'45" W	30.4cm	Pumice 5.1cm	Second of four airfall units.
—	72DS1 Divide Surface	Aqua Fria: 35°40'37" N 106°04'30" W	>76.2cm	Pumice 1.27cm	Overlying the Divide Surface of Spiegel and Baldwin (1963).

* Ash = <2 mm Pumice = vesicular lapilli; >2 mm <64 mm (Fisher, 1961)

Appendix A2a: Refractive indices of pyroxene and amphibole phenocrysts

Procedure:

The hornblende, clinopyroxene and orthopyroxenes from eight stratigraphically important tephra layers have been studied. These tephra were chosen on the basis of their 1) significance to establishing the geologic history of the Española Basin, and 2) relatively unaltered and uncontaminated condition. Several of these tephra layers represent major eruptions. With future discovery and study of other tephra layers in New Mexico and the Great Plains, further correlations should be possible. The tephra are thus important as time-stratigraphic markers (Izett and others, 1972).

Tephra layers were sampled in the field and notations made of maximum unit thickness, maximum clast size observed if in the pumice range, and apparent degree of alteration and contamination by addition of detrital material during reworking. Laboratory preparation included careful hand crushing of each sample to free phenocrysts from the glass, sieving to <100 mesh, elutriation of fine (<230 mesh) fraction, and separation of this size fraction into three specific gravity separates using bromoform and bromoform/acetone mixes. The specific gravity separates were <2.42 (glass fraction), >2.42 and <2.85 (quartz and feldspar fraction), and >2.85 (heavy mineral fraction). The former two fractions were used to obtain the data given in table 1.

Phenocrysts were chosen for this study from the heavy mineral fraction. Only phenocrysts with adhering glass were used in order to avoid possible contaminants. Where possible a minimum of five phenocrysts of each mineral were analyzed. The refractive indices and optic sign were determined using a spindle stage and the focal masking technique (Wilcox, 1959 and 1975). Results are given in the following pages and are summarized on Table 2. In the Truchas sample a few orthopyroxenes are present but it was not possible to get reliable indices. Refractive index determinations may vary for each mineral because of chemical and crystallographic variations, difficulties encountered during measurement (extensive glass mantling and twinning), alteration, or imprecision between available refractive index oils in the higher range.

Table 4. Refractive indices of pyroxene and amphibole phenocrysts.

Sample # and name	Mineral		Refractive Index nx	ny	nz
72035	Clinopyroxene				
Windmill	grain:	#1	1.683	1.690	1.712
		#2	1.683	1.691	1.712
		#3	1.685	1.692	1.713
		#4	1.687	1.693	1.713
	Orthopyroxene		Sign = positive		
	grain:	#1	1.682	1.692	1.696
		#2	1.680	1.690	1.692
		#3	1.683	1.692	1.695
		#4	1.682	1.689	1.693
		#5	1.684	1.692	1.697
72030	Hornblende				
Sebastian	grain:	#1	1.643	1.660	1.668
		#2	1.646	1.664	1.666
		#3	1.642	1.660	1.667
		#4	1.643	1.663	1.668
		#5	1.644	1.660	1.670
		#6	1.644	1.658	1.668

Table 4. Continued

Sample # and name	Mineral		Refractive Index nx	ny	nz
72027	Hornblende				
Orilla	grain:	#1	1.646	1.667	1.669
		#2	1.648	1.666	1.670
		#3	1.639	1.661	1.663
		#4	1.645	1.658	1.667
		#5	1.642	1.660	1.670
		#6	1.645	1.660	1.669
75T1	Hornblende				
Cueva	grain:	#1	1.644	1.664	1.666
		#2	1.650	1.663	1.670
		#3	1.647	1.665	1.672
		#4	1.648	1.666	1.667
		#5			
72P2	Hornblende				
Puye Cliffs	grain:	#1	1.654	1.668	1.678
		#2	1.652	1.666	1.674
		#3	1.650	1.664	1.673
		#4	1.650	1.669	1.676
		#5	1.649	1.667	1.672
	Orthopyroxene		Sign = negative		
	grain:	#1	1.679	1.686	1.689
		#2	1.678	1.684	1.689

Table 4. Continued

Sample # and name	Mineral		Refractive Index nx	ny	nz
72P3	Hornblende				
Santa Clara	grain:	#1	1.661	1.667	1.683
		#2	1.658	1.674	1.682
		#3	1.664	—	1.682
		#4	1.662	—	1.684
		#5			
	Orthopyroxene				
	grain:	#1	1.686	1.691	1.696
		#2	1.687	1.697	1.700
		#3	1.688	1.694	1.698
		#4	1.689	1.696	1.699
		#5	1.688	1.696	1.700
73A2	Hornblende				
Ancha	grain:	#1	1.684	1.693	1.696
		#2	1.684	1.691	1.694
		#3	1.683	1.693	1.694
		#4	1.680	1.693	1.694
		#5	1.683	1.695	1.696
	Clinopyroxene				
	grain:	#1	1.683	1.686	1.715
		#2	1.684	1.690	1.712
		#3	1.684	1.689	1.712

Table 4. Continued

Sample # and name	Mineral		Refractive Index nx	ny	nz
73A2	Clinopyroxene (continued)				
	grain:	#4	1.682	1.688	1.712
		#5	1.685	1.690	1.713
72T16	Clinopyroxene				
Truchas	grain:	#1	1.734	1.742	1.748
		#2	1.736	1.739	1.745
		#3	1.730	1.738	1.754
		#4	1.733	1.733	1.753
		#5	1.732	1.733	1.752
	Orthopyroxene		Sign = negative		
	grain:	#1	1.683	1.689	1.695
		#2	1.686	1.669	1.709
		#3	1.688	1.707	1.704
		#4	1.688	—	1.696
		#5	1.688	1.694	1.698

Appendix A2b: Chemical analyses of glasses

Using an Applied Research Laboratories microprobe at the Denver Laboratories of the U.S. Geological Survey, I have made partial chemical analyses of twelve glasses from tephra of the Española Basin. Runs were made for Si, Al, Ca, Fe, Mn and Mg on all samples. Runs for Na and K were done only on young tephra (<3 m.y.) with the exception of the Puye Formation samples. In these, the presence of numerous microlites prevented use of the wide beam necessary for counting Na and K. Older tephra were not analyzed for Na and K due to the high mobility of these cations and my belief that measurement of present concentrations would be unrepresentative of original composition.

For all runs, except for Na and K, the output voltage was 15 KV, emission current 200 microamps and beam width <3μ. Beam width was increased to 6μ for Na and K to reduce volatilization and counting time was increased several seconds. The instrument was set for fixed counts, therefore the count time varied: approximately 10.5 seconds for the major elements; 13.5 seconds for Na and K.

For each sample three counts were taken on each of at least ten separate shards. Counts were totaled and means and standard deviations computed for each sample as a whole. Some obviously spurious counts were eliminated so that not all means represent the same total number of points. Totals range from 26 to 31 separate points per sample.

Percentages were calculated by comparison of sample counts to counts run for standards. When possible, standards were counted at both the beginning and end of each run to check for severe drift of the instrument. Where front and end counts were made, values for the standards were calculated from the average.

The standards used were quartz (OLPX #1) and two rhyolitic glasses (OLPX #2-GSC and OLPX #4-GSE). Quartz standard counts provided background (except for Si) which was then subtracted from all sample counts. Counts per weight percent for Si were determined by averaging the three standards. Counts per weight percent for other elements were then calculated for both standard glasses and averaged for comparison with sample counts. In the case of Mn, standards varied from .03% for GSC to .08% for GSE so instead of averaging these standards, samples were compared to that standard having the most similar concentration.

All computations were done using a Hewlett-Packard 55 calculator.

Sample 75T1 was prepared for analysis but was too altered to yield reliable data.

Table 5. Partial chemical analyses of glasses

Sample #	SiO_2	Al_2O_3	FeO**	MgO	CaO	MnO	Na_2O	K_2O
OLPX #1*	100.0							
OLPX #2-GSC*	62.04	14.20	6.34	3.89	5.00	.03	4.06	3.60
OLPX #4-GSE*	61.14	14.78	5.84	3.64	5.28	.08	4.67	3.06
72035	65.41	16.18	2.41	.81	2.51	.05		
72030	75.56	12.54	.55	.12	.63	.04		
72027	73.51	13.83	.80	.24	1.10	.03		
75C2	67.70	16.32	1.79	.55	1.88	.04		
75C1	76.85	14.13	.54	.05	.35	.05		
72P2	74.24	12.75	.72	.14	.61	.03		
72P3	72.13	14.85	1.19	.23	1.36	.04		
73A2	65.53	16.59	2.31	.76	2.35	.05	3.88	3.00
72T16	75.02	13.20	1.18	.005	.25	.06	4.22	3.90
72B2	73.69	14.01	.85	.04	.33	.04	3.48	4.61
75E1	78.70	13.45	1.27	.04	.52	.04	3.48	4.58
72DS1	76.53	13.48	1.21	.007	.25	.07	4.41	3.98

* Standards in use at the Denver U.S. Geological Survey.

** Total Fe calculated as FeO.

Appendix B

Fission track dating of selected tephra from the Española Basin

1. Orilla pumice (72027)
2. Chamita Formation lower tuffaceous zone (75C2)
3. Chamita Formation upper tuffaceous zone (75C1)
4. Puye Formation Puye Cliffs pumice (72P2)
5. Ancha Formation pumice (73A2)
6. Cueva pumice (75T1)

Procedure:

Zircons were separated from six tephra samples by crushing, sieving to <60 mesh, and elutriating the fine fraction, to reduce the sample size and concentrate the zircons. Further concentration was achieved by repeated use of a Franz magnetic separator, bromoform and methylene iodide.

Zircon concentrates were then mounted in epoxy, polished, etched to enlarge the fission tracks, remounted in lexan and irradiated. This procedure follows that of Charles Naeser (written commun., 1974). Etchant used was a 250°C mixture of 11.2 g KOH and 8 g NaOH. Times for etching varied with the sample from 1.5 hours to 3.25 hours.

Before irradiation, cleavage flakes of muscovite were taped over each sample. These serve as detectors. After irradiation fission tracks were counted in both zircons (Ps) and muscovite (½Pi) image to provide control for the uranium concentration in

each mineral. The muscovite tracks were etched in 48% HF before counting.

The age calculation was made using the following formula:

$$T = \ln \left[1 + 9.45 \times 10^{-18} Ps/Pi\phi\right] 6.49 \times 10^{9}$$

where: Ps = density of fossil tracks

Pi = density of induced tracks

ϕ = reactor flux

Standard deviations were calculated on the basis:

$$6 = \sqrt{\left(1/\sqrt{f}\right)^2 + \left(1/\sqrt{i}\right)^2}$$

where: f = number of fossil tracks

i = number of induced tracks

For the calculation of ϕ, glass standards, from the U.S. National Bureau of Standards, were irradiated with the unknowns.

For each sample dated, a minimum of six grains were counted. Ages, with one standard deviation, were calculated for these grains individually. For each sample age a weighted average was figured using all grain counts together and a 95% confidence level. Calculations were made using a Computer Design Corporation 320G calculator.

Any grain ages not falling within one standard deviation of any other grain ages for that sample were considered contaminants and eliminated from the calculations. This was necessary for two zircons from 75C1 and one from 72P2.

Table 6. Fission-track data

Sample	Grain and age		Weighted age
72027	#1	12.1±2.0	Ps=207/95=2.18
Orilla	#2	11.3±2.0	Pi=1356/95=14.27
	#3	8.0±1.8	Ps/Pi=.153
	#4	10.8±2.0	T=10.8±1.6 m.y.
	#5	10.9±2.0	
	#6	10.9±2.0	
75T1	#1	9.4±1.9	Ps=234/95=2.46
Cueva	#2	14.0±2.9	Pi=1260/95=13.26
	#3	11.4±1.8	Ps/Pi=.19
	#4	12.0±2.2	T=12.7±1.8 m.y.
	#5	10.7±1.9	
	#6	16.7±2.5	
75C2	#1	6.5±1.7	Ps=144/153=.941
Lower Chamita	#2	4.2±.9	Pi=944/153=6.17
	#3	7.8±1.5	Ps/Pi=.153
	#4	3.9±.8	T=5.2±1.0 m.y.
	#5	4.2±1.5	
	#6	5.4±1.4	
75C1	#1	6.5±1.8	Ps=182/132=1.38
Upper Chamita	#2	4.8±.9	Pi=1114/132=8.44
	#3	4.7±.7	Ps/Pi=.16
	#4	8.0±1.6	T=5.6±.9 m.y.
	#5	5.0±1.3	
	#6	7.2±1.7	
72P2	#1	3.3±.5	Ps=144/156=.923
Puye Cliffs	#2	2.5±.5	Pi=1680/156=10.77
	#3	2.8±.6	Ps/Pi=.086
	#4	3.1±.8	T=2.9±.5 m.y.
	#5	3.0±.8	

Table 6. Continued

Sample	Grain and age		Weighted age
73A2	#1	2.6±.4	Ps=131/153=.86
Ancha	#2	3.7±.7	Pi=2782/153=18.18
	#3	2.1±.8	Ps/Pi=.047
	#4	2.8±.7	T=2.7±.4 m.y.
	#5	2.2±.5	
	#6	2.0±.6	

Appendix C

Petrographic description and K-Ar dating of four basalts from the Española Basin

1. Black Mesa Basalt
2. Vadito Basalt
3. Ancho Canyon Basalt
4. Ancha Canyon Basalt

The four basalts were described and dated by F M Consultants, Herne Bay, Kent, England (Manley, 1976b). The petrographic information reported here is taken from their reports. Financial support was received from NSF Grant GA 39850. One sample was redated by Harald Mehnert of the U.S. Geological Survey, Denver. Error margins are reported for two sigma.

Analytical Data

F M Consultants	$\lambda\ \varepsilon = 0.584 \times 10^{-10}/yr$
	$\lambda\ \beta = 4.72 \times 10^{-10}/yr$
H. H. Mehnert	$\lambda\ \varepsilon = 0.585 \times 10^{-10}/yr$
	$\lambda\ \beta = 4.72 \times 10^{-10}/yr$

Black Mesa basalt

The basalt capping Black Mesa, at the northern end of the Española Basin, is the southernmost extension of the Servilleta Formation, whose flows have been dated near Taos as ranging between 3.6 and 4.5 m.y. (Ozima and others, 1967). This sample is a fresh microvesicular olivine-tholeiite with essential olivine, pyroxene, plagioclase and opaque oxides. Rare patches of an iron-rich glassy mesostasis occupy the interstices between feldspar laths. The only sign of alteration is incipient oxidation of opaque oxides and incipient replacement of olivine by iddingsite.

Conventional whole rock age determinations were run in triplicate:

Sample 72S6

Location: 36°08'50" N. 106°01'50" W.
T. 22 N., R. 9 E., unsurveyed
Lyden Quad., Rio Arriba Co.

K_2O%	$*Ar^{40}/\Sigma Ar^{40}$	Apparent age
.42	2.50	2.96±2.96
.42	6.90	2.74±0.44
.42	7.00	2.81±0.44

Preferred average = 2.78±0.44 m.y.

Run 1 revealed that the rock was very young: the experiment was halted and considerably larger volumes of sample were loaded for

runs 2 and 3, which enabled more precise determinations to be made. Thus, the average of runs 2 and 3 is preferred.

Vadito basalt

An isolated flow northeast of the town of Vadito on the northeast plateau was mapped by Miller and others (1963) as part of the Servilleta Formation. However, the age and petrology of this flow are sufficiently different from the Servilleta flows (Lipman, 1969) that it may be better considered related to the feldspathoidal basalts of Pliocene to Holocene age on the High Plains (Lipman and Mehnert, 1975). This sample is a fresh, fine-grained and sparsely vesicular microporphyritic basanite. The microphenocrysts are of marginally iddingsitized olivine, corroded feldspar and euhedral pyroxene. They are set in a fine-grained matrix of olivine, pyroxene, plagioclase, opaque oxides, alkali feldspar and analcite.

Conventional whole rock age determinations were run in triplicate:

Sample 72S9

Location: 36°11'14" N. 105°37'02" W.
NE 1/4 Sec. 36, T. 23 N., R. 12 E.
Tres Ritos Quad., Taos Co.

K_2O%	$*Ar^{40}/\Sigma Ar^{40}$	Apparent age
2.03	14.1	4.86±1.00
2.03	13.9	4.83±0.96
2.03	43.2	5.64±0.56

Average = 5.11±0.84 m.y.

Run 3 was made on an extremely large sample volume, thus reducing the atmospheric contamination error.

Ancho Canyon basalt

This basalt from the Cerros del Rio field in White Rock Canyon directly overlies the Totavi Lentil of the Puye Formation. The sample is a relatively fresh alkali-olivine-basalt. Small euhedral microphenocrysts of olivine (occasional pyroxene and plagioclase) are carried in a flow-aligned plexus of plagioclase laths, pyroxene and opaque oxide grains. Olivine is sometimes fresh, otherwise partially or totally pseudomorphed by secondary alteration products. Calcite, analcite, serpentine, chlorite, zeolites and clay minerals are present as secondaries. Calcite and zeolites fill the rare amygdules.

Sample 74-11-12-1

Location: 35°46'36" N. 106°13'30" W.
T. 18 N., R. 7 E., unsurveyed
White Rock Quad., Sandoval Co.

K_2O%	$*Ar^{40}/\Sigma Ar^{40}$	Apparent age
1.29	13.3	2.6±0.40 m.y.

Minor alteration of this sample could indicate that it was subject to an argon loss discrepancy when first dated by F M Consultants. The sample was redated by Harald Mehnert at the U.S. Geological Survey and that age determination is reported here. The date determined by F M Consultants--1.17±0.18 m.y.--is inconsistent

with field relationships and recent zircon fission-track dating of a pumice layer in the Puye Formation (Manley, 1976a).

Ancha Canyon basalt

The Cerros del Rio flow along the southwest side of Cañada Ancha caps the Ancha Formation. This rock is a very fine-grained, slightly vesicular, microporphyritic alkaline intermediate lava showing a marked flow-alignment of feldspar laths in the matrix. The microphenocrysts present include ortho- and clinopyroxene and plagioclase feldspar. A small amount of xenocrystic and xenolithic material is also present. The trachytic-textured matrix is rich in minute feldspar laths of intermediate composition, opaque oxides and pyroxene grains. The potassium-content and petrographic characteristics of this lava suggest that it is an alkaline intermediate differentiate from alkali-olivine-basalt magma, possibly a latite or latibasalt. Very minor amounts of secondary carbonate are present in the matrix. The rock is virtually unaltered and thus argon loss discrepancy is unlikely.

Conventional whole rock age determinations were run in duplicate.

Sample 75-5-19-3

Location: 35°46'17" N. 106°07'02" W.

T. 18 N., R. 8 E., unsurveyed

Horcado Ranch Quad., Santa Fe Co.

K_2O%	$*Ar^{40}/\Sigma Ar^{40}$	Apparent age
3.20	18.64	1.96±0.06
3.20	19.14	1.50±0.04

Preferred age = 1.96±0.06 m.y.

The second analysis was made using severe pre-heating which induced a loss of radiogenic argon. The age determined is therefore a minimum age.

Appendix D

Sedimentary descriptions

1. Size analysis of the piedmont facies of the Tesuque Formation
2. Clast counts from gravel beds in the Española Basin
   a. Chamita Formation
   b. Puye Formation
   c. Servilleta Formation
   d. Surface gravels
   e. Embudo terrace gravels
   f. Cejita Member and possible Cejita Member
   g. Piedmont facies of the Tesuque Formation

1. Size analysis of the piedmont facies of the Tesuque Formation.

Procedure:

Three sections of the piedmont facies were measured and grain size analyses were made at 1.5 metre (5-foot) intervals. The sediments at these intervals were sieved with the use of square sieves 38 cm on a side. These sieves were constructed of wood frames and wire mesh, or, in the case of the largest, inset wire rods. Three sizes were used: for cobbles (64 mm), pebbles (4 mm), and granules (2 mm). Sand, silt and clay fractions were accumulated together in a pan and weighed as the sand fraction. Each fraction was weighed at the site with a spring scale. Weight percents were calculated

on the basis of weight per size fraction per total weight of sample at that interval, excluding cobbles. Cobbles were noted but not weighed.

2. Clast counts from gravel beds in the Española Basin.

Procedure:

Clast counts were made on several gravel units in the Española Basin. Each count was made on medium pebbles and small cobbles (32-128 mm). A restricted size range allows for comparisons from site to site. The disadvantage lies in the tendency of some lithologies to dominate a different size range (e.g., granites that grussify). Therefore the counts do not necessarily reflect a volume percentage composition for the gravels. Visual inspection was made of the granule fraction to ensure against any drastic biomodality of lithologic distribution. At each site 100 pebbles were counted; percentages given in the following tables are equivalent to actual counts.

The maximum clast size was measured directly. Average clast size was determined by visually estimating the most common or the median clast size present and measuring that size. Average clast size should not be considered a precise measure for a particular site but rather a figure useful for comparing one site with another.

Sphericity and roundness were estimated by comparing Figure 57 to the average clast size. Both characteristics are

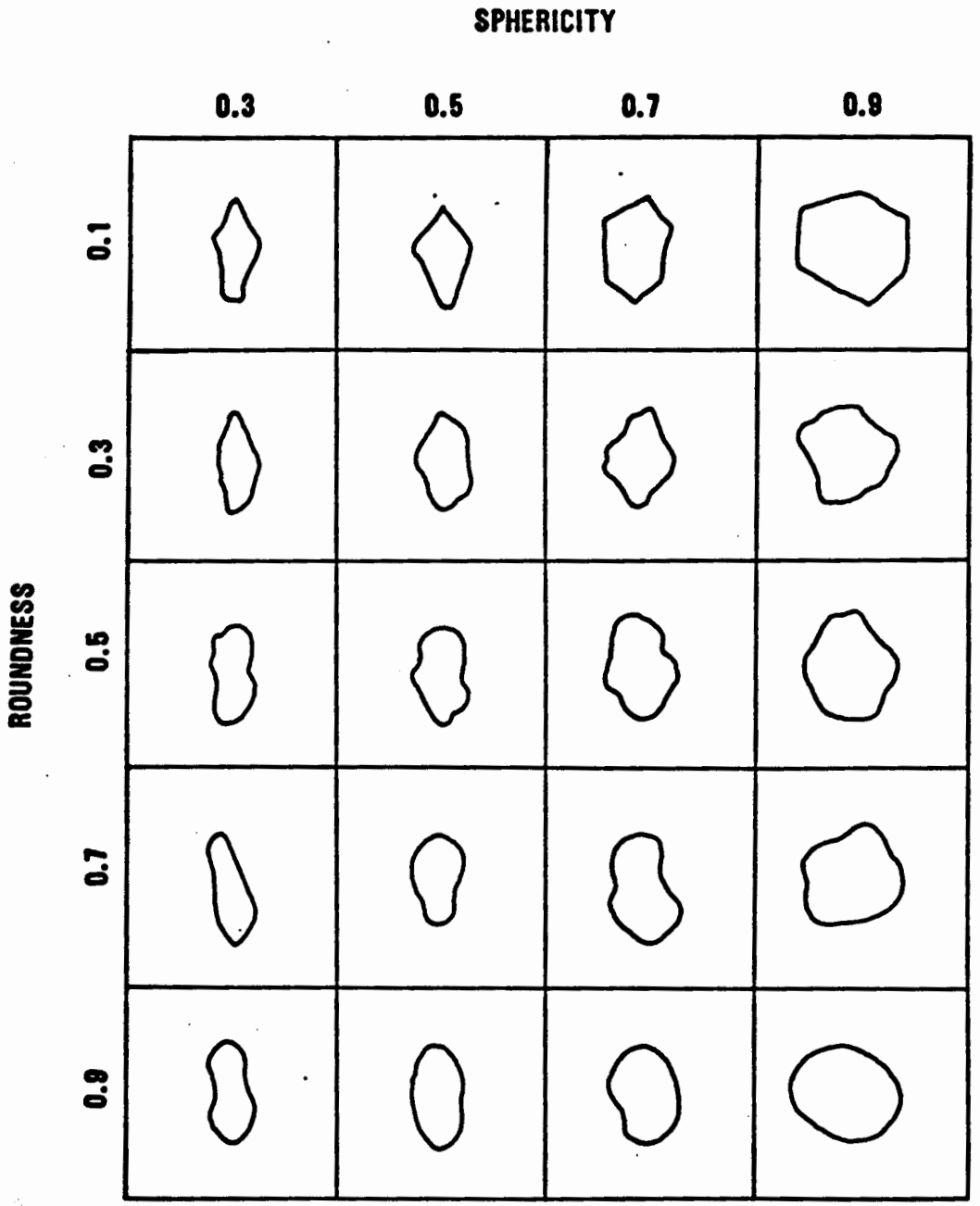

Figure 57. Sphericity and roundness comparison chart.

greatly influenced by lithology. Quartzites tend to be less rounded than Paleozoic sedimentary rocks. The former are also more rod-shaped.

Measurements were originally made in inches and have been subsequently converted to metric measurements. This has resulted in the necessity of rounding to the nearest millimetre.

Table 7. Weight percentages of pebbles, granules and sand from the piedmont facies, Tesuque Formation.

	Pebbles	Granules	Sand	Cobbles		Pebbles	Granules	Sand	Cobbles
Exposure T1					Exposure T1				
1	36	19	45		21	3	3	94	
2	60	10	40	X	22	0	0	100	
3	75	6	19	X	23	0	0	100	
4	57	12	31		24	0	0	100	
5	5	5	90		25	3	5	92	
6	34	12	54	X	26	29	15	56	
7	57	9	34	X	27	3	6	91	
8	64	6	30		28	42	18	40	
9	72	14	14		29	63	8	29	
10	28	20	52		Exposure T3				
11	1	2	97		1	69	11	20	
12	3	4	93		2	27	27	46	
13	20	21	59		3	83	3	14	X
14	28	22	50		4	52	17	31	
15	2	7	91		5	16	7	77	
16	25	11	64	X	6	8	12	80	
17	20	15	65		7	4	11	85	
18	9	17	74		8	63	5	32	X
19	2	2	96		9	45	22	33	X
20	3	5	92		10	42	11	47	

Table 7. Continued

	Pebbles	Granules	Sand	Cobbles		Pebbles	Granules	Sand	Cobbles
Exposure T3					Exposure T2				
11	24	14	62		15	65	13	22	
12	4	12	84		16	60	11	29	X
13	26	21	53		17	63	10	27	X
14	50	18	32		18	65	12	23	X
15	61	10	29		19	41	13	46	
Exposure T2					20	6	6	88	
1	53	13	33	X	21	57	5	38	
2	72	9	19		22	43	9	48	
3	58	12	30	X	23	10	13	77	
4	55	16	29		24	39	13	48	
5	76	7	17		25	41	11	48	
6	59	12	29		26	19	4	77	X
7	28	23	49		27	41	14	45	
8	7	6	87		28	3	4	93	
9	56	9	35		29	22	15	63	
10	61	13	26		30	58	16	26	
11	43	14	43		31	7	7	86	X
12	65	9	26	X	32	67	7	26	
13	45	14	41		33	4	4	92	
14	66	11	23	X	34	58	15	27	

Table 7. Continued

	Pebbles	Granules	Sand	Cobbles	Pebbles	Granules	Sand	Cobbles
Exposure T2								
35	17	14	69	X				
36	61	9	30					
37	58	19	23					
38	61	8	31	X				
39	53	4	43					
40	0	3	97					
41	66	5	29					
42	25	11	64					
43	33	19	48					
44	19	19	62					
45	42	23	35					
46	8	6	86					

Table 8. Clast counts: Chamita, Puye and Servilleta Formations

Sample	Max. Size	Ave. Size	Sphericity	Roundness	Volcanic Rks: Mafic	Volcanic Rks: Inter+ Silicic	Quartz	Granite	Schist+ Gneiss	Phyllite	Quartzite	Paleozoic ss,sh,ls + Conglomerate	Chert
					Composition								
a. Chamita Formation													
C1	5.1	1.3	.6	.4		3	47	5			25	20	
C2	7.6	3.8	.5	.5		6	4	6		2	39	43	
C3	20.3	10.1	.5	.8		3	4	2			29	62	
C4	12.7	7.6	.5	.6		1	5	3	1	2	63	25	
C5	15.2	5.1	.6	.8		2	3	3	1		69	22	
C6	17.8	3.8	.6	.6		1	45	10	2	1	32	9	
C7	5.1	.6	.6	.4		3	49	7	1	<1	30	10	
C8	15.2	2.5	.7	.6		2		7		<1	39	52	
b. Puye Formation: Totavi Lentil					*Indicates percentage of volcanic breccia.								
P1					2*	28		13	1		45	6	5
P2					1	28	1	24	1		40	3	2
P3					1*1	29	1	32	1		31	2	2
P4					1*3	27	1	17			47	2	2
P5					2*	30	1	11	1		49		6
c. Servilleta Formation Basal gravels													
S1	50.8	7.6	.6	.9	<1	<1	1	1	1	1	94	2	
S2	20.3	8.9	.7	.9				3	2		85	10	

Table 8. Continued

Sample	Max. Size	Ave. Size	Sphericity	Roundness	Volcanic Rks: Mafic	Volcanic Rks: Inter+ Silicic	Composition: Quartz	Granite	Schist+ Gneiss	Phyllite	Quartzite	Paleozoic ss,sh,ls + Conglomerate
c. Servilleta Formation												
S3	33.0	10.2	.6	.9		<1	4	1	2	1	90	2
S4	76.2	10.2	.4	.3		1	4		1	15	80	

Table 9. Clast counts: Surface and Embudo terrace gravels

Sample	Max. Size	Ave. Size	Sphericity	Roundness	Volcanic Rks: Mafic	Volcanic Rks: Inter+ Silicic	Quartz	Granite	Schist+ Gneiss	Phyllite	Quartzite	Paleozoic ss,sh,ls + Conglomerate
								Composition				
d. Surface gravels												
Oso surface												
01	25.4	10.2	.7	.8			2	8	<1		90	
02	20.3	7.6	.6	.8			1	2	2		95	
Truchas surface												
Tr1	30.5	10.2	.6	.9				6	1		93	
Tr2	38.1	12.7	.5	.8			1	5			94	
Santa Barbara												
SB1	45.7	12.7	.8	.8				1			29	70
SB2	30.5	10.2	.8	.8							5	95
Santa Cruz												
SC	76.2	12.7	.6	.9				20	5		75	
Chamisal												
CM	91.4	17.8	.8	.9	1				1		13	85
e. Embudo terrace gravels												
E1	61.0	6.4	.6	.8				5	1		60	34
E2	30.5	3.8	.6	.8				2			58	40
E3	45.7	6.4	.6	.9			1	8	3		54	34
E4	50.8	7.6	.5	.8				3			50	47
E5	38.1	5.1	.6	.9				5	2		46	47

Table 10. Clast counts: Cejita Member and possible Cejita Member

Sample	Max. Size	Ave. Size	Sphericity	Roundness	Volcanic Rks: Mafic	Volcanic Rks: Inter+ Silicic	Quartz	Granite	Schist+ Gneiss	Phyllite	Quartzite	Paleozoic ss,sh,ls + Conglomerate
								Composition				
fl. Cejita Member												
Cj1	25.4	3.8	.5	.6		2					45	53
Cj2	20.3	2.5	.7	.6		1		2	<1		43	55
Cj3	25.4	10.2	.7	.5							60	40
Cj4	20.3	2.5	.6	.5		<1		2	<1		43	55
Cj5	17.8	2.5	.6	.5			<1	1			53	46
Cj6	25.4	7.6	.7	.8							44	56
Cj7	30.5	7.6	.8	.8				1			36	63
Cj8	15.2	1.3	.6	.6		5		<1			20	65
Cj9	25.4	5.1	.7	.8			10				61	29
Cj10	25.4	7.6	.5	.5		<1		2	<1		65	33
Cj11	25.4	3.8	.7	.8				1	<1		46	53
Cj12	45.7	7.6	.7	.8		1	8	1			53	35
Cj13	25.4	12.7	.8	.8			2		1		34	63
Cj14	15.2	1.9	.6	.7				2			31	67
Cj15	20.3	2.5	.7	.4		<1					61	39
Cj16	30.5	7.6	.6	.6		1	<1				7	92
Cj17	76.2	12.7	.8	.8							43	57
Cj18	45.7	12.7	.7	.8		2					31	67

Table 10. Continued

Sample	Max. Size	Ave. Size	Sphericity	Roundness	Composition: Volcanic Rks: Mafic	Volcanic Rks: Inter+ Silicic	Quartz	Granite	Schist+ Gneiss	Phyllite	Quartzite	Paleozoic ss,sh,ls + Conglomerate
Cj19	35.6	15.2	.6	.7					5		30	65
Cj20	61.0	12.7	.7	.8		<1					5	95
Cj21	25.4	5.1	.8	.7		<1					48	52
Cj22	12.7	3.8	.8	.8		<1					47	53
Cj23	25.4	3.8	.7	.7			<1	<1			40	50
Cj24	15.2	3.8	.5	.5		5		<1			25	70
Cj25	45.7	15.2	.6	.8		1	3	5			46	35
f2. Possible Cejita Member												
Oj	17.8	6.4	.8	.5				2			56	42
Lt	45.7	7.6	.6	.5			1	2			11	86

Table 11. Clast counts: Piedmont facies of the Tesuque Formation

Sample	Max. Size	Ave. Size	Sphericity	Roundness	Volcanic Rks: Mafic	Volcanic Rks: Inter+ Silicic	Quartz	Granite	Schist+ Gneiss	Phyllite	Quartzite	Paleozoic ss,sh,ls + Conglomerate
								Composition				
g. Piedmont facies												
Tp1	15.2	1.2	.6	.5				48	2		50	
Tp2	10.2	2.5	.6	.4				28	2		70	
Tp3	17.8	5.1	.6	.6			2	16	1		81	
Tp4	12.7	2.5	.6	.7			2	9	<1		89	
Tp5	12.7	1.3	.5	.5			1	31	2		65	
Tp6	6.4	1.3	.6	.4			1	46	1		52	
Tp7	17.8	2.5	.6	.4			1	25	4		70	
Tp8	15.2	1.3	.5	.4			1	31	1		67	
Tp9	6.4	1.3	.7	.5				35			65	
Tp10	15.6	3.8	.5	.4			5	11	2		82	
Tp11	12.7	2.5	.6	.7			1	3	1		95	
Tp12	25.4	2.5	.5	.6			2	15	3		80	
Tp13	6.4	1.9	.7	.5				45	10		45	
Tp14	2.5	1.3	.5	.3			5	10	2		83	
Tp15	12.7	5.1	.4	.4			2	30	1		67	
Tp16	3.2	0.6	.7	.4				25			75	
Tp17	12.7	2.5	.6	.4				8			92	
Tp18	61.0	12.7	.6	.5				20	1		79	

Table 11. Continued

Sample	Max. Size	Ave. Size	Sphericity	Roundness	Composition: Volcanic Rks: Mafic	Volcanic Rks: Inter+ Silicic	Quartz	Granite	Schist+ Gneiss	Phyllite	Quartzite	Paleozoic ss,sh,ls + Conglomerate
Tp19	12.7	5.1	.5	.5			3	17	<1		78	
Tp20	91.4	15.2	.5	.6				25	2		73	
Tp21	45.7	12.7	.7	.6				51	1		38	
Tp22	10.2	3.8	.6	.4				49	1		50	
Tp23	8.9	1.3	.7	.4				48	2		50	
Tp24	5.7	1.3	.7	.4				30			70	
Tp25	11.4	2.5	.7	.5				40	20		40	

Note: See Fig. 9 for locations of Tp16 to Tp25.