# STRATIGRAPHY OF THE SANTA FE GROUP, NEW MEXICO

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# ABSTRACT

THE TYPE AREA of the Santa Fe Group is the region north of Santa Fe, New Mexico, between the Sangre de Cristo Mountains on the east and the Jemez Mountains on the west. This area was part of Hayden's (1869) type section of the Santa Fe marls, which was later called the Santa Fe Formation by Bryan, Smith, Cabot, Denny, and others. Bryan (1938, p. 205), following part of Hayden's original description, mentioned the area north of Santa Fe as the type locality of the Santa Fe Formation, but Denny (1938, 1940b) first formally designated a specific type locality for the Santa Fe Formation as given above. Kottlowski (1953, p. 144) first suggested that the Santa Fe Formation be elevated to group rank. Spiegel and Baldwin (1963, p. 38) proposed an extension of the term Santa Fe Group to include all the sedimentary and volcanic rocks related to the Rio Grande trough, with a range in age from middle(?) Miocene to Pleistocene(?).

The present report proposes to restrict the use of Santa Fe Group to the rocks of the type and contiguous areas. The middle Miocene to middle to upper Pliocene deposits of the type area, heretofore undifferentiated, are divided among five members of the Tesuque Formation, and the Chamita Formation. This division of the group is based on the results of field and laboratory studies since 1924 by the Frick Laboratory of the American Museum of Natural History. The two formations from lowermost to uppermost are: (1) Tesuque Formation and (2) Chamita Formation. Formal names are proposed for the members of the Tesuque Formation.

Deposits of the Tesuque Formation, which is the lowest formation of the Santa Fe Group as here recognized, are divided into five members: (1) the Nambé Member, (2) the Skull Ridge Member, (3) the Pojoaque Member, (4) the Chama-el rito Member, and (5) the Ojo Caliente Sandstone. Fossils collected from the Nambé and Skull Ridge members range in age from medial to late Miocene. The Pojoaque, the Chama-el rito, and the Ojo Caliente Sandstone have produced a large collection of early Pliocene mammalian fossils. These members are lithologically distinct, and, although they may have been deposited through the same general period of time, the beds are advisedly separated as members rather than as facies.

The Chamita Formation, which is the uppermost formation of the Santa Fe Group, represents deposits from a markedly different sedimentary environment compared with the underlying Ojo Caliente Sandstone. Moreover, fossils of medial Pliocene age have been collected from the beds of the formation, with even a few fossils indicative of an early part of the late Pliocene.

Type sections of the Nambé and Skull Ridge members of the Tesuque Formation have been designated in the thick belt of alluvial-fan deposits exposed between Nambé Creek and the Santa Cruz River. The type section of the Pojoaque Member of the Tesuque Formation lies north of the Pojoaque River, northwest of Pojoaque, New Mexico. Most of the sediments of the Pojoaque Member were derived from the predominantly granitic rocks of the Sangre de Cristo Range; these were part of a great system of coalescing alluvial fans arranged along the mountain front. At the same time that the Pojoaque Member was being deposited, as shown by the extensive collection of fossils obtained from each member, another system of alluvial-fan deposits was being built along the northern and northwestern part of the type area of the Santa Fe Group. These volcanic rocks are herein named the Chama-el rito Member of the Tesuque Formation. They were derived from volcanic rocks of the San Juan region of northern New Mexico, and southern Colorado and are lithologically distinct from those of the Pojoaque Member, which are essentially granitic in origin. Although the Chama-el rito was deposited through a long period of time, as is shown by the presence of *Brachycrus* in a locality near Abiquiu, New Mexico, which indicates an equivalency with a part of the Skull Ridge Member, the greatest part of the member was deposited at the same time as the Pojoaque Member. In the area between Battleship Mountain and the Sacred Spring, the uppermost beds of the Chama-el rito are observed to overlie beds of the Pojoaque Member.

The Ojo Caliente Sandstone has been assigned member status and is composed of about 450 feet of light gray to light pinkish gray, eolian, soft, friable sandstone. These beds interfinger at the base with the Chama-el rito Member and obviously represent a marked change in sedimentary environment. The southernmost good exposure of the Ojo Caliente Sandstone is on Battleship Mountain where it is no more than 40 feet thick and overlies Chama-el rito beds. The Ojo Caliente Sandstone has been extensively reworked into the basal beds of the overlying Chamita Formation. In some parts of the area, this reworking superficially resembles interfingering, but it is quite different, and also indicates a distinctive change in sedimentary environment.

Beds of the Chamita Formation are lithologically different from all others in the type area of the Santa Fe Group; they overlie the Ojo Caliente Sandstone, and, moreover, they contain fossil mammals that show them to be the latest beds of the Santa Fe Group in the type area. The type section of the Chamita Formation lies 2 miles northwest of the San Juan Pueblo.

The total thickness of the Santa Fe Group, as restricted in this report, is at least 4500 feet and may be as much as 4800 feet. These figures were obtained by our measuring correlated fault blocks in the type area. The thicknesses assigned to the ideal sections of members or formations have been the basis for the estimates.

The sediments of the Santa Fe Group include alluvial-fan and eolian deposits, including conglomerates, gravel, loosely consolidated sandstones, siltstones, volcanic ash, bentonites, tuffaceous deposits, conglomeratic sandstones, intraformational breccias and conglomerates, concretions of various kinds, calcareous and cherty strata, and a small amount of clay. Interbedded volcanic flows are few and of small extent.

Strata of the Santa Fe Group were deformed by high-angle, normal, strike faults during the post-Santa Fe deformation. The faults are closely spaced, and the strata in the resultant fault blocks in the Espanola Valley commonly dip westward 3 to 9 degrees. Maximum dip may be as much as 30 degrees. North of Black Mesa dips may be easterly.

Detailed correlations in the Tesuque Formation were made from studies of the stratigraphic position of 38 differentiable volcanic-ash beds. Ash beds are particularly useful as horizon markers in the Skull Ridge Member. Small groups of volcanic-ash strata were used in comparable correlations in the Pojoaque Member of the Tesuque Formation. Two distinctive tuffaceous zones are useful for correlations in the Chamita Formation.

About 1000 feet of gray sandstone deposits in the Jemez Creek and Northern Ceja del Rio Puerco localities, southwest of the type area of the Santa Fe Group, were described by the senior author in 1966 as the Zia Sand Formation. These beds formerly had been included in the Santa Fe Formation but were separated on lithologic criteria, supported by evidence from contained fossils, which were demonstrated to be early to medial Miocene in age—more precisely, equivalent within the framework of the North American Land-Mammal provincial classification to late Arikareean (Harrison Formation equivalent) to late Hemingfordian (Sheep Creek Formation equivalent) in age.

The Rio Grande depression was formed in at least two distinct periods of deformation, one prior to the deposition of the Santa Fe Group and the other post-Santa Fe Group in age. The outlines of the two deformations closely but not exactly coincided. In the earlier structural basin the El Rito Formation and the Galisteo Formation were the first Tertiary deposits to be laid down. A widespread period of volcanism resulted in the deposition of three formations composed of volcanic debris, as follows: (1) Abiquiu Tuff, (2) Picuris Tuff, and (3) Espinaso Volcanics. These were followed by more than 4000 feet of sediments assigned to the Santa Fe Group that are lithologically distinct and obviously are from entirely different provenances. The Santa Fe overlapped the original structural basins, as is shown by the thick blocks of Santa Fe sediments caught in footwall blocks along some of the bounding faults of the present Rio Grande depression.

After the post-Santa Fe deformation, previously isolated sedimentary basins along the original structural depression were integrated by a through-flowing perennial river—an ancestral Rio Grande. Tremendous volumes of sediments were removed from the Rio Grande depression, and the present complex geomorphology of the type area of the Santa Fe Group remains merely as a fragmentary record of important Pleistocene events.

# INTRODUCTION

THE SANTA FE FORMATION has been the subject of numerous general geological reports and observations for more than 100 years, but in that time few observations on the stratigraphy of the formation have appeared. Almost exactly a century ago Hayden (1869, p. 66) named the beds "the Santa Fe marls," and with the passing of the years the name has been changed to Santa Fe Formation and finally to Santa Fe Group. To date several circumstances have prevented the publication of a definitive report on the Santa Fe. The present report, far from being definitive, is regarded by the writers as an introduction to the stratigraphy of the Santa Fe Group, to which, as an adjunct to the interpretation of the stratigraphy, many data on the structure and geomorphology of the region have been added. Our purpose is to present a reconnaissance study of the Santa Fe Group in which attention is directed to those features that we believe are salient to an understanding of the stratigraphic framework of the group. Analyses of individual sediments or sedimentary structures, petrographic or petrologic analyses of rocks of whatever origin, or complex compilations of minutiae of many kinds are purposely omitted. Detailed investigations of many of the features mentioned in this report can serve better as projects for in-depth studies by specialists who may become interested in the Santa Fe type area.

Sandy or conglomeratic deposits that crop out at many places in the Rio Grande depression from Colorado through New Mexico into Texas have been correlated as part of the Santa Fe Formation. Apparently many of these correlations were made because the workers suspected that they were dealing with probably late Tertiary or Pleistocene beds, and, inasmuch as the Santa Fe Formation happened to be the only late Tertiary formation described in the region, it was selected as a "wastebasket" formation to receive the problematical beds. Such correlations often were made, although the referred deposits showed faint, if any, resemblance to the deposits of the type area of the Santa Fe Formation.

The cumulative effects of a succession of such unfortunate correlations have been a dilution of the concept of the Santa Fe Formation as a rock-stratigraphic unit, which is even more confusing when biostratigraphic data are presented as justification for the correlation and are based on a fauna not compatible in any way with that obtained from the type area. In this way the term Santa Fe Formation has been extended to include a wide variety of deposits of uncertain age, and its usefulness to geology and paleontology thereby has been greatly diminished. Its present vague significance is somewhat comparable with that currently applied to the Wasatch, the "Loup Fork," and the "Republican River" formations.

Spiegel and Baldwin (1963) raised the term Santa Fe to group status, but this device merely transferred the general confusion surrounding the Santa Fe Formation to an even greater geographic area and the faunal connotation of the term Santa Fe to greater segments of geologic time. Such broad usage is to be deplored, and we hope that the restricted use of the term Santa Fe Group as proposed in this report will enable subsequent workers to use both rock-stratigraphic and faunal data in seeking solutions to problems relating to the Santa Fe Group, and thereby delimit and revitalize the term.

Most of the deposits of the Santa Fe type area were laid down by coalescing alluvial fans in a pre-Santa Fe structural basin that conformed rather closely to the outlines of the present Rio Grande depression as defined by Bryan (1938). A period of post-Santa Fe deformation fractured and tilted the beds and formed large numbers of closely spaced fault blocks. These fault blocks were outlined by eastward- and by westward-dipping normal strike faults often, but not in every case, arranged *en echelon.* The correlation of the numerous fault blocks and the determination of the relative ages of their sedimentary sequences have been major stratigraphical problems.

We recognize the controversy that exists among geologists and paleontologists, both North American and European, concerning the precision, applicability, appropriateness, and relative usefulness of the time scales that have been proposed for measuring Tertiary history. Furthermore we are aware of the difficulties that have arisen as a result of applying to North American rocks and fossil faunas the time terms for the epochs of the Tertiary Period that were originally defined in Europe. One problem of particular complexity involved the selection of

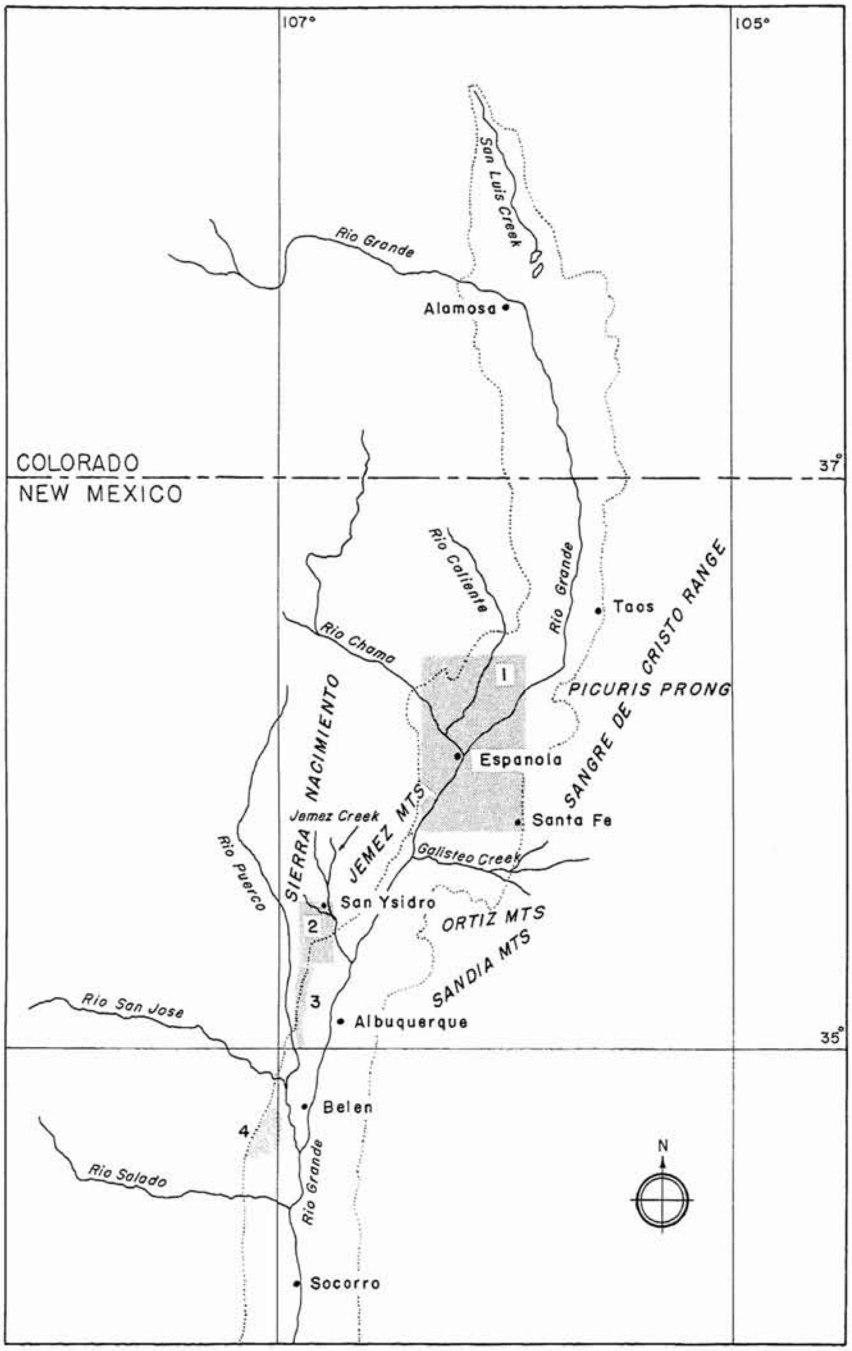


FIG. 1. Index map showing (1) type area of Santa Fe Group, (2) Jemez Creek area, (3) Ceja del Rio Puerco area, and (4) Gabaldon badlands area, all in New Mexico. Dotted outline shows approximate configuration of the Rio Grande depression.

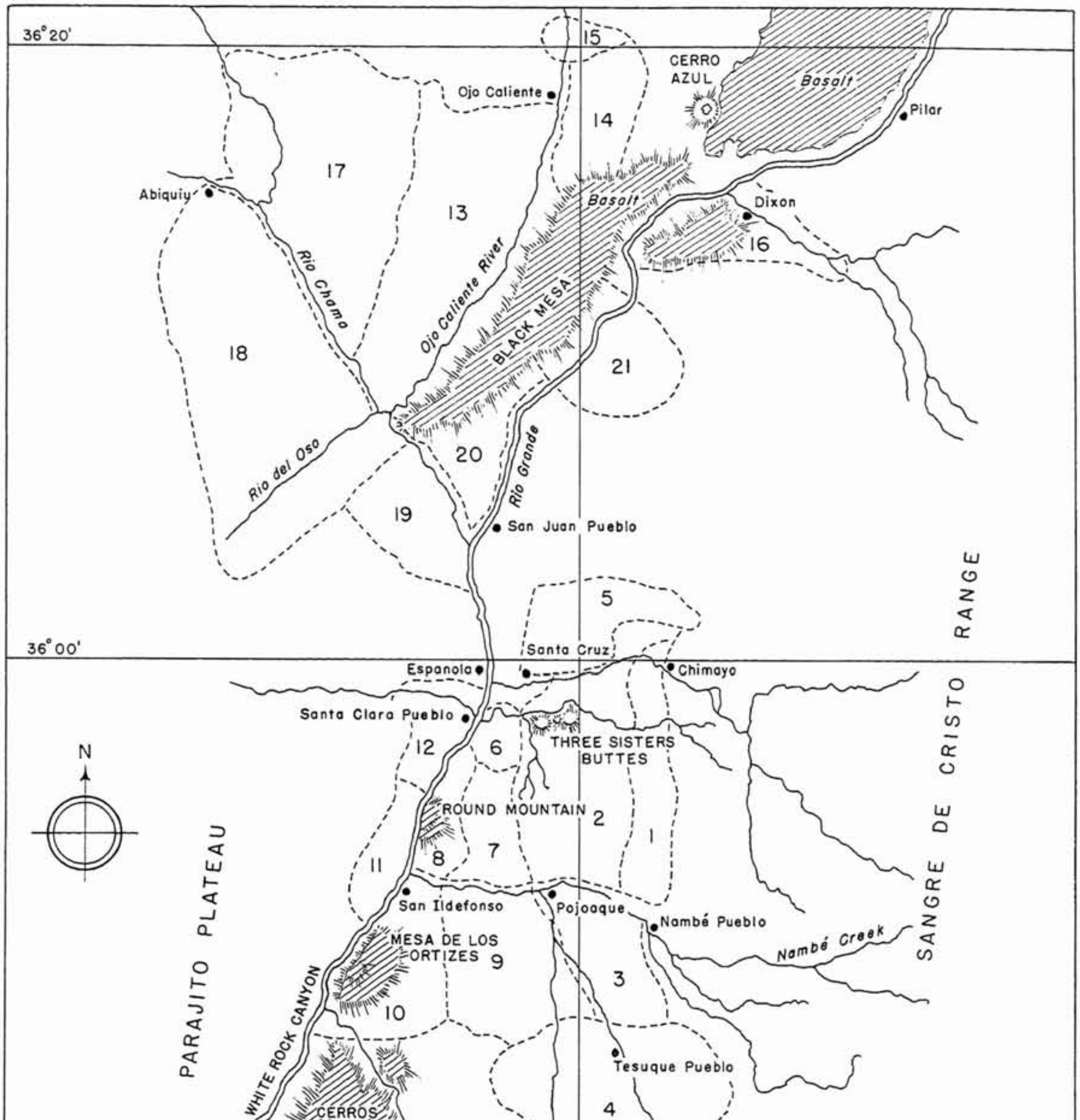


FIG. 2. Map of fossil-collecting localities worked by Frick Laboratory field parties in the type area of the Santa Fe Group, New Mexico. (1) Nambé; (2) Skull Ridge; (3) East Cuyamunque; (4) Tesuque; (5) Santa Cruz; (6) North Pojoaque Bluffs; (7) Central Pojoaque Bluffs; (8) Lower Pojoaque Bluffs; (9) West Cuyamunque; (10) South San Ildefonso; (11) San Ildefonso; (12) Santa Clara; (13) Ojo Caliente; (14) East Ojo Caliente; (15) North Ojo Caliente; (16) Dixon sub-basin; (17) Chama-el rito; (18) Rio del Oso-Abiquiu; (19) Hernandez; (20) San Juan; and (21) Osbornoceros-Lyden.

the time or age terms that are used throughout this report. We provide two charts (figs. 9 and 10), which are designed to show general age references and to enable the reader to orient his concepts regardless of his preference for a particular scheme of age determinations.

We use the European terms Miocene and Pliocene in a general way, fully cognizant of the probability that further refinement in Europe is likely to alter the concepts of the boundaries between these epochs. We believe, however, that the Wood Committee (Wood et al., 1941) North American Provincial Ages, or North American Land Mammal Ages (a change in Wood Committee terminology suggested by Savage, 1962), have proved more effective for use in North American continental deposits than have the terms Miocene and Pliocene, and others of the international geological time scale. We use Land-Mammal Age terms in a general way and, moreover, would favor the introduction of a Land-Mammal Age to represent a segment of time represented by the fauna of the Valentine Formation of Nebraska as revised by Skinner, Skinner, and Gooris (1968, p. 404).

The chief purpose of this report is to present rock-stratigraphic and biostratigraphic information in an effort to clarify some of the problems peculiar to the Santa Fe Group. Other objectives are: (1) to enable subsequent workers to identify areas of Santa Fe Group deposits and correlate them with greater precision; (2) to present the information on the Santa Fe Group in a manner that can be useful in the field and in the laboratory without the necessity of the field man's personally working out the details of the geology; (3) to provide a stratigraphic framework on which the extremely large fossil collections from the Santa Fe area in the Frick Collection can be based (this will require that the mammalian remains be interpreted according to the sequence in which the specimens actually occur in the rocks); (4) to place emphasis on description and to hold interpretation to a

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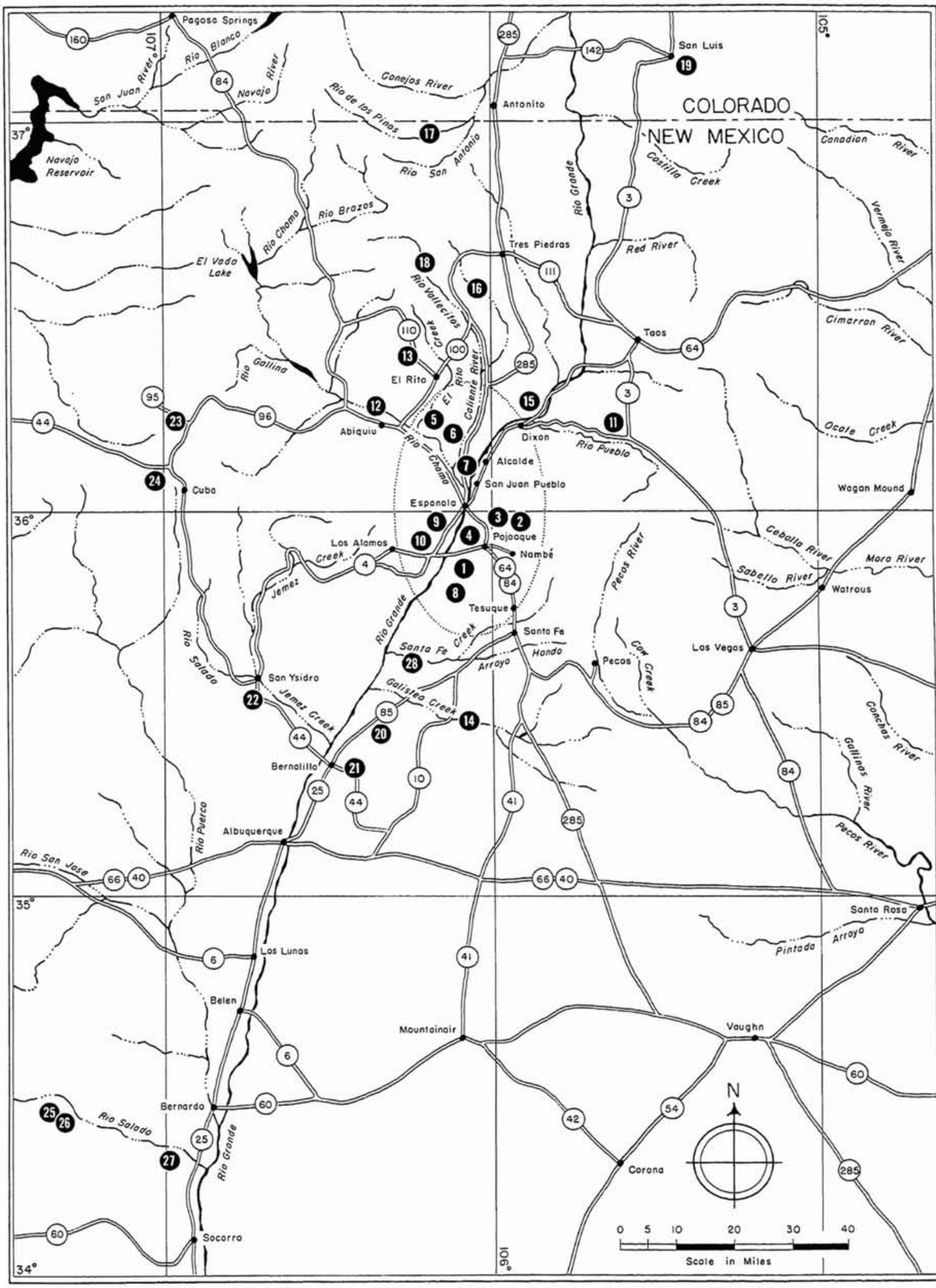
FIG. 3. Index map showing type areas, type localities, type sections, or well-exposed, described areas of some Cenozoic rocks in the Rio Grande depression in north-central New Mexico and adjacent areas. Large dotted ellipse shows type area of Santa Fe Group as restricted in this report. Small, numbered, dark circles identify the following localities:

1. Tesuque Formation, Spiegel and Baldwin, 1963
2. Nambé Member, new name
3. Skull Ridge Member, new name
4. Pojoaque Member, new name
5. Chama-el rito Member, new name
6. Ojo Caliente Sandstone, new name
7. Chamita Formation, new name
8. Ancha Formation, Spiegel and Baldwin, 1963
9. Puyé Conglomerate, Griggs, 1964
10. Bandelier Tuff, Griggs, 1964
11. Picuris Tuff, Cabot, 1938
12. Abiquiu Tuff, Smith, 1938
13. El Rito Formation, Smith, 1938
14. Galisteo Formation, Hayden, 1869
15. Servilleta Formation, Montgomery, 1953
16. Carson Conglomerate, Just, 1937
17. Los Pinos Gravel, Larsen and Cross, 1953
18. Ritito Conglomerate, Barker, 1958
19. Vallejo Formation, Upson, 1941
20. Espinaso Volcanics, Stearns, 1953
21. Placita Marl, Cope, 1875
22. Zia Sand Formation, Galusha, 1966
23. San Jose Formation, Simpson, 1948
24. Nacimiento Formation, Keyes, 1906
25. Baca Formation, Wilpolt and others, 1946
26. Datil Formation, Winchester, 1920
27. Popotosa Formation, Denny, 1940a
28. Tuerto Gravel, Stearns, 1953


Pagosa Springs
160
107°
Rio Blanco
San Juan River
84
Navajo River
Conejos River
Rio de los Pinos
17
285
Antonito
142
San Luis
19
105°
COLORADO
NEW MEXICO
37°
Navajo Reservoir
Rio San Antonio
Costilla Creek
Canadian River
Rio Grande
3
Rio Brazos
Rio Chama
El Vado Lake
Vermejo River
18
Tres Piedras
Red River
111
Rio Vallecitos
16
110
Creek
100
13
El Rito
Taos
64
Cimarron River
Rio Gallina
285
El Rito
Caliente River
15
95
3
23
96
12
Abiquiu
5
6
11
44
Dixon
Rio Pueblo
Ocate Creek
Rio Chama
7
Alcalde
24
Cuba
San Juan Pueblo
Wagon Mound
Espanola
36°
9
3
2
4
Pojoaque
Ceballo River
Mora River
Los Alamos
10
Nambé
Creek
4
1
64
Pecos River
Sabello River
Watrous
Jemez
8
84
Tesuque
3
Rio Grande
Santa Fe
Santa Fe Creek
Hondo
Arroyo
Cow Creek
Pecos
Los Vegas
Rio Salado
28
San Ysidro
Galisteo Creek
Jemez Creek
22
85
14
85
84
Conchas River
20
44
Bernalillo
21
10
25
44
41
Gallinas River
84
285
Rio Puerco
Albuquerque
Pecos River
Rio San Jose
66 40
66 40
35°
Santa Rosa
Pintada Arroyo
Los Lunas
6
41
Belen
Mountainair
Vaughn
6
60
N
54
Bernardo
60
42
25
26
Rio Salado
25
Rio Grande
27
Corona
285
60
Socorro
0 5 10 20 30 40
Scale in Miles
106°
34°

minimum, and to attempt to mark plainly hypothetical interpretations; and (5) finally, to present a field report that may prove helpful to workers of the future in preparing more precise and penetrating reports on the geology, stratigraphy, sedimentology, and paleontology of the Santa Fe region than have appeared in the past.

Childs Frick first sent an expedition into the type area of the Santa Fe Group in 1924, and he immediately recognized the need for faunistic as well as stratigraphic studies of the deposits. Subsequent work carried on each field season since, with the exception of the years 1932, 1943, 1944, 1958, 1961, 1963, and 1965, reflects his unwavering interest in the paleontology and stratigraphy of the formation.

This report brings together many of the data obtained by the field collectors of the Frick Laboratory.[1] Necessarily numerous details must be eliminated, owing to limitations on the amount of pertinent material that can be published. Workers in the future who will deal with the Frick Laboratory collections made in the Santa Fe Group in the last 30 years will find relatively complete documentation in the Frick Laboratory records, field books, and archives.

Studies by the field parties of the Frick Laboratory in the Santa Fe area previous to 1940 were mostly confined to finding and collecting fossils from the principal fossiliferous localities and in correlating both faunal and stratigraphic data in an effort to differentiate the late Miocene and early Pliocene deposits. In 1940 we began an intensive study of the stratigraphy of the fossiliferous localities, and in 1941, 1942, 1945, 1946, and 1947 extended the detailed investigations to include all deposits in the type area.

Much work also has been done since 1945 in outlying regions in which deposits of presumably Santa Fe age have been reported. The field seasons of the period 1949 to 1953, for the most part, were spent in correlated areas. Mammalian fossil remains have been obtained at several localities, and detailed study and mapping have been made of the deposits from which they were collected. Principal localities studied include Jemez Creek, Galisteo Creek, and Santo Domingo valleys; various areas along the Ceja del Rio Puerco, the Belen-Bernardo locality, the San Acacia area, and the Socorro area in New Mexico. The San Luis Valley in Colorado, the Truth or Consequences and Las Cruces areas, and other isolated areas along the Rio Grande in New Mexico have been visited from time to time.

[1]The Frick Laboratory was merged with the Department of Vertebrate Paleontology of the American Museum of Natural History in 1968.

Adequate topographic maps were not available for the type area of the Santa Fe Group, as here restricted, during the years that most of the field mapping was done. We mapped directly on uncontrolled aerial photographic mosaics taken in 1935–1936 by the Fairchild Aerial Surveys, Inc., for the United States Soil Conservation Service as part of the Rio Grande Watershed Project 3500, Identification WO-8979. A map traced from these uncontrolled mosaics serves as the base for the geologic map (fig. 38). Inasmuch as this geologic map was essentially completed prior to 1953, the year in which the United States Geological Survey published a series of 7.5-minute quadrangles providing coverage for the type area, we decided to publish the map as compiled rather than to re-map the area, using the quadrangles as bases.

TABLE 1

United States Geological Survey Topographic Maps in the 7.5-Minute Series Available (1969) for the Type Area of the Santa Fe Group, New Mexico

| |
|---|
| Agua Fria Quadrangle, 1951 |
| Santa Fe Quadrangle, 1952 |
| Guaje Mountain Quadrangle, 1952 |
| White Rock Quadrangle, 1952 |
| Lyden Quadrangle, 1952 |
| Puye Quadrangle, 1952 |
| El Rito Quadrangle, 1953 |
| Ojo Caliente Quadrangle, 1953 |
| Espanola Quadrangle, 1953 |
| Cundiyo Quadrangle, 1953 |
| San Juan Pueblo Quadrangle, 1953 |
| Tesuque Quadrangle, 1953 |
| Chimayo Quadrangle, 1953 |
| Vallecitos Quadrangle, 1953 |
| Horcado Ranch Quadrangle, 1953 |
| Abiquiu Quadrangle, 1953 |
| Chili Quadrangle, 1953 |
| Velarde Quadrangle, 1953 |
| Medanales Quadrangle, 1953 |

Table 1 lists the United States Geological Survey topographic maps that are now (1969) available for the type locality. Names for washes

TABLE 2
CORRELATION OF NAMES OF WASH AND DRAINAGE SYSTEMS USED BY FRICK LABORATORY COLLECTORS WITH NAMES LATER USED ON UNITED STATES GEOLOGICAL SURVEY TOPOGRAPHIC MAPS

| Frick Names | U.S. Geol. Surv. Names | New Mexico Quadrangles |
|---|---|---|
| Boundary Wash | Unnamed | Tesuque, 1953 |
| Rio Tesuque | Rio Tesuque | Tesuque, 1953 |
| East Cuyamunque Wash | Arroyo Cuyamunque | Tesuque, 1953 |
| Arroyo Ancho | Arroyo Ancho | Horcado Ranch, 1953 |
| West Cuyamunque Wash | Arroyo Jacona | Horcada Ranch, 1953 |
| First large wash north of the south boundary of the Santa Clara Grant | Arroyo Madrid | Espanola, 1953 |
| Second large wash north of the south boundary of the Santa Clara Grant | Arroyo la Mesilla | Espanola, 1953 |
| Joe Rak Wash | Unnamed tributary of Arroyo Seco | Espanola, 1953 |
| Santa Clara Canyon | Santa Clara Creek | Puye, 1952 |
| Third Wash | Arroyo de la Morada | Chimayo, 1953 |
| Fourth Wash | Arroyo de los Martinez | Chimayo, 1953 |
| Fifth Wash | Arroyo de la Cuesta de los Vaqueros | Chimayo, 1953 |
| Sixth Wash | Arroyo de los Ajuelos | Chimayo, 1953 |
| Seventh Wash | Cañada del Mogote | Chimayo, 1953 |
| Eighth Wash | Arroyo de los Encinos | Chimayo, 1953 |
| Ninth Wash | Cañada del Ojito | Chimayo, 1953 |
| Tenth Wash | Arroyo de la Cañada Ancha | Chimayo, 1953 |
| Arroyo Seco; Big Wash | Arroyo Seco | Cundiyo, 1953 |
| White Operation Wash | Unnamed | Cundiyo, 1953 |
| Nambé Creek | Pojoaque Creek | Cundiyo, 1953 |
| First Wash | Arroyo del Llano | San Juan Pueblo, 1953 |
| Second Wash | Arroyo Quarteles | San Juan Pueblo, 1953 |
| Dike Wash | Arroyo del Palacio | Chili, 1953 |
| Rio del Oso | Rio del Oso | Chili, 1953 |
| Spring Wash | Arroyo Ojito | Chili, 1953 |
| South Wash | Arroyo de la Presa | Chili, 1953 |
| Three Sand Hills Wash | Cañon la Madera | Medanales, 1953 |
| Three Sand Hills Wash, Camel Fork | Cañon la Madera | Medanales, 1953 |
| Three Sand Hills Wash, South Fork | Cañon la Madera | Medanales, 1953 |
| Tributaries of South Fork of Three Sand Hills Wash | | |
| 1. Conical Hill Wash | Cañon la Madera | Medanales, 1953 |
| 2. Aelurodon Wash | Cañon la Madera | Medanales, 1953 |
| 3. Lobato Branch | Cañon la Madera | Medanales, 1953 |
| 4. Deer Springs Branch | Cañon la Madera | Medanales, 1953 |
| 5. South Branch | Cañon la Madera | Medanales, 1953 |
| Shorty Moore Wash | Arroyo del Torro | Medanales, 1953 |
| Chama-el rito Wash | Cañada Honda | Medanales, 1953 |
| Kunya Ruins Wash | Unnamed | Abiquiu, 1953 |
| Junction Wash | Unnamed | Abiquiu, 1953 |
| First Steep Walled Wash | Arroyo de las Mulas | Ojo Caliente, 1953 |
| Second Steep Walled Wash | Cañada de Tio Pula | Ojo Caliente, 1953 |
| Adobe Walls Wash | Cañada Ancha | Ojo Caliente, 1953 |
| Adobe Walls Wash | Cañada Ancha | Lyden, 1952 |
| Old Mastodon Wash | Cañada Abeque | Lyden, 1952 |
| Mastodon Wash | Cañada de la Cruz | Lyden, 1952 |
| Middle Ojo Caliente Wash, North Fork | Unnamed | Lyden, 1952 |
| Middle Ojo Caliente Wash, South Fork | Cañada de los Alamos | Lyden, 1952 |
| Prince Ranch Wash | Unnamed | Lyden, 1952 |
| Cerro de las Minas Wash | Arroyo del Perro | El Rito, 1953 |

or drainage systems on these topographic maps rarely even resemble those used by Frick Laboratory field parties for the same washes or drainage systems. Therefore, table 2 is included to enable workers of the future, who may be using Frick collections and records, to correlate these two sets of names. Where such duplicated names for washes or drainage systems appear in the body of this report, the United States Geological Survey name appears in parentheses after the Frick Laboratory term.

Type localities of some of the Cenozoic formations in north-central New Mexico are shown in figure 3, whether valid or not, and their authors and the dates on which they were described are also added as an aid to students of the Santa Fe Group.

## ACKNOWLEDGMENTS

The late Mr. Childs Frick was particularly interested in the stratigraphy and paleontology of the Santa Fe Group, and we are greatly indebted to him for making it possible for us to study the geology of the Santa Fe area and to prepare this report.

Acknowledgments for aid are due to the leaders and members of Frick Laboratory field parties whose investigations through the years since 1924 in the Santa Fe area have been the basis for some of the concepts of the stratigraphy of the Santa Fe Group herewith presented. Prominent among these field men were the late Mr. Joseph Rak, the late Mr. Charles H. Falkenbach, the late Mr. Carl O. Long, also Messrs. William Klaus and Jack Wilson.

Mr. Morris F. Skinner studied the horses of the Santa Fe Group, and Mr. Beryl E. Taylor studied the camels, merycodines, and carnivores. Both gave generously of their interpretations of the biostratigraphic correlations.

Deep appreciation is expressed to Dr. Glenn L. Jepsen and to Dr. Franklyn Van Houten for their criticisms and helpful suggestions in the early phases of work on the manuscript. Dr. Malcolm C. McKenna, Dr. Richard H. Tedford, Mr. Morris F. Skinner, and Mr. Beryl E. Taylor read the manuscript, and their help is gratefully acknowledged.

We are especially indebted to Mr. Raymond J. Gooris for his skillful preparation of the figures.

It is a pleasure to acknowledge with warm appreciation the courtesies and much help that has been given to us by many residents of the Espanola, New Mexico, area during the several years of field work. Those to whom particular thanks are due include: Mr. and Mrs. Carl Holmquist, Mr. C. V. Hunter, Mr. W. P. Cook, Mr. Clarence Brashar, and Mr. G. Kenneth Brashar, also the late Mr. F. R. Frankenburger, the late Mr. Howard Barbee, and the late Mr. John Davenport. For many years Mr. Gordon Bond of Albuquerque generously provided us with permits to work on Bond Company ranches in the Jemez Creek and Northern Ceja del Rio Puerco areas.

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## HISTORICAL SKETCH

### WORK BY OTHER GEOLOGISTS

Early exploring expeditions to the west often made Santa Fe, at the end of the Santa Fe Trail, one of their outfitting points. Geologists were occasionally attached to these expeditions, and several of them made reconnaissance geological explorations in the vicinity of Santa Fe, but most of their published accounts were of the Carboniferous, Triassic, and Cretaceous rocks of the region, and of the igneous and metamorphic rocks of the Sangre de Cristo Range. Cenozoic rocks were considered of secondary importance.

The first geological observations of the Santa Fe region were those of Wislizenus (1848) on his tour of northern Mexico in 1846 before the annexation of the Territory of New Mexico by the United States. He was soon followed by military expeditions, on which some officers, such as Lt. J. W. Abert (1848) and Major W. H. Emory (1848), included geological observations in their official documents.

Marcou (1856) and Blake (1856, pp. 314–319) were connected with railroad surveys of the west.

Newberry (1861, pp. 97–99) was a member of two expeditions and was the first to report the presence of Cenozoic rocks in the Santa Fe region. He mentioned the Cenozoic beds along the Rio Puerco in his description of his 1858 trip. The following year, 1859, he was attached to the exploring expedition from Santa Fe to the junction of the Grand and Green rivers under Captain Macomb, and in the report of the expedition stated (1876, p. 52): "Tertiary rocks are not a marked feature in the geology of the vicinity of Santa Fe, but they are visible in a great number of exposures, and usually form isolated patches of limited area, the remnants of more extensive deposits, now for the most part removed by surface erosion, to which their yielding nature has offered little resistance, as is true of patches of Tertiary lying along the eastern bases of the mountains. These beds are of very unequal thickness in different localities, and in many instances, are mere local accumulations, filling depressions or excavations in the surfaces on which they were deposited. So far as my observations extended, they contained no fossils." Newberry also briefly described the lithology.

LeConte (1868) was the geologist with a survey for the extension of the Union Pacific Railway from the Smoky Hill River of Kansas to the Rio Grande. Like the earlier investigators, with the exception of Newberry, he did not mention the Tertiary deposits of the Santa Fe area.

In the summer of 1869 Hayden visited the Santa Fe area as part of his survey of the Territories of Colorado and New Mexico. He described the deposits at length and named them the "Santa Fe marls."[1] Excerpts from his preliminary field report of the United States Geological Survey of Colorado and New Mexico (1869, pp. 66, 69, 70), quoted below, include the original description of the Santa Fe Formation: "From Santa Fe to the banks of Gallisteo [*sic*] Creek, eighteen miles, we pass over the recent marls and sands which seem to occupy the greater portion of the valley of the Rio Grande, above and below Santa Fe' which I have called the Santa Fe marls. These are mostly a light cream-color, sometimes rusty yellow, and sometimes yellowish white, and with layers of sandstones, varying in texture from a very fine aggregate of quartz to a moderately coarse pudding stone. These marls and sands weather into unique forms north of Santa Fe, like the 'Bad Lands' or 'Mauvais Terres' of Dakota. . . . From Santa Fe to Embudo Creek and mostly even to Taos, the Santa Fe marls cover the country. On the east side of the Rio Grande I did not observe a single dike, from the Cerrillos to the mouth of the Chama Creek. North of that the melted material has been poured over the marl so as to form broad mesas. On the west side there are numerous outbursts of igneous matter. These Santa Fe marls reach a great thickness north of Santa Fe, in the Rio Grande Valley, from one thousand two hundred to one thousand five hundred feet, and have tendency to weather into similar monumental and castellated forms, as in the 'Bad Lands.' The upper portions are yellow and cream colored sandstones, sands, and marls. Lower down are some gray coarse sand beds with layers of sandstone. All these marls dip westward three to five degrees. The Rio Grande wears its way through these marls with a bottom about two miles wide. On the west side are distinct terraces with the summits planed off smoothly like mesas. The first one is eighty feet above the river; the second one, two hundred feet. These marls extend all the way between the margins of the Santa Fe Mountains on the east and the Jemez Range on the west. Most of the Chama Hills, and I think the entire hills, are composed of it. At the junction of the Chama Creek with the Rio Grande, a point comes down between the two rivers which is covered with basalt. This continues into the San Luis Valley nearly to Fort Garland."

The best-known works on the Santa Fe are those of Cope, who, in 1874, collected fossils near Pojoaque and San Ildefonso. Cope (1874a, 1874b) correlated the Santa Fe marls with the "Loup Fork" of Colorado and Nebraska. He

[1]In this Historical Sketch and in subsequent citations in the text, the terms Santa Fe marls, Santa Fe Formation, or Santa Fe Group are used as each author published them, and no attempt is made to discuss them uniformly at the rank of group.

collected late Miocene fossils from the beds north of Pojoaque, but obtained the bulk of his collection, consisting of early Pliocene forms, from the beds north of San Ildefonso and contiguous areas. For more than 90 years the initial mixing of the fauna has confused the paleontological and geological literature on the Santa Fe Group. Cope (1875a, 1875b) did not specifically describe the beds from which he obtained the fossils, but he did describe briefly the geology and lithology of the Santa Fe beds in the vicinity of Embudo, Ojo Caliente, and in the Chama River valley. Cope correlated the fauna as equivalent to the "Loup Fork" Formation, then regarded as Miocene, but repeatedly called the beds "Pliocene" in his 1874 field notebook, which is preserved in the Osborn Library of the American Museum of Natural History. Cope (1874a, 1874b, 1875a, 1875b, 1884a) published a series of papers on the vertebrate fauna from the Santa Fe marls.

Stevenson (1881) was attached to the Wheeler Surveys west of the 100th Meridian in 1878 and 1879 and studied the Galisteo Creek area south of Santa Fe, New Mexico. The deposits in that area that he referred to the Santa Fe marls are now regarded as Quaternary. Herrick (1898) wrote several papers on the geology of New Mexico, particularly on beds in the Albuquerque-Belen basin, but he did not correlate them with the Santa Fe marls. Matthew (1899, pp. 26, 65) in his provisional classification of the fresh-water Tertiary of the West, following Cope and others, regarded the Santa Fe marls as lake beds. He also included a faunal list. Herrick and Johnson (1900) collaborated on the geology of the Albuquerque Sheet and for the first time recognized Tertiary rocks in the Jemez Creek valley.

Reagan (1903) was the first to point out that the Rio Grande was younger than Pliocene, and to recognize Pliocene strata in the Jemez Creek valley. He cited deposits in several localities that since have been correlated with the Santa Fe Formation.

In 1903, Johnson published a report on the geology of the Cerrillos Hills, and he was the first investigator to write extensively on the lithology of the Santa Fe Formation. The deposits that he described as part of the Santa Fe Formation are now known to be Quaternary, but his excellent and exhaustive descriptions established the theory of fluviatile origin of the Santa Fe beds as opposed to the lacustrine theory as propounded by Hayden and Cope. Although the deposits that he described were not a part of the Santa Fe Formation, or of the Santa Fe Group as here restricted, his observations directed attention to the alluvial fan or fluviatile origin of the beds and profoundly affected subsequent work on the Santa Fe.

Ogilvie (1905) described an erosion surface or surfaces near the Ortiz Mountains south of Santa Fe as a high altitude conoplain; these surfaces are known now as the Ortiz pediment or the Ortiz erosion surface. The Ortiz surface has figured prominently in geomorphological studies of the region.

Keyes (1907a) cited Santa Fe marls as 500 feet thick and later (1907b) showed the Santa Fe sands as 800 feet thick, and remarked on the confusion that existed regarding the beds.

Osborn and Matthew (1909) published a bulletin on Cenozoic mammal horizons of North America and listed Santa Fe mammals.

Bryan, in 1909, published the first of a long list of papers on the beds of the Rio Grande Valley, and of the Rio Puerco, and many of these have dealt directly with the deposits of the Santa Fe Formation. Two of his later papers, published in collaboration with McCann (1937, 1938) reported on beds of the Ceja del Rio Puerco, which these authors correlated with the Santa Fe Formation and separated into three divisions: (1) Lower Gray Member,[1] (2) Middle Red Member, and (3) Upper Buff Member. The three divisions are not applicable to the beds of the type area of the Santa Fe Group for many reasons explained at length elsewhere in this report. Bryan's most significant work on the Santa Fe seems to be his report (Bryan, 1938) on the geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico, in which he made important contributions to the knowledge of the deposits along the Rio Grande. As would be expected, we have found that many of Bryan's generalizations and conclusions regarding the Santa Fe beds are open to other interpretations, and, where a divergence of opinion exists, the subjects are discussed under appropriate headings.

Writing on the geology and physiography of the Rio Grande Valley as a background for their

[1]Galusha (1966) designated this the Zia Sand Formation.

studies on Pueblo Culture, Hewett, Henderson, and Robbins (1913) presented a surprisingly modern account of the beds in the area, particularly those now called the Bandelier Tuff.

Osborn (1918, p. 34) regarded the Santa Fe marls as transitional between the Miocene and the Pliocene, but placed them at the base of his Pliocene section.

The first published use of the term Santa Fe Formation replacing the old term "Santa Fe marls" was by Darton (1922, pp. 187, 221) in his report on the geologic structure of parts of New Mexico.

Simpson (1925) published a short note on the Santa Fe Formation, in which he concluded that the sediments were derived chiefly from the Santa Fe Range to the east.

Frick (1926a, 1926b, 1926c) described remains of *Hemicyon* from the Santa Fe area in 1926; a study of the tooth sequence in certain trilophodont-tetrabelodont mastodonts appeared later in the same year; and an article in *Natural History* dealt with the romantic aspects of the search for fossils in the area and foreshadowed his lifelong interest in the Santa Fe beds and fauna.

In his paper on the "Red Beds" and associated formations in New Mexico, Darton (1928b) devoted two short paragraphs to the description of the Santa Fe Formation and its fauna, but mapped large areas of unconsolidated later Tertiary and Quaternary deposits as Santa Fe, thus adding to the confusion regarding the identity and extent of the formation.

Renick (1931) described Santa Fe beds along Jemez Creek in his report on the geology and ground-water resources of western Sandoval County, New Mexico. Parts of the beds that he included in the Santa Fe were removed as the Zia Sand Formation by Galusha (1966).

Atwood and Mather (1932, pp. 19, 98) listed several localities in the Abiquiu area in which Santa Fe beds are exposed; they correlated these beds with their Conejos and Los Pinos formations of Colorado. The principal basis for correlation was the presence, in the gravel beds of the Abiquiu localities, of andesite breccia that they regarded as derived from, or equivalent to, the Conejos Andesite.

A gravity separation and thin-section study of three selected sedimentary samples from the "Santa Fe Marls" were made by Howard (1932, pp. 12, 21).

Frick (1933, p. 549) described new remains of trilophodont-tetrabelodont mastodonts from the Santa Fe area and discussed the age of the beds.

Simpson (1933) published a glossary and correlation chart of North America mammal-bearing horizons, with a brief comment on the Santa Fe.

At a meeting of the Washington Academy of Sciences, Hunt (1934) attempted the dating of structural events in the Mt. Taylor region, Nacimiento uplift, and Sandia Mountains on the basis of the then supposed age of the Santa Fe beds.

Stirton (1936), Osborn (1936), and Wilmarth (1938) all published brief comments on the age of the Santa Fe Formation.

Just (1937) described the Carson Conglomerate and also directed attention to beds of the Santa Fe Formation in the Picuris and Petaca areas.

The period 1936 through 1938 saw a quickening of interest in the geology and geomorphology of the Santa Fe and adjacent areas. Much of this was due to the work of Bryan (1938), Bryan and McCann (1936, 1937, 1938), and by Bryan's students or associates. Cabot (1938, p. 88) reported on the fault border of the Sangre de Cristo Mountains north of Santa Fe, New Mexico, and briefly described the adjacent Santa Fe beds.

Denny (1938) published a brief note on the Santa Fe Formation in which he emphasized and restricted the type area.

The Tertiary geology of the Abiquiu Quadrangle was described by Harold T. U. Smith (1938, p. 933), who made valuable contributions to the geology of the area by mapping the El Rito Formation and the Abiquiu Tuff. These formations previously had been mapped as part of the Santa Fe Formation.

Church and Hack (1939) regarded the basalt capping Cerro Pedernal as part of the Santa Fe Formation and cited several hypotheses concerning the former and present extent of the Santa Fe at the north end of the Jemez Mountains.

Beds in the San Acacia area south of Albuquerque were treated by Denny (1940a) in considerable detail. He correlated some of them with the Santa Fe Formation, but the fossils that he cited as evidence for correlation are lacking in the deposits of the type area and furthermore suggest late Pliocene or early Pleistocene. These rocks are probably nearer in age to the Gila Conglomerate of Arizona and southern New Mexico than to any rocks in the type area of the Santa Fe Group. Lithologically these beds near San Acacia should be described as a new formation, and many data can be adduced to show that the deposits named the Upper Buff Member of the Santa Fe Formation by Bryan and McCann (1937) should be included in the same Formation. Later, in the same year, Denny (1940b) made a reconnaissance of a part of the Santa Fe Group in the Espanola Valley in the type area. He briefly described the lithology and structure and speculated at length on the origin and source of the formation.

During 1941 the formations lying north of the Santa Fe Group received attention, and the Vallejo Formation was described and its relation to the Santa Fe beds was discussed by Upson (1941).

Stearns (1943) mapped the Galisteo Formation in the Galisteo-Tonque area and removed from the Santa Fe Formation large areas of Pleistocene and other deposits. Beds along the western edge of the Galisteo-Tonque area were mapped as part of the Santa Fe Formation, but the ages of these beds have not been proven.

Sayre and Livingston (1945, p. 39) referred deposits in the El Paso area, Texas, to the Santa Fe Formation and summarized Bryan's (1938a) work as evidence for the correlation.

Wright (1946) applied Bryan and McCann's system of division of the Santa Fe Formation to the Lower Rio Puerco area, the deposits of which he described in great detail. He presented extensive hypotheses relating to the source, mode of origin, transportation, and deposition of the Santa Fe Formation. Wright referred deposits in the Lower Rio Puerco to the Santa Fe Formation that the present writers believe should be included in other formations.

Butler (1946) mentioned the Santa Fe beds in his report on the geology of the Tusas-Tres Piedras area.

Simpson summarized the information known concerning the Santa Fe Formation, in Colbert et al. (1950), for a guidebook for the Fourth Field Conference of the Society of Vertebrate Paleontology. This was probably the first of a series of guidebooks for field conferences by various geological societies extending over a period of about 12 years. It is regrettable that some of the information in these guidebooks could not have been published widely and thus made more available to the general public.

Kelley (1952, p. 93) dealt with the tectonics of the Rio Grande depression, and some of his conclusions relating to the Espanola Valley and environs are discussed below in the section on Structure.

Two reports on the Galisteo-Tonque area were published by Stearns (1953a, 1953b) in which important new pre-Santa Fe formations were described and their relations to supposed Santa Fe beds were described in detail. The supposed Santa Fe beds in the Galisteo-Tonque area are discussed in this report under the heading Zia Sand Formation.

Montgomery (1953), working on Precambrian geology of the Picuris Range, mapped and described the relations of the Santa Fe beds in that locality.

A tectonic map by Kelley (1954) of a part of the Rio Grande area makes no pretense at separating pre-Santa Fe and post-Santa Fe faults, which leads to an exaggeration of the concept of the fault border of the Sangre de Cristo Mountains between Chimayo and Santa Fe.

In 1956, in a guidebook for the New Mexico Geological Society, Kelley gave his interpretation of some of the stratigraphy and structure of the Santa Fe type area. That guidebook also contained Baldwin's (1956) article in which he first proposed expanding the term Santa Fe to group status, and Montgomery's (1956) condensed remarks on the Picuris Range. McKinley (1956, 1957) dealt with Tertiary volcanic rocks to the north of the Santa Fe type area.

Larsen and Cross (1956), in a paper on the geology and petrology of the San Juan region, explored still further the relation between the volcanic rocks of the San Juan region and areas in northern New Mexico. Santa Fe beds were reported by Tonking (1957) in the Puertocito Quadrangle, but that correlation is questionable.

Disbrow and Stoll (1957), working in the Cerrillos area, added information concerning the beds underlying the Santa Fe and commented at length on the Ancha Formation about six years before the Ancha was formally proposed by Spiegel and Baldwin (1963).

Significant additions to the knowledge of the rocks underlying the Santa Fe were provided by Sun and Baldwin (1958).

Barker (1958), in the Las Tablas Quadrangle, correlated the Cordito Member of the Los Pinos Formation with the Santa Fe Formation.

Powell (1958), working in the San Luis Valley in Colorado, correlated a few small exposures with the Santa Fe Formation, but stated that (p. 20) "The Santa Fe Formation underlies almost all the San Luis Valley." He cited numerous well logs as penetrating Santa Fe beds to various depths, but also indicated that in some wells the top of the formation was not reached at 3645 feet, and, furthermore, he stated that the Santa Fe beds may exceed 5000 feet in thickness in the San Luis Valley. A hypothesis that these beds may, in fact, represent a distinct formation should be investigated. Moreover, they more nearly may be correlatives of beds in the adjacent Arkansas River valley a few miles to the north than to beds in the Espanola Valley more than 150 miles to the south.

The Bishop's Lodge Member of the Tesuque Formation and the Tesuque Formation were informally proposed by Baldwin (1956). The Bishop's Lodge Member was studied by Boyer (1959), who suggested that the member and the beds underlying it should be separated from the Tesuque Formation.

Miller and Wendorf (1959) presented evidence for an interpretation of the late terraces in the Tesuque Valley.

Budding, Pitrat, and Smith (1960), in the Guidebook of the New Mexico Geological Survey for the Chama River country, described additional areas of the El Rito Formation. They regarded the Abiquiu Tuff as a member of the Santa Fe Formation and correlated the upper part of the Abiquiu Tuff and the lower part of the Santa Fe Formation with the Los Pinos Formation in north-central Rio Arriba County, New Mexico.

Kelley and Clinton (1960, p. 53) reported that 9000 feet of Tertiary rocks were drilled in Humble Oil Company's Santa Fe No. 1 well on the Gabaldon anticline along the southwest side of the Albuquerque-Belen basin.

Kottlowski (1960) mapped the Santa Fe Group in the Las Cruces Quadrangle.

Another guidebook by the New Mexico Geological Society carried two useful articles on virtually unmapped areas. Spiegel (1961) suggested that two unnamed formations exist in the Santa Fe Group, in the Lower Jemez Creek region, but failed to name them. Cogent explanations of the relations of the volcanic rocks of the Jemez Mountains by Ross, Smith, and Bailey (1961) add greatly to the knowledge of the western border of the type area. A paper by Ross and Smith (1961) dealt exhaustively with ash-flow tuffs in general, and specifically with welded and nonwelded ash-flow tuffs of the Jemez Mountains (Valles Mountains).

A voluminous report on the geology and water resources of the Santa Fe area by Spiegel and Baldwin (1963) unfortunately covered only the extreme southern portion of the type area of the Santa Fe Group, as here restricted, and consequently only a small fraction of the beds were treated. The terms Santa Fe Group and Tesuque Formation were formally proposed. These, and various subjects covered in their paper, are discussed in detail under several headings in our report.

Miller, Montgomery, and Sutherland (1963) mapped beds in the Picuris area of the Sangre de Cristo Mountains and made observations on beds of the Santa Fe Group and on the Servilleta Formation.

Siems (1964) summarized the correlation of Tertiary strata in mountain basins in southern Colorado and northern New Mexico and, in so doing, emphasized, and occasionally compounded, the problems relating to correlations in the Santa Fe area.

Beds overlying the Santa Fe Group along the western border of the type area were described by Griggs (1964), and part of the beds correlated by Spiegel and Baldwin (1963) as the Santa Fe Group were separated as the Tewa Group.

Dane and Bachman (1965) published a generalized geologic map of New Mexico. Baltz (1965) attempted a correlation of rocks in the San Luis Valley of Colorado with those of the Santa Fe Group.

Albritton and Smith (1965) discussed beds in the Sierra Blanca area of Hudspeth County, Texas, and explored the possibility of correlating them with the Santa Fe Group, but understandably they were unwilling to do more than suggest a correlation.

Lambert (1966) included the Picuris Tuff, Tesuque Formation, and Servilleta Formation in the Santa Fe Group in the Taos-Questa area and directed attention to several sets of younger sedimentary rocks.

The Zia Sand Formation in the Jemez Creek area was described by Galusha (1966).

Bingler (1968) treated Cenozoic rocks quite briefly in his study of the geology and mineral resources of Rio Arriba County and expressed the opinion (p. 38) "that the lower 300 feet of Precambrian clast gravel included in the Abiquiu Tuff are the lateral equivalent of the Ritito Conglomerate and that the upper 1000 feet of conglomerate represent the southwestern extension of the Los Pinos Formation." The Santa Fe beds were treated as a formation, not as a group, and were said to intertongue with the Los Pinos Formation east of El Rito Creek through Ojo Caliente, La Madera, and Servilleta Plaza.

The recently published circular on the Santa Fe Group in the south-central New Mexico border region by Hawley and others (1969) summarizes the current knowledge of the beds that are included in the Santa Fe Group in southern New Mexico and parts of west Texas and northern Chihuahua, Mexico. In our opinion an unbiased analysis of the data and arguments presented in the circular will show that the report is its own best unintentional advocate for the proposal to separate the deposits of the border area from those of the type area of the Santa Fe Group. Obsolete terms such as Herrick's (1898) "Rio Grande Series" or "Rio Grande Gravels," or Bryan's (1909) "Rio Grande Beds," should be seriously re-examined for possible change in rank to Rio Grande Group as an appropriate name to receive the deposits of the border area.

The Bailey, Smith, and Ross (1969) report on the stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico, as was the Hawley circular listed above, arrived too late to be included in the discussions in our report, but it contains new and important information, particularly pertaining to radiometric dates of volcanic rocks cropping out in areas contiguous to the type area of the Santa Fe Group.

During the past hundred years the Santa Fe marls have become known as the Santa Fe Formation and finally as the Santa Fe Group. The concept of Santa Fe has grown from the original type area to encompass any late Tertiary or Pleistocene volcanic or sedimentary beds in the Rio Grande trough, a distance of 1800 miles.

## WORK BY THE FRICK LABORATORY

Paleontologic and stratigraphic work that extends over years of intensive investigation of any specific area can result only from a well-planned program carried out with vision and tenacity of purpose. A history of the work of the many Frick Laboratory field collectors since 1924 who have labored in the Santa Fe area can be deciphered partly from a search of the archives of the Frick Laboratory. These archives are composed primarily of the carefully preserved copies of Childs Frick's letters to the leaders of his field parties, and the equally complete files of their replies, reports, maps, diagrams, photographs, and specimen lists covering their work.

Frick's decision to start work in the Santa Fe area was a direct result of his recognition of remains of the genus *Hemicyon* Lartet in the Frick Collections from the Barstow beds of southern California; *Hemicyon* had been found previously only in Europe. He then recognized that a fragment of mandible that Cope had obtained in the Santa Fe Marls in New Mexico in 1874 and had called *Canis ursinus* was really *Hemicyon*. A short trip to natural history museums in Paris and Lyon, France, confirmed his identification. On his return to the United States he asked W. D. Matthew, who then was leading an expedition for the American Museum of Natural History in Texas, to undertake a survey of the Santa Fe area in the hope that additional *Hemicyon* material might be found. Matthew sent his assistant, G. G. Simpson, and Charles Falkenbach, to the area; within five days Simpson and Falkenbach had discovered the only *Hemicyon* skeleton that has been found in the Santa Fe area.[1]

The *Hemicyon* skeleton figured prominently in a report by Frick (1926a) on the Hemicyoninae and an American Tertiary bear, in which he succinctly stated a philosophy for collecting fossils, a philosophy to which he closely adhered throughout the remainder of his life (p. 19): "Curiously enough this was the one and only specimen of *Hemicyon* found during some nine weeks in the field. This splendid and unique trophy, which the storms and disintegration of another season might have utterly destroyed, has greatly increased our knowledge of this

[1]One additional partial skull of *Hemicyon*, and a few isolated jaws and teeth, are all the remains of that genus that have been collected under prolonged and intensive search in the area since 1924.

Fig. 4. General view of part of Espanola Valley looking slightly south of west from a high ridge south of Chimayo, New Mexico. White Operation Wash drains beds in foreground and enters Santa Cruz River in right middle distance near line of trees, marking course of Santa Cruz River near its mouth on Rio Grande at Espanola, New Mexico. Rio Grande flows from right to left in valley (above center of photograph), passing through Espanola and along farther side of Round Mountain (left). Santa Clara Canyon was cut through well-marked terrace underlain by Puyé Conglomerate west of Rio Grande (just left of town of Espanola). Nambé Member of Tesuque Formation underlies foreground and covers about half of photograph. Red Wall is prominent bluff (slightly above center, extreme left), and No. 1 White Ash stratum at its base marks start of Skull Ridge Member of Tesuque Formation. Skull Ridge Member is shown by belt of cliffs on each side of White Operation Wash. Pojoaque Member of Tesuque Formation, somewhat less rugged than Skull Ridge Member, lies beyond it. North Pojoaque Bluffs lie at extreme left, just below and almost in line with Round Mountain. Across the Rio Grande, sloping surface of Puyé Conglomerate shows plainly; highlighted promontories of overlying Bandelier Tuff in left two-thirds of photograph visible along base of Jemez Mountains. Thickness of Bandelier Tuff increases toward south (left); that of Puyé Conglomerate decreases toward south. Battleship Mountain is prominent bluff right of and slightly above Round Mountain. Tschicoma Peak is snow-capped peak on right skyline; Abiquiu Peak is at extreme right.

genus, the characters of the skull and skeleton of which have heretofore been unknown.

"The recent recognition of *Hemicyon* in America illustrates the danger, in the present state of paleontological knowledge, of too greatly stressing the absence from any particular fauna of any particular species, as well as the great need of active and sustained field work in old as well as new localities. For only by the continued collection of the remains of the life of the past, as brought to the surface through the seasonal erosion of ancient accumulations of sand and clay, data available today and gone forever tomorrow, may we learn the history of nature's course in the production of existing forms, of those that were in the broad sense ancestral to the faunas of today, and of those strange and unthought of forms that predominated in and vanished with the faunas of the past."

Owing to the excitement generated by the discovery of the *Hemicyon* skeleton, Frick transferred his then main collector, Joseph Rak, to Santa Fe; hence, within five weeks of Simpson and Falkenbach's arrival in the Santa Fe area, two fossil collecting parties were hard at work. Rak remained in the field six weeks longer than Simpson and Falkenbach and was successful enough that Frick sent him back to the Santa Fe the following spring, thus establishing a collecting pattern that continued with scarcely a break for more than 40 years.

During the 1925 field season Frick twice visited the Santa Fe field and for several years thereafter made an annual visit to the area. During this first full year of work Rak had Charles Christman of the American Museum as an assistant. Frank Naranjo, the first Santa Clara Indian assistant, was also hired, setting a precedent for later Frick Laboratory parties, for many of the Santa Clara men became excellent fossil hunters and several of them were hired year after year. The greatest number of Indians that worked at one time was nine in 1927.

By 1926 Frick began requiring more precision in designating the localities from which specimens were collected and further expanded the requirements of field correlations within the area. In addition to the report on the Hemicyoninae, Frick (1926c) published a popular account of the geology and paleontology of the Santa Fe area. This was the era in which the Santa Fe beds were an essentially virgin field for fossil collecting, not having been prospected since the E. D. Cope expedition of 1874. The great collection of mastodont specimens from the Santa Fe, made primarily by the Joseph Rak party, formed a large part of two reports on the mastodonts by Frick. One of these (1926b) concerned the tooth sequence of certain trilophodont-tetrabelodont mastodonts, and the other (1933) described new remains of trilophodont-tetrabelodont mastodonts. These two reports were considered by Frick to be contributions to the information being amassed by Osborn as a basis for the latter's (1936) monograph on the Proboscidea.

Two of Joseph Rak's early maps are reproduced (figs. 5, 6). These were made before adequate base maps were available and, although not drawn to scale, present a reasonably faithful reproduction of the actual topography as it would be seen in the field. Charles Falkenbach joined Rak's party in 1926 and was later to work in the Santa Fe area intermittently during the next 25 years.

The Red Layers of the Santa Cruz locality were worked extensively in 1927, and the field party of 11 men made a very large collection. Much attention was given to geology and stratigraphy as was shown by the exchange of letters for the year.

In 1928 Frick first brought John C. Blick, who had been collecting at Keam's Canyon in Arizona, to the Santa Fe area to join Joseph Rak. Blick was later to take full charge of the Santa Fe field, but, as part of Frick's policy of continuity of field work, Blick worked with Rak for several years. 1928 was the year in which the first of several sites and small quarries were discovered in beds that are now called the Chamita Formation.

Rak had an able young assistant, Jack Wilson, working with him in the Barstow beds of California and during the 1929 summer season took Wilson with him to Santa Fe. The following year, 1930, Rak put Wilson in charge of actual field work, although he retained supervision. Rak had developed serious foot trouble, which prevented further field work and finally culminated in his death from multiple tuberculosis on August 17, 1932. Jack Wilson remained in charge of collecting through 1931. No work was done in the Santa Fe area in 1932, ostensibly because the collectors were busy in other fossil fields from which information was urgently needed.

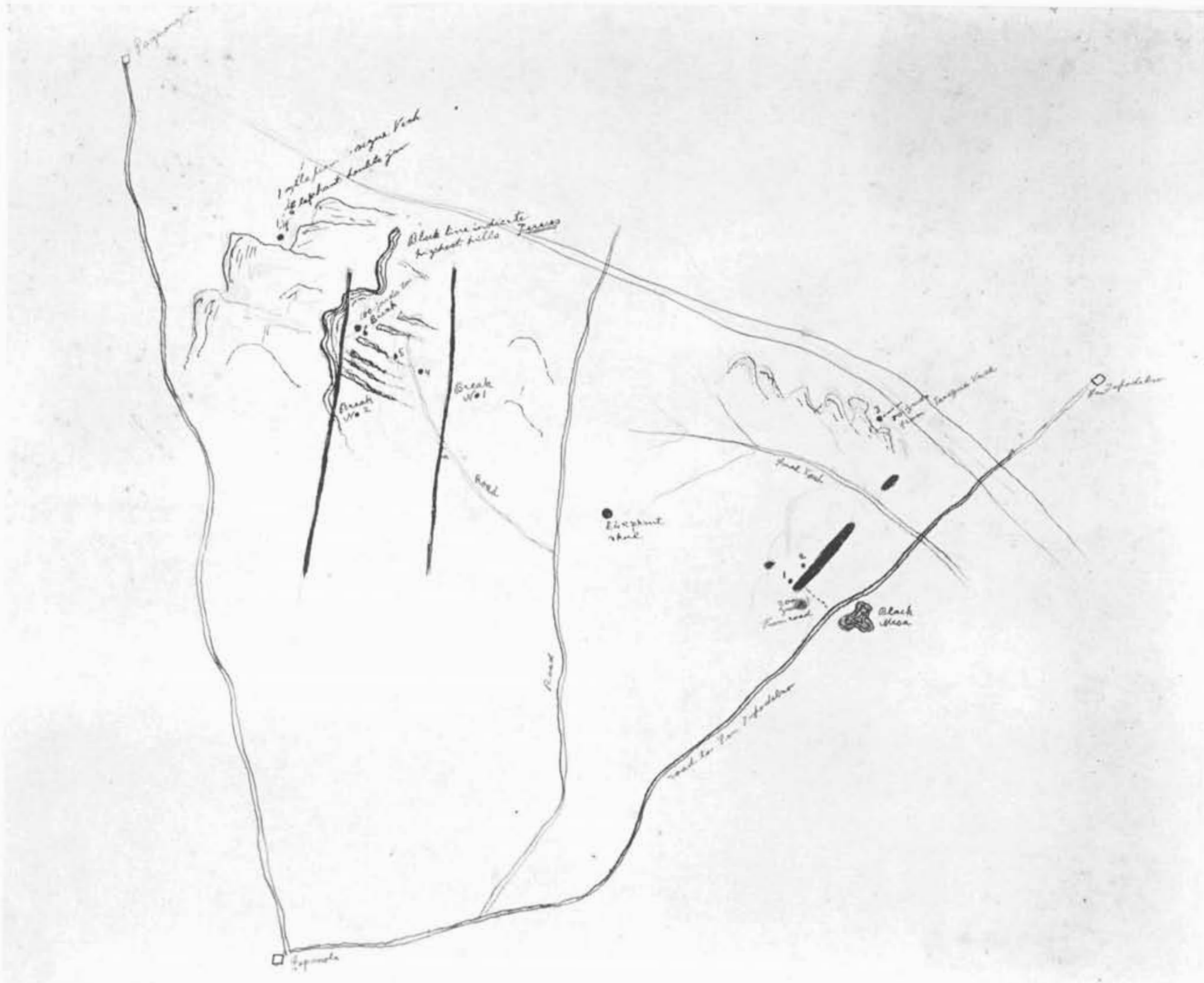



FIG. 5. First map of Espanola fossil-collecting area drawn by Joseph Rak, in 1924, shortly after start of work by the Frick Laboratory. Highest hills at left are the central Pojoaque Bluffs (United States Geological Survey: Los Barrancos).

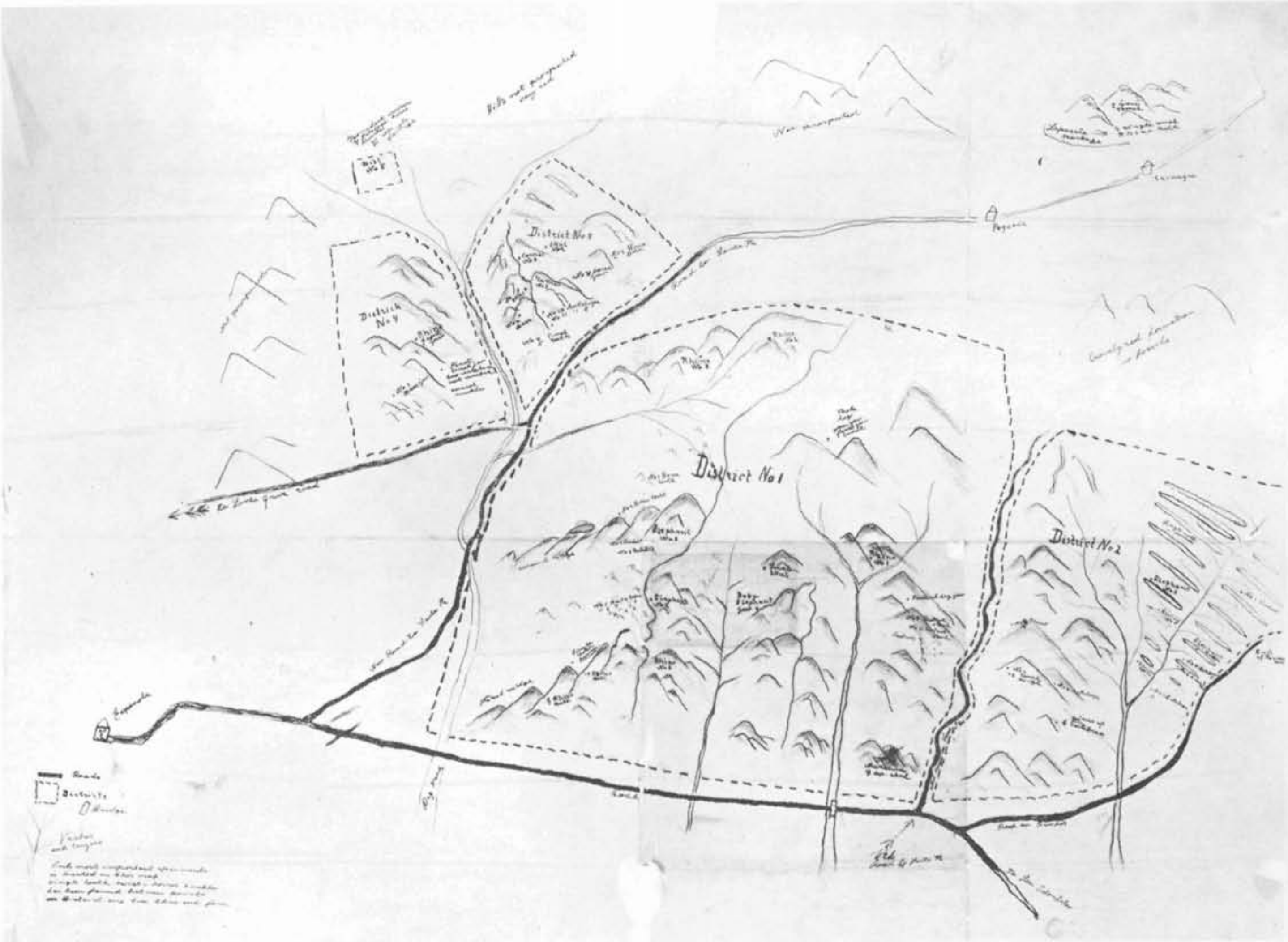


FIG. 6. Map of Espanola area drawn by Joseph Rak at end of 1924 collecting season. Area was divided into districts to aid in locating specimens in the field.

John C. Blick assumed control of the Santa Fe field party in 1933 and began an extensive study of the structure and stratigraphy of the area; these studies continued through 1934. Blick became ill in 1935, and consequently Charles Falkenbach was transferred to the area accompanied by his assistant, Everett De Groot. Falkenbach and De Groot continued to lead parties in the area in 1936; during this period most of the work in the Round Mountain Quarry was done. Views of the early stripping in this quarry are shown in figure 8. Blick drew a map of the area in 1936, which is shown in figure 7. Blick returned to the field for a few weeks in early 1937 but soon left to collect Pleistocene fossils near Fairbanks, Alaska, leaving Everett De Groot in charge, although Falkenbach and William Klaus also sent in material that year. Klaus had worked with Blick in various fields since 1933 and was in charge of Santa Fe operations from 1938 through 1941 whenever Blick was not in the field. In 1937 Frick published his monograph on the horned ruminants of North America, in which he recognized or described 17 genera, subgenera, or species of the Cervidae and the Antilocapridae, and also two genera of the Camelidae, from the Santa Fe area, New Mexico.

Frick decided to begin intensive work on the geology and stratigraphy of the Santa Fe beds, as well as carry on the usual collecting activities, and accordingly, by 1940, Ted Galusha was transferred from the Hay Springs, Nebraska, field to work with Blick on the stratigraphy of the area. Blick and Galusha continued to work on the geology through the 1941 field season and the early part of the 1942 season. Blick then left the field, leaving Galusha in charge of collecting and the study of the geology.

The first of Schultz and Falkenbach's studies of various subfamilies of oreodonts was published in 1940. This series was recently completed (1940, 1941, 1947, 1949, 1968) and has included descriptions of several new forms, together with brief remarks on the biostratigraphy of the Santa Fe beds based on the oreodonts.

No work was done in 1943 in the Santa Fe area, but in 1944 and 1945 Blick, Falkenbach, and George Sternberg collected a few fossils. On November 1, 1945, Galusha returned to the Santa Fe field to work on geology and resumed leadership of the fossil collecting party as well. Blick remained actively interested in the geology and made annual visits until 1955, two years before his death. He generously shared his field observations with Galusha, and these observations formed the bases for many of the early working hypotheses on the geology and stratigraphy of the area. Galusha has continued to work in the Santa Fe area to the present time and is responsible for the compilation, organization, and interpretation of the field data, and for the writing of this report, which is only a digest of a small part of the amassed information.

An analysis of the work by the Frick Laboratory in the Santa Fe beds emphasizes several salient features, with perhaps the most outstanding being Frick's profound and unflagging interest in the paleontology, stratigraphy, and general geology of the area—an interest sufficiently great to span a period from 1924 to his death in 1965. This interest was so keen that even lean months or years of collecting could not cause him to abandon the field. The search for new, additional, or better material from stratigraphically controlled collections was the aim of Frick Laboratory field parties, especially after 1940, and much work was done on unproductive or nearly unproductive horizons in attempts to fill gaps in the biostratigraphy. No other fossil field has had a more sustained investigation than that of the Santa Fe area, nor has any fossil field had a more carefully controlled continuity of field work.

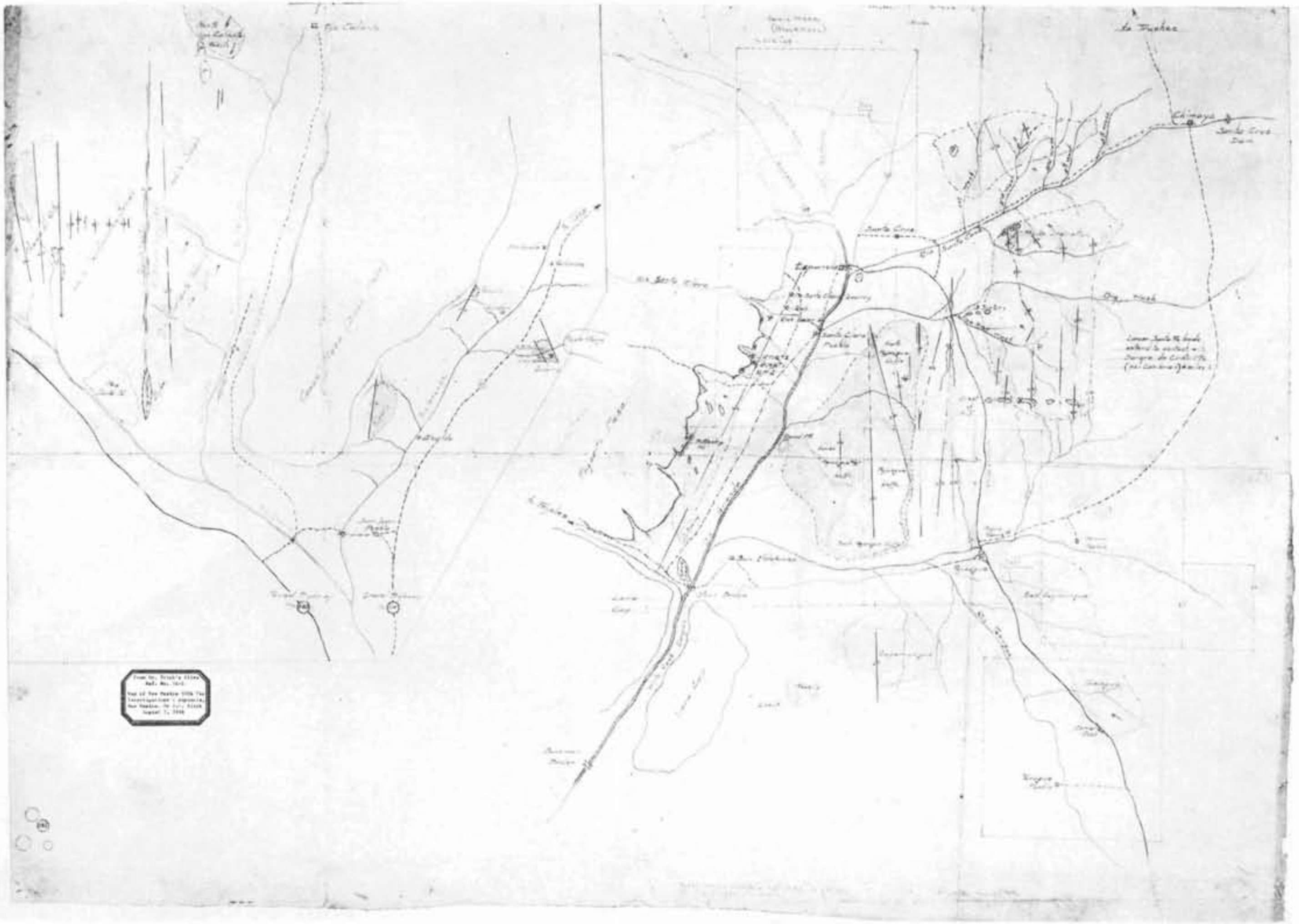

FIG. 7. Two-part map of Espanola area drawn by John C. Blick in 1936. Inset at left shows an area lying north and northwest of that on main part of map. Reference points for the two parts are San Juan Pueblo, confluence of Rio Chama and Rio Grande, and southwestern tip of Black Mesa.


FIG. 8. Round Mountain Quarry. A. Excavation at Round Mountain Quarry in 1936. Boulders on slope at left are latite and porphyritic latite eroding from Puyé Conglomerate. B. Productive fossil layer at Round Mountain Quarry (X). William Klaus, party leader, second from right, is standing at contact of Chamita Formation with overlying Puyé Conglomerate; contact can be seen clearly just above light-colored strata (midway in photograph).

# STRATIGRAPHY

THE STRATA OF THE pre-Santa Fe Group appear to include the first of the Tertiary system deposited in the Rio Grande depression, which is a complex series of structural depressions first recognized by Lee (1907) but named by Bryan (1938, p. 197). Beds in this division that crop out in the type area of the Santa Fe Group are the Galisteo Formation (Hayden, 1869) and the El Rito Formation (Harold T. U. Smith, 1938). Beds outside the type area that may belong in this grouping are those described by Upson (1941) as the Vallejo Formation of the easternmost re-entrant of the San Luis Valley in Colorado. The Baca Formation was described by Wilpolt et al. (1946) who stated, "It is quite possible that the Baca formation is correlative with the Galisteo sandstone (Tertiary) of the Galisteo basin, for lithologically they are similar." The age and correlation of the McRae Formation have not been firmly established, although Cretaceous dinosaur material has been found in the lower part of it, but Kelley and Silver (1952) chose to separate it as a new formation rather than to include it in the Baca as proposed by Wilpolt et al. (1946).

Another recognizable broad grouping of beds overlies the El Rito and Galisteo formations and is composed predominantly of tuff or other volcanic debris. Three formations in this second grouping are recognized in the type area of the Santa Fe Group, i.e., the Abiquiu Tuff (Harold T. U. Smith, 1938), Picuris Tuff (Cabot, 1938), and the Espinaso Volcanics (Stearns, 1953b). The Popotosa Formation (Denny, 1940a) of the Socorro area may belong in this division. The upper part of the Datil Formation of Winchester (1920) may also be equivalent. The third division contains one formation, the Zia Sand Formation (Galusha, 1966), comprised of two members. The lower or Piedra Parada Member produced the first early Miocene (Arikareean) fauna reported from New Mexico. The upper or Chamisa Mesa Member contained early medial Miocene fossils of approximately Hemingfordian age.

In this report most of these formations are discussed under separate headings.

We propose to restrict the term Santa Fe Group to those deposits that crop out in the classic type area of the Santa Fe marls of Hayden (1869) and Cope (1875a). Bryan (1938, p. 205) stated that these beds had become generally known as the Santa Fe Formation and then added "the main body of sedimentary deposits of the Rio Grande depression, from the north end of the San Luis Valley to and beyond El Paso, is considered to be of the same general age and to belong to the Santa Fe formation." Denny (1940b, p. 678) designated the type area of the Santa Fe Formation as "the region north of Santa Fe, New Mexico, between the Sangre de Cristo and Jemez Mountains." Moreover, he recognized that the unconsolidated deposits in the Rio Grande depression were divisible into several formations, both above and below the Santa Fe Formation. His observations were disregarded by Spiegel and Baldwin (1963, p. 38) who proposed "that the term Santa Fe be raised to group status, and that all the basin fill, whether Tertiary or Quaternary, be included in the Santa Fe group." In addition they further extended the term (p. 39) to include additional concepts as follows: "Therefore, the Santa Fe group is here considered to be a broad term including sedimentary and volcanic rocks related to the Rio Grande trough, with a range in age from middle(?) Miocene to Pleistocene(?)."

As restricted by the present writers, the Santa Fe Group is comprised of two formations: (1) the Tesuque Formation and (2) the Chamita Formation (new name).

The Tesuque Formation was formally proposed by Spiegel and Baldwin (1963, pp. 39–40), but that formation in the present report has been restricted and redefined and now has five members: (1) the Nambé Member, (2) the Skull Ridge Member, (3) the Pojoaque Member, (4) the Chama-el rito Member, and (5) the Ojo Caliente Sandstone. A section of this report is assigned to a discussion of each of the members of the Tesuque Formation and includes the details of the rock-stratigraphic and biostratigraphic evidence.

The uppermost formation of the Santa Fe Group, as restricted in this report, is the Chamita Formation. The beds of this formation are lithologically and faunistically distinctive and appear to represent deposits that accumulated through a large portion, but not all, of medial Pliocene time (Hemphillian).

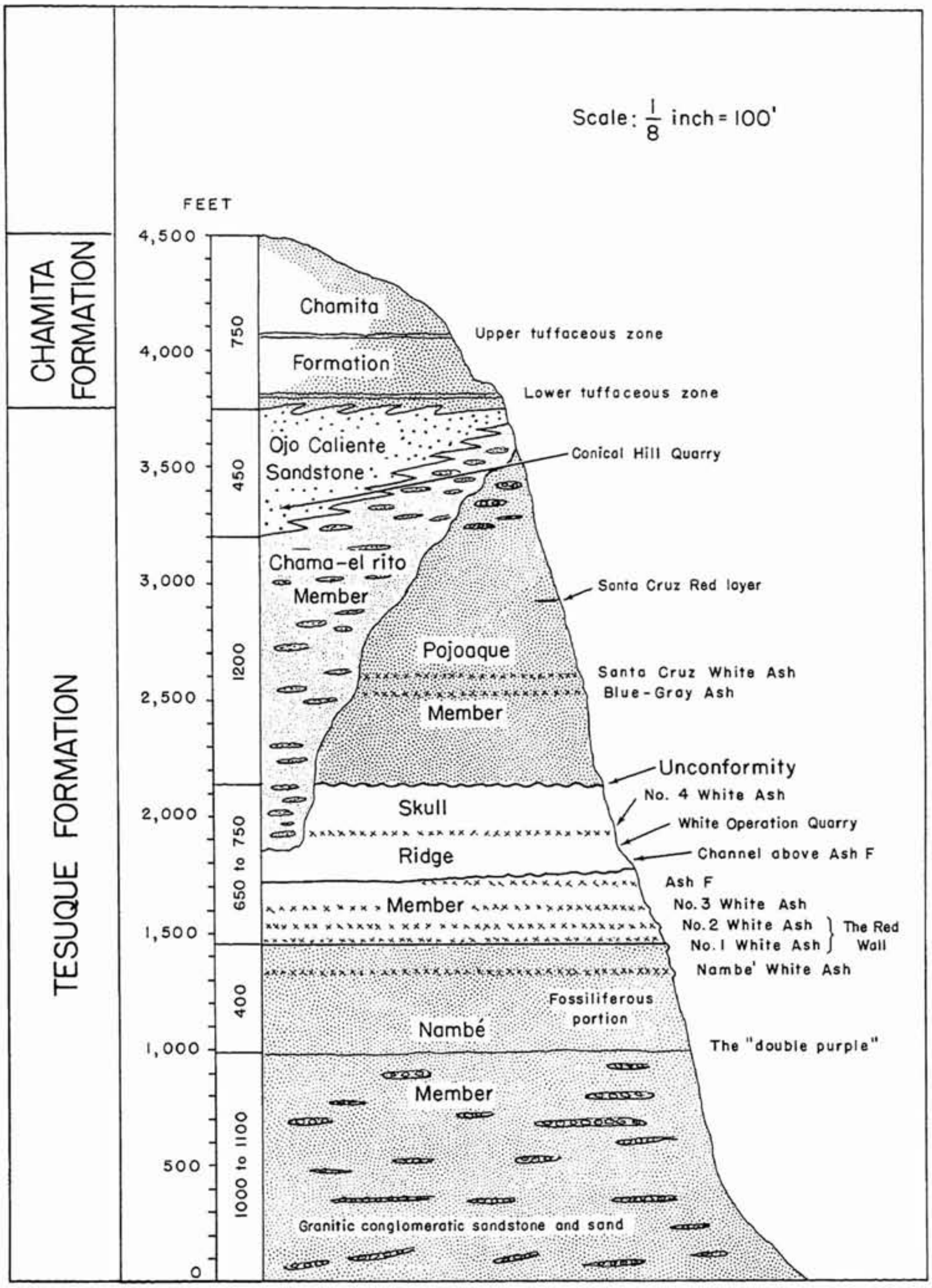


FIG. 9. Composite stratigraphic section and correlation chart of Santa Fe Group. Some of the main ash beds and important stratigraphic horizons are shown. Approximate age relations and thicknesses of strata are included.

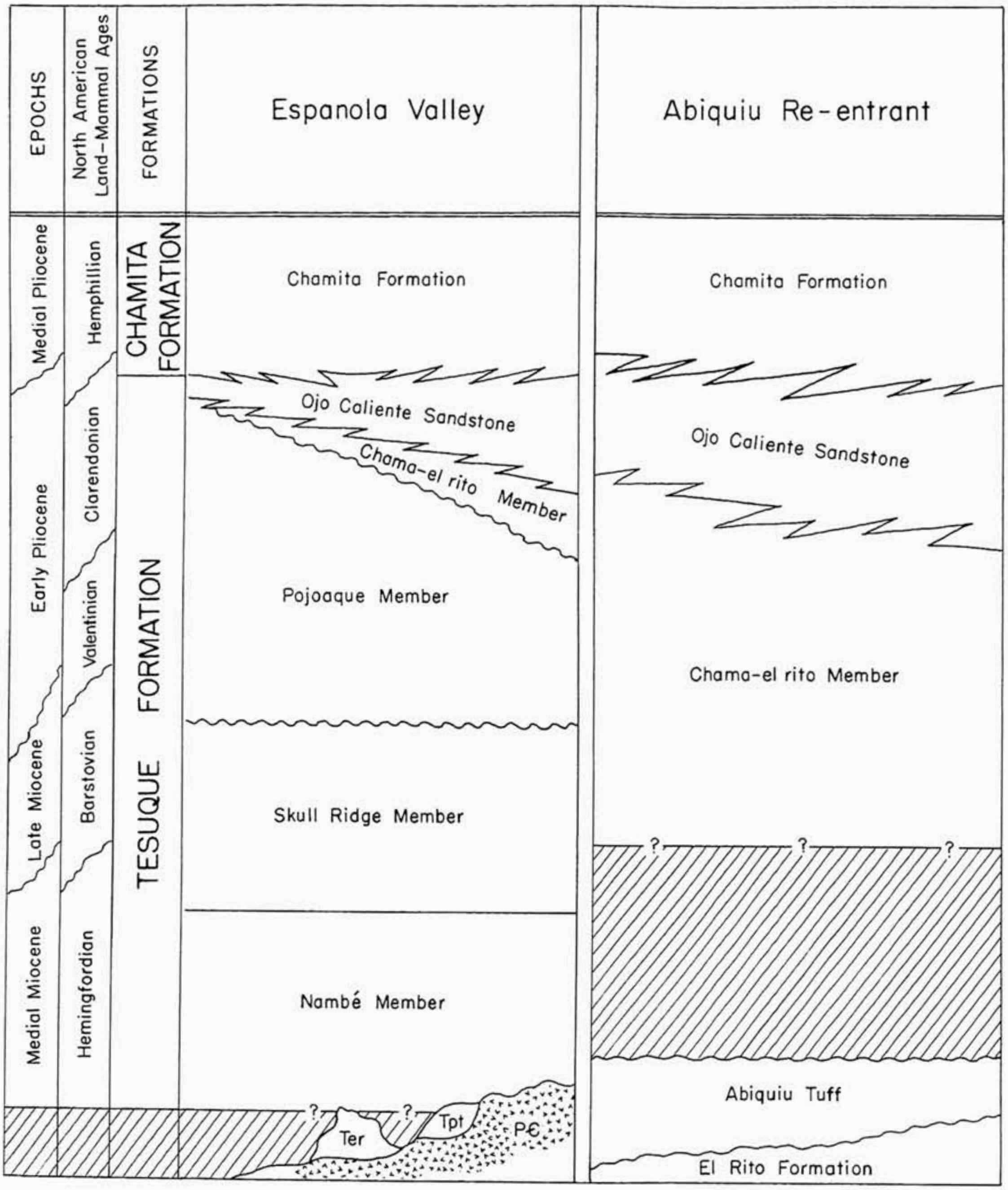


FIG. 10. Correlation diagram showing stratigraphic relations of members of formations of Santa Fe Group in Espanola Valley compared with those of Abiquiu re-entrant. Tpt, Picuris Tuff; Ter, El Rito Formation. Age relations of various members are shown on two geologic-time scales.

The Pleistocene and Recent formations that are exposed in the type locality of the Santa Fe Group are diverse lithologically and commonly are of small extent; however, the small area covered by each of these formations is hardly an index to its importance in the geologic sequence. These post-Santa Fe Group formations include a wide variety of deposits. The diversity of these later deposits, even in the type area of the Santa Fe, emphasizes the utter confusion that would result if these were to be included in the Santa Fe Group. Discussed in this report in appropriate sections are the following: (1) Puyé Conglomerate, (2) Ancha Formation, (3) deposits on erosion surfaces, (4) Zia Marl, (5) Servilleta Formation, (6) Espanola Formation, (7) varved or rhythmical sediments, (8) Otowi Lava Flow, (9) Bandelier Tuff, (10) Cerros del Rio lava flows, (11) high-level basalts, (12) volcanic rocks, (13) Rio del Oso dikes, and (14) Round Mountain.

In the present state of the investigation, an accurate correlation of events and deposits corresponding to the Glacial and Interglacial stages of the Pleistocene is not possible, but evidence exists in this area and adjacent ones which if properly integrated may lead to surprising results.

If the mappable formations that crop out along nearly 1800 miles of the Rio Grande depression were all considered a part of the Santa Fe Group, the only characteristics they would have in common would be that some of them would be classified as conglomerate, conglomeratic sandstone, silty sandstone, siltstone, and some clay or claystone. Not even color could be pressed into service as an aid in correlation. The beds along the Rio Grande depression were deposited in separate basins, as pointed out by Lee (1907) and elaborated later by Bryan (1938). These deposits were derived from different source rocks, at different times, and were obviously laid down in a great variety of sedimentary environments. Distinctive lithologic characteristics rarely can be correlated between these basins, and heterogeneity cannot be cited logically as a basis for correlation, inasmuch as many of the supposedly unfossiliferous beds can be shown to have been deposited at widely different times. These disparities emphasize the need to use every available tool in correlating late Tertiary and Quaternary formations, and the beds of the Santa Fe Group and contiguous beds in particular.

Fossils have not been used as criteria for defining the formations of the Santa Fe Group in this report. Fossils have been, however, a most useful tool for our determining in which portion of the geologic section intensive search should be made for observable physical features that would serve as a basis or foundation for the study of the stratigraphy of the group. Inasmuch as fossils were used as guides to the recognition of useful boundaries that are meaningful for rock stratigraphic work, it should be apparent at once that fossils should be utilized further, wherever possible, to add the necessary verification of stratigraphic position. To do otherwise is to accept such premises as that it is impossible to assemble a type section (Spiegel and Baldwin, 1963, p. 39), or to present a complete stratigraphic column (Denny, 1940b, p. 680) because of faults and variability of the beds, or to know whether the fauna comes from the base or the top of the formation (Bryan, 1938, p. 205). We do not accept these premises, but hereinafter present many data drawn from rock-unit and biostratigraphic-unit sources, seeking to provide a balanced explanation of the geology, stratigraphy, and some of the broader aspects of the biostratigraphy of the Santa Fe Group.

## PRE-SANTA FE GROUP TERTIARY FORMATIONS

### EL RITO FORMATION

The name El Rito Formation was applied by Harold T. U. Smith (1938, p. 940) to a narrow belt of brick-red deposits along the northwestern edge of the Rio Grande depression in the Abiquiu Quadrangle. The formation consists of well-consolidated sandstone, conglomerate, and breccia, in which quartzite pebbles are dominant and the maximum thickness is 200 feet. As pointed out by Smith, the rock is so well consolidated at many localities that it will break across the fragments and pebbles rather than around them. The principal localities, as given by Smith, are: in the Ortega Mountains, along both branches of El Rito Creek, in the badlands west of Cerro de las Minas, on the north bank of the Chama about 5 miles west of Abiquiu, and in the vicinity of Cañones. Other localities were cited as cropping out along Arroyo Hondo about 4 miles south of the town of Santa Fe and along little Tesuque Canyon 5 miles northeast of Santa Fe.

We have found one exposure of the El Rito Formation in the vicinity of Chimayo, New Mexico, where the El Rito deposits crop out in a short wash on the south side of the Santa Cruz River less than 1 mile below the mouth of the Rio Quemado. The beds preserved at this point are remnants of a small fault block bounded on the east by the finer sediments of the Tesuque Formation of the Santa Fe Group, and on the west by predominantly coarse, reddish to light sand in which pebbles and cobbles are numerous. Small, terraced, irrigated fields surrounding the low ridge of El Rito sediments effectively prevent lateral tracing of the exposure. The low ridge is not more than 15 to 20 feet high and less than 300 feet long. More than 50 small to very large blocks of dark to bright red conglomerate of jasperoid appearance are associated with this ridge of sediments. Some of the blocks are larger than 15 feet long, 15 feet wide, and 6 feet thick. The rock breaks smoothly across quartzite pebbles and finer-grained matrix. The coarser clastics had been originally stratified, and the bedding planes are well marked on weathered surfaces on which the rounded quartzite pebbles and cobbles stand out in sharp relief. These large blocks indicate that they had been undercut in approximately their present position and then slumped to their present attitude. No block was observed to be resting on an original bedding plane.

A comparison of samples of sediments from the locality near Chimayo with samples from sites near El Rito, New Mexico, and near Abiquiu shows close adherence to the general lithologic pattern of the type El Rito Formation. The Chimayo samples, however, are finer-grained; the conglomerate is more dense, with smaller pebbles, but all other characteristics appear common to the three localities, such as those cited by Smith (1938, p. 940) as being dominantly composed of quartzite pebbles with volcanic material absent, deep red stain, and being so well cemented that it breaks across rather than around the fragments and pebbles.

The age of the El Rito Formation is uncertain, for no fossils have been reported from it. Smith (1938, p. 958) placed it as "at least pre-Upper Miocene, and conceivably it may even be as old as Eocene." The El Rito seems to be the first unit in the Abiquiu area deposited subsequent to the faulting that formed the original Rio Grande depression. In the area immediately south of Santa Fe, New Mexico, this same relation is shown by the Galisteo Formation. Stearns (1953b, p. 468) correlated with his Espinaso Volcanics certain red conglomeratic beds in Arroyo Hondo that Smith (1938, p. 943) cited as typical localities of the El Rito Formation. These beds are regarded by the present writers as part of the red-bed phase of the upper part of the Galisteo Formation. The red-bed phase of the Galisteo Formation that crops out along the escarpments southwest of Lamy, New Mexico, and along United States Highway 85 at La Bajada Hill suggests a close similarity between the El Rito Formation and the upper part of the Galisteo Formation. The La Bajada Hill red beds also were mapped by Stearns (1953b, pl. 1) as Espinaso Volcanics, and consequently a continuity of correlation is suggested by several workers for this series of beds. Spiegel and Baldwin (1963, pp. 37, 38) differed from both Smith and Stearns in their interpretation of the beds in Arroyo Hondo. The El Rito Formation was extended by Budding, Pitrat, and Smith (1960, p. 82) to additional areas along El Rito Creek and in valleys east of Arroyo del Cobre, east of Madera Canyon, and near the crest of Magote Ridge. They present alternative explanations of the origin of the red matrix to that presented by Smith, Stearns, and others.

## GALISTEO FORMATION

Variegated sand and sandstones along the valley of Galisteo Creek near Los Cerrillos, New Mexico, were described by Hayden (1869, pp. 40, 67, 90) as the Galisteo sand group and assigned by him to the middle Tertiary. Lee and Knowlton (1917, pp. 184, 185) discussed the relations of the Galisteo sand and suggested that it might be correlative with the Wasatch. Previously the Galisteo sand had been considered Triassic by Cope, and Cretaceous by Stevenson, Johnson, and others. Darton (1928b) mapped the Galisteo Sandstone as part of the upper Cretaceous Montana Group but noted that it was probably early Tertiary in age (p. 52). Stearns (1943, p. 301) redefined the formation and mapped it in greater detail than had any previous investigator. Stearns (1953b), in a later report, greatly increased the detail of his geologic map and speculated at length on the basins of north-central New Mexico and the part the Galisteo basin and its deposits played in the geologic history of the region. Unfortunately, out-of-register color patterns make unclear the exact contact between the Galisteo and the overlying Espinaso Volcanics in the critical area along State Highway 10 in and adjoining the old Sweet's Ranch east of Los Cerrillos, New Mexico. From this general locality, Robinson (1957) reported a *Coryphodon* molar that indicated an early Eocene age for some of the lower beds. Stearns (1943, p. 310) reported the first mammalian fossils from the formation, and these were interpreted as Duchesnean in age. There is no general agreement among paleontologists and geologists as to whether the Duchesnean should be considered latest Eocene or earliest Oligocene. In any event, the Galisteo Formation, on present evidence, appears to have been accumulating during most, if not all, of the Eocene Epoch.

A small collection of mammalian fossils made by the Frick Laboratory in and near the "petrified forest" on Sweet's Ranch, east of Los Cerrillos, New Mexico, and also south of Galisteo Creek southeast of the ranch are of late Eocene aspect. On the evidence now available, a late Eocene age is indicated for a large part of the uppermost beds of the Galisteo Formation.

The Galisteo Formation is composed of fluviatile deposits including sandstone, sand, conglomerate, clay, limestone, and water-laid tuff. Silicified wood is abundant in many beds of the formation, and at a few localities (notably Sweet's Ranch) large, horizontally lying logs are fairly numerous; however, smaller fragments scattered over the exposures are more typical. Lee and Knowlton (1917) and Stearns (1943, p. 308) described and figured Galisteo beds near Hagan, an abandoned mining camp in the Tonque Wash area at the northeast end of the Sandia Mountains.

In the Jemez Creek valley south of the town of San Ysidro we discovered a new locality of the Galisteo Formation. The correlation is based on lithologic similarity; the presence of silicified wood, a few logs of which measured more than 20 feet in length; and mammalian fossil content. In the new locality silicified wood is fairly abundant and is confined mostly to beds of yellowish and white cross-bedded coarse sand. Conglomerates are not so prevalent as in the type locality near Cerrillos, and in general the beds are softer, with slightly different weathering characteristics. Red, green, yellow, and brown colors predominate in the section. These beds were mapped by Renick (1931, p. 308) and referred by him to the Lower Wasatch, and are exposed only between the Sierrita fault and the Jemez fault. The small collection of fossils from these beds consists of the skull, mandible, parts of several rami, and other skeletal parts of a titanothere, and a few fragments of teeth and bones of other mammals.

Brick-red and maroon clay and sandy-clay beds crop out southwest of Lamy, New Mexico, and along Highway 85 at La Bajada hill. Thin beds of white sandstone are commonly associated with these red beds. As mentioned above in the section on the El Rito Formation, we regard these red beds as a part of the upper beds of the Galisteo Formation. Disbrow and Stoll (1957, p. 11) also suggested that the El Rito Formation may be correlative with the Galisteo Formation. The exposures of the El Rito Formation at Chimayo, New Mexico, and at Arroyo Hondo, south of Santa Fe, support the hypothesis that the El Rito Formation and the Galisteo red-bed phase are probably equivalent. Fossils are few in the red-bed phase of the Galisteo, and to date none have been reported from the El Rito, but eventually fossils may be found in both and provide the biostratigraphic information needed to supplement rock-stratigraphic data.

The Galisteo beds of the Pajarito fault wedge, which is situated at the base of St. Peter's Dome (Ross, Smith, and Bailey, 1961, p. 140), contain lenses of cobbles in which occasional boulders as much as 4 feet in diameter have been observed. These cobbles are of limestone, quartzite, granite, gneiss, sandstone, and other rocks. They are not so densely packed nor are they so firmly held by the red-stained matrix as is characteristic of the El Rito Formation in its type locality. The boulders are larger than any noted by the writers in the Galisteo Formation or in the Espinaso Volcanics, but are not so large as some in the El Rito Formation. At this locality the Galisteo beds dip westward at a high angle and are estimated to be more than 200 feet thick; they display characteristics that are reminiscent of both the El Rito Formation (Harold T. U. Smith, 1938) and the red-bed phase of the

Galisteo Formation. That these characteristics occur in the same sequence of beds we believe provides proof of the equivalence of at least part of the two formations, and marks this as a significant, if not critical, outcrop of the Galisteo Formation. A yellowish set of sandstone and cobble-conglomerate deposits lies with strong angular unconformity on some of the red beds. The matrix between the cobbles is relatively fine and suggestive of Galisteo lithology, although a similar fine, but red instead of yellowish, matrix has been observed locally in the El Rito Formation in the Abiquiu area.

The coarse beds of the Pajarito fault wedge suggest the interesting hypothesis that a major source of the Galisteo sediments lay to the north or northwest, because the clasts in the conglomerate in the wedge average significantly larger than those found in the type locality of the Galisteo Formation.

## ABIQUIU TUFF

The Abiquiu Tuff was first described by Harold T. U. Smith (1938, p. 944) and is composed mainly of thick, stream-laid tuff and volcanic conglomerate deposits, although concentrations of granitic and quartzitic cobbles and boulders are not infrequent, especially in the lower part of the formation. The Abiquiu Tuff rests unconformably on the El Rito Formation and older rocks. The deposits range from white to purplish gray or brownish gray in color. Considerable variation in color and lithology is observed laterally in the formation, and almost as much variation can be seen in the vertical section.

Smith (1938, p. 945) stated that "The Abiquiu Tuff underlies about one-eighth of the total area of the Abiquiu quadrangle." The outcrop belt is widest west and southwest of the Ortega Mountains and in the vicinity of the town of El Rito. The formation narrows toward the southwest and passes under the Canones Andesite south of the Chama River in the vicinity of the town of Abiquiu. Smith (1938, p. 945) cited other detached areas in the Abiquiu Quadrangle.

Beds in adjacent areas have been correlated with, or questionably correlated with, the Abiquiu Tuff by Stearns (1943, p. 317; 1953b, pp. 469, 496), Disbrow and Stoll (1957, p. 27), Budding, Pitrat, and Smith (1960, p. 84), Ross, Smith, and Bailey (1961, p. 142), Spiegel and Baldwin (1963, p. 57), and others. Much has been written concerning the fact that the Abiquiu Tuff and most of the deposits correlated with it underlie beds of the Santa Fe Formation, or beds believed to be of Santa Fe age. This has led to speculation concerning the age of the Abiquiu Tuff, based primarily on the concept of a middle Miocene and early Pliocene age for the Santa Fe, and this speculation has often influenced the interpretation of age for volcanic and other rocks in northern New Mexico and southern Colorado.

We collected extremely fragmentary fossils from Abiquiu Tuff deposits, but these fossils were not numerous enough or well preserved enough to prove surely diagnostic for age determinations of the formation. More fossil mammalian material probably could be found in the Abiquiu Tuff if it were intensively prospected; this might prove to be a rewarding research field for future investigators.

Smith found no sharp contact between the Santa Fe Formation and the underlying Abiquiu Tuff. We, however, found contacts between the Abiquiu Tuff deposits and the Santa Fe Group deposits at several localities. Contacts were observed in the headward forks of Cerro de las Minas Wash (United States Geological Survey: Arroyo del Perro); along the east side of El Rito Creek; and the best exposure of all is on the flanks of the Ojo Caliente intrusive, which is about 2 miles southwest of the town of Ojo Caliente. A well-marked and well-exposed unconformity exists between the Chama-el rito Member (see p. 64) of the Tesuque Formation of the Santa Fe Group and the Abiquiu Tuff east of the Ojo Caliente intrusive. The Abiquiu Tuff, at this point, consists of greenish tuff with included, isolated, angular blocks of crystalline rocks scattered throughout the deposit. The included rocks are not numerous and range in size from pebbles to small boulders. The dip of the tuff along most of the contact is about 14 degrees east. The dip of the overlying beds of the Chama-el rito Member adjacent to the contact is about 9 degrees east. The beds are so closely parallel that it is difficult to differentiate them without instruments. The Santa Fe beds adjacent to the contact consist of thick beds or lenses of volcanic gravel of usually smaller-than-cobble size, with rare concentrations of small boulders. The thick gravel beds are loosely cemented by calcium carbonate. Thin strata of fine sand, typically buff, tan, or pinkish in color, are intercalated among the gravel lenses, and the fine sand may contain very small pebbles or granules of the volcanic rock. The color of the gravel deposits, viewed from a distance, is a dark brownish or reddish gray, and on many slopes the pebbles that have eroded from the gravel lenses form a mantle of rock, which imparts a dark color to the hills in contrast to the light shades of buff, tan, or pink that are the usual colors of the finer-grained sediments of the Chama-el rito Member. The lithology is very different along the line of contact.

Another locality on the Ojo Caliente intrusive, farther south and west of the one described above, shows an irregular surface of unconformity. At one point all but the lowermost of the Chama-el rito beds at the contact have been stripped away, and the actual surface of contact can be studied over a small area. Still farther west, in the vicinity of the west-throwing fault along the southwest side of the intrusive, an angular unconformity has been observed.

Fossil fragments and specimens of Chama-el rito Member age have been collected from the thin, intercalated, buff sand layers, and a few have been obtained less than 6 feet above the contact. Along the south side of the intrusive the Chama-el rito beds are in direct contact with an eroded surface of metamorphosed tuff and intrusive rock.

## PICURIS TUFF

Tuffaceous deposits similar in lithology to parts of the Abiquiu Tuff crop out at widely separated points along the western border of the Sangre de Cristo Mountains north of Santa Fe, New Mexico; these were described as the Picuris Tuff by Cabot (1938, p. 91). In the type area, near the town of Vadito (Badito in Cabot's report) in the Picuris Range, Montgomery (1953, p. 52, pl. 1) mapped in detail additional exposures of the Picuris Tuff. Cabot mapped other localities of volcanic rocks north of Santa Fe as part of his Picuris Tuff, and the degree to which isolated outcrops, particularly of volcanic rocks, can be shuffled from one formation to another by different investigators is well shown by the treatment that has been accorded these rocks: Harold T. U. Smith (1938, p. 934); Denny (1940b, p. 683); Stearns (1953a, p. 431); Disbrow and Stoll (1957, p. 24); Sun and Baldwin (1958, p. 22); Boyer (1959, pp. 64, 72); and Spiegel and Baldwin (1963, p. 43).

The Picuris Tuff was deposited during the widespread volcanic activity that preceded the deposition of the beds of the Santa Fe Group. The sediments equivalent to the Picuris Tuff from Chimayo, New Mexico, southward are dominantly gray tuff, in which the pebbles are mostly volcanic, although much granitic material is present. Along the mountain front between Chimayo and Santa Fe, several small remnants of amygdaloidal basalt flows crop out. One flow north of Nambé Creek along the base of Pinyon Mountain is similar to that mapped by Cabot (1938, p. 92) near En Medio and Chupadero. Another amygdaloidal flow is exposed just west of the Bishop's Lodge–Santa Fe road, about a quarter of a mile south of the entrance to the Lodge. Gray tuff is quite extensive in this locality. These beds, near Bishop's Lodge, have been described and mapped as the basal part of the Tesuque Formation by Spiegel and Baldwin (1963, p. 36). South of Santa Fe, in Arroyo Hondo, are gray tuff beds associated with fairly thick lava flows. The flows and tuff overlie red beds that were correlated by Smith (1938, p. 943) with his El Rito Formation, but mapped by Cabot as part of the Picuris. Stearns (1953a, p. 430; 1953b, p. 468) and Spiegel and Baldwin (1963, p. 37) each interpreted them differently. The red sediments are regarded by us as part of the Galisteo Formation, and the overlying gray tuff as part of the Espinaso Volcanics, which crop out in great thickness 10 to 15 miles to the south (Stearns, 1943, p. 304).

We consider the Picuris Tuff as part of the same general period of volcanic activity as that in which the Abiquiu Tuff and Espinaso Volcanics were deposited. The problem of stratigraphic correlation of these three formations should receive intensive study by an investigator, or investigators, who will bring to bear every available thread of evidence from sedimentology, volcanology, petrology, or related branches of geology. We hope, as a result of intensive field work, diagnostic fossils may be found that will be useful in establishing precise geochronologic correlations. Certainly with the radiometric techniques now available it would be possible to establish the age of these volcanics.

## ESPINASO VOLCANICS

Stearns (1943, pp. 303, 309, 310) briefly described the Espinaso Volcanics and discussed their relation to the underlying Galisteo Formation. He is undeniably the author of the formation, although he credited the name to an unpublished manuscript on the Santa Domingo Valley by Bryan and Upson. Ten years later Stearns (1953a, pp. 415–452) published an expanded description of the formation, in which he met all the requirements of establishing a formal name for the Espinaso Volcanics.

As stated above, we regard the Espinaso Volcanics, the Picuris Tuff, and the Abiquiu Tuff as broadly equivalent. Stearns (1953a, pp. 421, 422) stated that the Espinaso Volcanics are unconformably overlain by deposits that he assigned with a query to the Abiquiu Formation, which further emphasizes the desirability of future studies of the three formations. Radiometric studies carefully tied to a rock-stratigraphic framework may provide the desired margin of confidence for positive correlation. All three of these formations can be traced from one to the other with interruptions of only a few miles. They all crop out as isolated deposits around the periphery of the Santa Fe Group from Galisteo Creek northward along the western border of the Sangre de Cristo Range to the Picuris re-entrant near Dixon, New Mexico. Basalt mesas and some beds of the Santa Fe Group underlie an area a few miles wide that separates the Picuris Tuff from the Abiquiu Tuff deposits of the Abiquiu re-entrant. On some of their outcrops they are all observed to lie on formations that have bright to dark red color, that is, these volcanic formations lie on the El Rito Formation at the north and on the upper beds of the Galisteo Formation at the south. The Picuris Tuff and the Abiquiu Tuff directly underlie the deposits of the Santa Fe Group. At no point have the present writers observed the Espinaso Volcanics to underlie beds that they regard as part of the Santa Fe Group.

These deposits of volcanic debris must certainly have marked a distinctive climatic change from that characteristic of the El Rito stage, as was pointed out by Harold T. U. Smith (1938, p. 944). Stearns (1953a, p. 427), however, regarded the Espinaso Volcanics as succeeding the Galisteo Formation without a stratigraphic break, and ascribed the change in sedimentation to the formation of eruptive centers in and near the basin of deposition (p. 428).

The ages of these three formations can be bracketed as falling within the provincial Land-Mammal ages of Chadronian, Orellan, Whitneyan, and possibly early Arikareean.

## ZIA SAND FORMATION

The Zia Sand Formation described by Galusha (1966) crops out at several localities in the Jemez Creek drainage basin and in a few of the canyadas along the northern part of the Ceja del Rio Puerco in Sandoval County, New Mexico. No counterpart of this formation occurs stratigraphically in the type area of the Santa Fe Group, for no equivalent beds either lithologically or temporally have been recognized; therefore, the Zia Sand Formation has been removed from the Santa Fe Group.

The Zia Sand was divided into two members by Galusha (1966, p. 9): (1) the lower, or Piedra Parada Member, which is of late Arikareean age and approximately equivalent to the Harrison Formation of the Great Plains, and (2) the upper, or Chamisa Mesa Member, of Hemingfordian age.

These beds were described as belonging in the Santa Fe Formation by Renick (1931, p. 57), and the area selected as the type locality of the Zia Sand by Galusha was cited by Renick as the area in which the relation of the Santa Fe Formation to the Wasatch was exposed. Field work by us strongly suggests that Renick's Wasatch there was actually a part of the Galisteo Formation, for a late Eocene titanothere skull and several jaws were collected a few feet below the contact. Miocene fossils collected in the gray sand beds that Renick called Santa Fe were soon discovered to be appreciably older than any that had been collected in the type area of the Santa Fe Group. The Standing Rock Quarry and its extensions produced a large collection of *Stenomylus*, and many remains of *Daphoenodon*, *Cynarctoides*, *Promartes*, the Archaeolaginae, and a few rodents. Bryan and McCann (1937, p. 808) mapped these same gray sand deposits as their lowermost division of their threefold division of the Santa Fe Formation, which comprised (1) Lower Gray Member, (2) Middle Red Member, and (3) Upper Buff Member (p. 811). They based the conclusion that the Santa Fe Formation could be extended to the Ceja area on the following: "... that [p. 807] the term 'Santa Fe formation' may be properly extended to this area rests on two lines of evidence: (1) fossil evidence of equivalent age and (2) continuity of slightly dissimilar and deformed alluvial deposits extending from the city of Santa Fe southwestward to this area."

Extensive fossil collecting by the present writers in the Jemez Creek and Ceja del Rio Puerco areas has resulted in detailed stratigraphic sections on which the stratigraphic positions of all major fossil specimens have been plotted. Detailed areal maps have been constructed, and these studies have resulted in the decision to remove the Lower Gray Member of Bryan and McCann from the Santa Fe Formation partly because the lithology is sufficiently different from that of the Santa Fe type area that no basis exists for rock-stratigraphic correlation. Moreover, the contained fossils are not equivalent in age to those obtained from any beds that have been referred to the Santa Fe. Bryan and McCann (1937, p. 810) attempted to trace the Santa Fe Formation from its type locality north and west of the city of Santa Fe to the Ceja. Regrettably they failed to recognize that the beds they were tracing westward to the Cerros del Rio, and south to Galisteo Creek, were Pleistocene in age, and on rock-stratigraphic criteria should not have been considered a part of the Santa Fe Formation. Spiegel and Baldwin (1963, p. 45) recognized that these beds should be separated from the older deposits and proposed the name Ancha Formation to receive them. The beds that Bryan and McCann (1937, p. 810) thought were interbedded with basalts of the Cerros del Rio proved to be part of the Ancha Formation (Spiegel and Baldwin, 1963, p. 51). We determined, as early as 1941, that no beds that we recognized as Santa Fe in age were exposed south of the city of Santa Fe to Galisteo Creek east of the Cerrillos Hills, and this determination has been substantiated by the mapping of Spiegel and Baldwin (1963) except for one small group of outcrops, which they recognized as Santa Fe, along Arroyo Hondo, and by Stearns (1943, 1953b). The geologic map of New Mexico by Dane and Bachman (1965) shows the area as Santa Fe Group Undivided, following Spiegel and Baldwin's proposal (1963, p. 39) to broaden the use of the term Santa Fe Group, which effectively demonstrates how the generalized use of a group term can negate the precise mapping of an area, in this case by the men who proposed the broad term. Bryan and McCann (1937, p. 810) cited areas in Santo Domingo Valley from Rosario Siding to the vicinity of Bernalillo that they interpreted as Santa Fe beds, and here, again, the beds are not lithologically similar to those of the Santa Fe type area nor do they contain fossils that are equivalent to those of the Santa Fe type area. The beds in the Santo Domingo Valley that have been called a part of the Santa Fe Formation should be described as a new formation separate and distinct from any in the Santa Fe type area.

Bryan and McCann (1937, p. 810) stated that: "South of San Felipe and west of Bernalillo, fan deposits of a general reddish color are interfingered with the river gravel. The river gravel at the west end of the bridge over the Rio Grande at Bernalillo dips 2° to the south. On both sides of Jemez Creek, to the north and west of this locality, there are poorly exposed, deformed beds consisting largely of alluvial fan deposits. These beds resemble those of the Lower Gray Member (hereinafter defined) of the Santa Fe Formation and extend westward to the area here considered." The deformed gray sand beds that they cited as occurring on both sides of the Jemez Creek to the north and west are not equivalent to the Lower Gray (Galusha, 1966) but lithologically and faunally are similar to the Ojo Caliente Sandstone Member of the Tesuque Formation. This fact emphasizes the care that must be used in correlating similar-appearing beds in any of the areas in which possible Santa Fe equivalents are exposed. Spiegel (1961, pp. 133, 137) recognized that the Santa Fe beds in the Lower Jemez Creek could not be described adequately on the basis of Bryan and McCann's Upper Buff, Middle Red, and Lower Gray members and treated them as Lower Unnamed Formation and Upper Unnamed Formation, each of which had three or more members.

The Tesuque Formation (Middle Red of Bryan and McCann) was traced and prospected for fossils from the Canyada Piedra Parada eastward across the various fault blocks that have successively offset the Tesuque (Middle Red Member). The gray sand beds at the top of the Tesuque Formation increase in thickness in an easterly direction, with maximum thickness exposed southwest of Santa Ana Pueblo and south of Jemez Creek where cemented dikes commonly associated with fault zones are conspicuous topographic features. The red deposits underlying Santa Ana Mesa north of Jemez Creek, and those overlying the gray sand south of Jemez Creek, mentioned above, are part of the same formation. If fossils had not been available to point the way toward investigation of the stratigraphic position of these beds, it would have been natural to assume that the gray sand was a lateral facies of the Zia Sand, an early and medial Miocene (Arikareean and Heminfordian) formation. Actually they belong high in a set of strata of early Pliocene (Clarendonian) age. The Tesuque (Middle Red of Bryan and McCann) Formation can be shown to be faulted and buried by the Upper Buff in the Lower Jemez River region.[1] The red deposits in the Lower Jemez area that have been confused with the Middle Red are interfingered laterally toward the west with the buff beds of the Upper Buff of Bryan and McCann and presumably are essentially a facies of the same formation.

On purely rock-stratigraphic criteria all the various recognized subdivisions of the formations in the Jemez Creek, Ceja del Rio Puerco, and Lower Ceja del Rio Puerco should be described as separate formations and not correlated directly with the formations of the type locality of the Santa Fe Group.

The Zia Sand Formation of the Jemez Creek and Ceja del Rio Puerco areas is lithologically and temporally distinct from any beds in the type locality of the Santa Fe Group, and it was partly on this basis that the formation was described (Galusha, 1966). The Zia Sand is well exposed in the East Fork of the Canyada Piedra Parada (where a type section was designated and a type section figured by Galusha, 1966, p. 3, fig. 2). The type area lies west of the Jemez fault in sects. 11, 12, 13, 23, and 24, T. 14 N., R. 1 E., of the New Mexico Principal Meridian in Sandoval County, New Mexico. The type section was designated as starting a few yards north of the south line of the NW. ¼ of sect. 11, T. 14 N., R. 1 E., Sandoval County, and was then measured through the Standing Rock Quarry in a southerly to southeasterly direction across sect. 14 and the northern part of sect. 23.

The deposits of the Zia Sand Formation are extremely soft sandstones composed of slightly cemented medium- to coarse-grained quartz sand. A few thin beds of fine-grained sandstone, siltstone, and calcareous material crop out. In the Piedra Parada Member, which is the lower member, colors are dominantly light gray. In the upper member, the Chamisa Mesa Member, colors also are mostly gray, but yellowish gray or pinkish gray bands may be numerous toward the top of the member. A type section was figured for the Chamisa Mesa Member (Galusha, 1966, p. 10).

[1]Spiegel (1961, p. 132) described and mapped the Lower Jemez River Region and directed attention to two new unnamed formations.

## SANTA FE GROUP

The predominantly fluviatile, deformed, fossiliferous, slightly consolidated sedimentary rocks north of Santa Fe, New Mexico, have been described by various writers as the Santa Fe Formation. The beds were originally named the Santa Fe marls by Hayden (1869, pp. 66–67) who briefly described the beds and the area in which they were well exposed. Cope (1874a, 1874b, 1875a, 1875b) described fossils that he obtained near Pojoaque and San Ildefonso and made some geological observations of the deposits, which he called the Santa Fe marls. By 1922, Darton (1922, p. 57) recognized the beds as the Santa Fe Formation, and all subsequent workers followed that concept. Bryan (1938, p. 205) cited the type locality as being near Santa Fe, New Mexico, but on the same page first expanded the concept of the Santa Fe Formation: "The main body of the sedimentary deposits of the Rio Grande depression, from the north end of the San Luis Valley to and beyond El Paso, is considered to be of the same general age and to belong to the Santa Fe Formation."

One of Bryan's students, Denny (1940b, p. 678), formally established the type locality for the Santa Fe Formation, but other students followed, understandably, Bryan's broad concept of the Santa Fe as a term to be applied to any late Tertiary, slightly consolidated or unconsolidated, basin deposits occupying the Rio Grande depression, and even adjacent areas. Bryan (1938, p. 205) based his all-inclusive concept that the basin deposits were referable to a single period of deposition contemporaneous with the beds of the type locality near Santa Fe on four general criteria: "(1) All the beds are slightly cemented, and the finer-grained members have concretions of calcium carbonate; (2) all the deposits are deformed, mostly by normal faults, although in the centers of the basins the deformation is so slight as to pass unnoticed except under intensive search; (3) the beds within any one basin are of diverse lithologic types ranging from coarse fanglomerate to silt and clay, and abrupt changes in the kind and sizes of the contained pebbles are characteristic; and (4) these markedly different materials attributed to one formation conform in their arrangement to a geographic pattern consistent with the laws of deposition in basins." Kottlowski (1953, p. 144) suggested, and Spiegel and Baldwin (1963, pp. 38, 39) formally proposed, that the term Santa Fe be raised to group status. In our opinion such an extension renders the term useless, for the Rio Grande is 1800 miles long, with its valley now underlain by Cenozoic sedimentary rocks derived from extremely diverse provenances. We are opposed to applying either the term Santa Fe Formation or Santa Fe Group indiscriminantly to any sedimentary or volcanic beds related to the Rio Grande depression. We believe that Bryan's, and Spiegel and Baldwin's, proposals should be examined carefully and objectively, point by point. We also believe that under such scrutiny it will become obvious that the term Santa Fe Group should be restricted to those beds actually cropping out in the type area, or for those that can be shown to be traceable from the type area to contiguous areas.

The first of the four general criteria cited by Bryan (1938, p. 205) was, "(1) All the beds are slightly cemented, and the finer-grained members have concretions of calcium carbonate." This same observation can be made of many late Tertiary, and also of Pleistocene, deposits in Arizona, Colorado, Kansas, Nebraska, California, Texas, and other states. Therefore, the criterion, at best, should be afforded only supplementary consideration in correlations between basins.

The second criterion stated that "(2) all the deposits are deformed, mostly by normal faults, although in the centers of the basins the deformation is so slight as to pass unnoticed except under intensive search." Deformation of deposits can hardly be classed as a valid reason for extension of rock-stratigraphic units from one local area to a contiguous one; deformation is considerably less valid when applied to deposits of widely separated basins. Many writers have mapped normal faults in and adjacent to the Rio Grande depression; these faults have involved rocks ranging in age from Paleozoic to Recent. Evidence has been presented to show, moreover, that the deposits in the Rio Grande trough have been deformed at different times and at different degrees of intensity.

Nearly all strata of the Santa Fe Group of other authors, south of the Espanola Valley, are younger than those of the type area of the Santa Fe Group, as here restricted (this paper, p. 43). (Exceptions are the Zia Sand Formation and the equivalents of a part of the Pojoaque Member of the Tesuque Formation in the Jemez Creek and Northern Ceja del Rio Puerco areas. These areas are situated in the extreme northwestern corner of the Albuquerque-Belen basin.) Such younger beds are less deformed than are those of the type area, as would be expected, and the fact that the youngest sediments would normally be deposited near the centers of the basins would seem a plausible explanation of Bryan's observation that in the centers of basins the deformation is slight. In the type area (Espanola Valley) the beds of the restricted Santa Fe Group are strongly deformed. No difference can be detected between the amount of deformation of the restricted beds in the center of the valley and that of the restricted beds in other parts of the valley. Some beds not included in the Santa Fe Group are only slightly deformed, for example, Ancha Formation, Puyé Conglomerate, Bandelier Tuff, Espanola Formation (defined in this report), and other later deposits. Where these later beds are at the surface, careful search for faults must be made. These later beds are separated from the Santa Fe Group on several lithologic and other criteria. Deformation of the beds, although observable, cannot properly be a basis for designation or correlation of a rock-stratigraphic unit.

Bryan's third criterion was, "(3) the beds within any one basin are of diverse lithologic types, ranging from coarse fanglomerate to fine silt and clay, and abrupt changes in kind and sizes of the contained pebbles are characteristic." No evidence exists to prove that "the diverse lithologic types" mentioned by Bryan could qualify under Article 6, Remarks (a) category (ii) of the Code of the American Commission on Stratigraphic Nomenclature (1961, p. 650) as "repetitions of two or more lithologic types," nor would it qualify under category (iii), "extreme heterogeneity of constitution which in itself may constitute a form of unity compared to adjacent rock units." A much stronger argument could be presented to show that the diverse lithologic types cited by Bryan would serve better to differentiate the various formations than as a basis for bringing them together.

The Rio Grande depression was named by Bryan (1938, p. 197), who drew upon the descriptions of Lee (1907, pp. 12–16). Kelley (1952, p. 92) expanded and refined the concept in his discussion of the tectonics of the depression. Essentially, the Rio Grande depression is a series of structural basins, apparently arranged *ên echelon*. They are primarily the result of faulting, and each was filled with sediments during some part or parts of Tertiary or Quaternary time, or during both.

Each structural basin is rimmed by vastly differing mountain ranges, uplands, or platforms. They vary markedly in size and shape, and the formations that are now exposed on the peripheries of these basins are different in lithology and in age. Sediments derived from such diverse lithologies and deposited in the separate basins would necessarily result in lithologic heterogeneity. The ancestral Rio Grande was not a factor in the filling of the Rio Grande depression until after the major period of deformation in late Pliocene, when the various basins became linked as drainage basins rather than as depositional basins. The deposits of the separate basins, before they were integrated by the Rio Grande, would have had only grade size of the clastic sediments in common, such as clay, silt, sand, cobbles, and boulders (with the possible exception of volcanic tuffs derived from volcanic-ash falls). Stratigraphic lacunae (Gignoux, 1955, p. 15) representing significant periods of nondeposition or erosion and recognized as disconformities unquestionably have had a profound effect on the beds south of the type area, especially those of the southern part of the Albuquerque-Belen basin and farther south.

The fossils that have been collected from the various basins in the Rio Grande depression show that the beds that are now exposed were deposited at different times; those south of the Espanola Valley are significantly younger (with the exceptions noted above under Bryan's second criterion). Fossils are excluded from consideration in the definition or differentiation of a rock-stratigraphic unit under the Code of Stratigraphic Nomenclature, but we believe that fossils can be a most useful tool if used properly. Our original purpose was to classify the rocks lithostratigraphically into their proper sequence, and this classification, when accomplished, paved the way for a plausible biostratigraphic interpretation. The end result is that "diverse lithologic types" are not so diverse when compared with beds of equivalent age. Only when late beds are compared with earlier ones are the differences compounded above and beyond that inherent in the deposition of sediments from different source rocks under varying conditions. We reject the third criterion as meaningless and inapplicable to correlation of beds in the Rio Grande depression.

The fourth criterion seemed to have been given particular weight by Bryan, for he followed it with a statement that has profoundly affected subsequent thought on the extent of the Santa Fe Formation. As cited the criterion is as follows: "... and (4) these markedly different materials attributed to one formation conform in their arrangement to a geographic pattern consistent with the laws of deposition in basins. The main body of sedimentary deposits of the Rio Grande depression, from the north end of the San Luis Valley to and beyond El Paso, is considered to be of the same general age and to belong to the Santa Fe Formation." Even a cursory analysis of the various basins of the Rio Grande depression shows that great variation exists in the pattern of deposition in them.

A paragraph on the ancestral Rio Grande in this report (p. 118) deals directly with the problem of late deposition in the Rio Grande depression. At no point have the deposits of a large perennial river been recognized in formations of the Santa Fe Group as here restricted. The deposits associated with the Rio Grande are younger, as pointed out above, and should be separated from those of the type area.

Spiegel and Baldwin (1963, pp. 38, 39) followed and expanded Bryan's concept of the Santa Fe Formation, raising the term to group status and including in it "all the basin fill whether Tertiary or Quaternary ... including sedimentary and volcanic rocks related to the Rio Grande trough, with a range in age from middle(?) Miocene to Pleistocene(?)." In our view this all-inclusive extension of the term Santa Fe is unjustified and will lead to a wholly unworkable concept of the lithology of the Santa Fe. Any advantage that could be gained by being able to assign beds indiscriminately to the Santa Fe Group in the Rio Grande trough would be more than offset by the loss of precision in the attempt to erect a stratigraphic sequence for the beds in the trough. The ultimate aim should be to elucidate and refine the historical geology of the beds in the trough rather than to extend the term Santa Fe, as proposed by Spiegel and Baldwin. We believe a better procedure would be to restrict the term to those beds that crop out in the type area. Such a procedure would be a valuable aid to paleontologists also, for the beds of the type area have produced the Santa Fe fauna, which has served since Cope's 1874 report as the basis for the concept of age for the Santa Fe beds. These fossils, and subsequently described ones, when tied to the proposed lithostratigraphic units in the restricted type area, should provide useful refinements of the concepts of historical geology of the area.

In this report we propose to restrict the type area of the Santa Fe Group to the region north of Santa Fe, New Mexico, in the Rio Grande Valley in the north-central part of New Mexico (see geologic map, fig. 38). This area is essentially that described by Hayden (1869), and by Denny (1940b), with some additional information added to define it further. It occupies parts of northern Santa Fe County, southeastern Rio Arriba County, and southern Taos County, and is bounded approximately by parallels 35° 40′ and 36° 50′ and by meridians of 105° 45′ and 106° 15′. It occurs in the extreme southern end of the Rocky Mountain Province as defined by Fenneman (1930), and the type area deposits are confined to a part of the structural basin described by Bryan (1938, p. 198, fig. 45) as the Rio Grande depression.

The type area, as restricted, in the past has been subdivided by the field collectors of the Frick Laboratory. These divisions were mainly geographical, particularly in the early stages of the investigations, and were made as an aid in identifying the localities from which fossil specimens were obtained. The fossil-collecting localities are shown in figure 2. Some of these locality names were used by Frick (1933, 1937) in reports on mastodonts and horned ruminants, and by Schultz and Falkenbach (1940; 1941, pp. 33–36, 44, 49; 1968, pp. 367, 368, 379) on oreodonts, and will surely be an integral part of reports on Santa Fe Group fossils in the future.

The Santa Fe Group, as here restricted, is divided into two formations (see fig. 9 and discussions in this paper, pp. 44, 71). These formations have been separated on lithologic characters, stratigraphic sequence, and other rock-stratigraphic criteria.

Theoretically, as noted above, rock-stratigraphic units should be designated without regard to the fossil content, but we believe that an extremely valuable tool for the study of the rocks would thereby be disregarded. We have used the mammalian fossil remains, laboriously collected and documented over the years, to help to determine in which parts of the sequence of the deformed rocks such boundaries reasonably could be expected to occur. The boundaries, however, specifically are not differentiated on the basis of the contained fossils, but the two disciplines work as powerful adjuncts to each other toward a clearer understanding of the stratigraphy.

The lower formation of the Santa Fe Group in the type area is the Tesuque Formation (fig. 10), originally named by Spiegel and Baldwin. In the present report the Tesuque is divided into five members. The two lowermost, the Nambé (pronounced Nahm-baý) and the Skull Ridge, are approximately medial to late Miocene in age or, more specifically, about equivalent to the Sheep Creek and Lower Snake Creek beds of the Great Plains.

The term Pojoaque Member is applied to beds that were derived primarily from the Precambrian rocks of the Sangre de Cristo Range and were deposited through most of Clarendonian (early Pliocene) time (see discussion in this paper, p. 12). These beds underlie a large area in the Espanola Valley. Equivalent in time to a part of the Skull Ridge Member and the whole of the Pojoaque Member, but of wholly different lithology, the beds of the Chama-el rito Member were derived from volcanic beds of northern New Mexico and the San Juan region of southern Colorado. Overlying the Chama-el rito are the distinctive beds of the Ojo Caliente Sandstone, predominantly of eolian origin. The Tesuque Formation apparently was deposited through part of Hemingfordian, Barstovian, and most, if not all, of Clarendonian (early Pliocene) time.

The Chamita Formation comprises the uppermost, the least extensive, and also the latest beds of the Santa Fe Group in the restricted area. The beds are lithologically distinct and contain fossils indicating an approximately Hemphillian (medial Pliocene) age for the formation.

The general sequence and the relationship of the beds of the Santa Fe Group are shown diagrammatically in figure 10. In addition, the general age relations of the various members are shown. It may be appropriate to direct attention to the use in the chart of an unconventional term of North American Land-Mammal Age (see Savage, 1962). The term Valentinian was proposed by Schultz and Stout (1961, p. 9) for a segment of time that they depicted as being represented by the fossils of five local faunas collected in the Valentine Formation of the Great Plains. We believe that many comparable fossil forms occur in the lower part of the Pojoaque Member and the equivalent portions of the Chama-el rito Member. It is not within the scope of this report to argue the validity of the use of Valentinian as a term of Land-Mammal Age; we use it here to indicate approximate equivalence of a portion of the Santa Fe Group with the more familiar Great Plains succession.

## TESUQUE FORMATION

Frick Laboratory field parties have used the term Santa Cruz consistently since 1925 to identify a collecting locality near Santa Cruz, New Mexico. As work progressed in the general area, other localities were found to contain a similar suite of fossils, and gradually a biostratigraphic concept evolved that identified them as the Santa Cruz fauna, and the beds that contained them were considered Santa Cruz equivalents. The specimens from these Santa Cruz equivalents were often listed together in Frick (1933, 1937) without special attention having been directed to the fact that they were from beds that were essentially of the same age. In 1940, when we began mapping the geology of the Santa Fe Group, we selected the term Santa Cruz Formation to serve as a rock-stratigraphic expression of the useful concept of Santa Cruz equivalent which had been derived from the careful study of mammalian remains from many collecting localities in the general Espanola area. Unfortunately the name had been used, in 1937, in a table for an Upper Cretaceous set of rocks in southeastern Arizona and could not be applied to the New Mexico beds, however desirable the use of the term might be for continuity of records in stratigraphy or paleontology.

A new name, the Tesuque Formation, was proposed by Spiegel and Baldwin (1963, p. 39) to replace "the term Santa Fe Formation in the restricted sense." We believe that geology, stratigraphy, and paleontology can be served better by restricting the use of the term Tesuque Formation to include only those beds in the type and contiguous areas of the Santa Fe Group that are of dominantly granitic origin. One exception to this method of categorizing the deposits of the area is the Chama-el rito Member, which is composed primarily of volcanic debris. The arbitrary type section of the Tesuque Formation as given by Spiegel and Baldwin (1963, pp. 39–40) was a most unfortunate selection, inasmuch as it contains only a small part of a single depositional cycle and hence is incomplete. Only a small part of the recognized sequence is exposed at the type section, and, because we have traced it northward to an area where an essentially complete section is present, we now find that it is desirable to subdivide the Tesuque. Therefore, the beds of the Tesuque Formation are divided in this report into five members, as follows: (1) Nambé Member, (2) Skull Ridge Member, (3) Pojoaque Member, (4) Chama-el rito Member, and (5) the Ojo Caliente Sandstone. Other, and quite unrelated, reasons also compel the recognition of the five members; these reasons are explored in detail under headings assigned to each member. The necessity of adjusting Frick Laboratory nomenclature to the concept of Tesuque Formation has presented unusual but not insuperable problems.

The Tesuque Formation is the most widely exposed formation (fig. 38) of the Santa Fe Group. The beds are more than 3700 feet thick in the Espanola Valley. Beds of the Nambé Member, particularly, are superficially difficult to distinguish from certain parts of the Pojoaque Member. The similarities are commonly more apparent than real between the two members, and the two can be separated on several criteria. In the field the most useful correlation tools have been the sequence of ash beds, gravel content, and clast type of certain beds, position of beds in a sequence, and fossil content. Fossil content (American Commission of Stratigraphic Nomenclature, 1961, pp. 649, 650), admittedly, should not be the sole criterion for distinguishing a rock-stratigraphic unit. In practice, in the Espanola area, however, mammalian fossils found in a group of beds commonly have provided working hypotheses that have pointed the way to the proper understanding of the stratigraphic position of the beds. Every available tool should be brought to bear in determining the stratigraphy of any area, and particularly of an area as difficult and complex as that of the Santa Fe Group.

The arbitrary type section of the Tesuque Formation as designated by Spiegel and Baldwin (1963, p. 39) is as follows: "An arbitrary type section can be given as being along the north boundary of T. 17 N., extending 9 miles westward from Tesuque Creek (NE¼ sec. 5, T. 17 N., R. 10 E.) to a point three-fourths of a mile east of the Buckman Road (NE¼NW¼ sec. 2, T. 17 N., R. 8 E.)." They stated (p. 39), "It is not possible to assemble a type section of the formation because structural complications probably exist in these beds in the Santa Fe area, good exposures are scattered, and recognizable horizons are absent." They did, however, figure a type section of the Bishop's Lodge Member as the basal part of their Tesuque Formation. Boyer (1959, p. 72) studied the Bishop's Lodge Member and concluded that "The changes in lithology, sedimentation and terrain which supplied the sediments, within the basal part of the Tesuque Formation as now constituted, coupled with the strong disconformity at the top of the Bishop's Lodge Member, suggest that the Bishop's Lodge and the basal Tesuque of this area should be separated from the typical Santa Fe type beds comprising the Tesuque Formation." We believe the Bishop's Lodge Member to be a part of the Picuris Tuff of Cabot (1938), and we do not recognize a lithologic counterpart of the Bishop's Lodge Member in the Tesuque Formation. It is clear that the ultimate correlation of the Bishop's Lodge Member will remain for future investigators to decide.

The Tesuque Formation, as here restricted and, in part, redefined, lies nonconformably upon the crystalline rocks of the Sangre de Cristo Range.

### Nambé Member, New Name

The name Nambé Member is proposed for the predominantly coarse-grained, alluvial-fan deposits of the lower part of the Tesuque Formation. The type locality occupies parts of sects. 11, 13, and 14, of T. 20 N., R. 9 E., and part of sect. 18, T. 20 N., R. 10 E., in Santa Fe County, New Mexico. The type section is shown in figure 13. Views of the Nambé Member are given in figures 14 and 15. The type locality extends from the cliffs of the Skull Ridge Member in White Operation Wash[1] eastward across part of Arroyo Seco to the contact with crystalline rocks of the Sangre de Cristo Range south of Santa Cruz Reservoir (see cross section, fig. 38). The member is named for the Nambé Indian Pueblo, which is situated about 6 miles south of the type locality. The beds of the member can be regarded as consisting of two parts, a lower or conglomeratic sandstone and sand portion, and an upper or fossiliferous portion.

The conglomeratic sandstone and sand portion of the Nambé Member lies nonconformably upon the crystalline rocks at more than 24 sites from the vicinity of Chimayo, New Mexico, south to Nambé Creek. An accessory spur of crystalline hills lies to the west of the Santa Cruz Dam and terminates in the prominent hill at Chimayo. Deposits of the conglomeratic sandstone and sand crop out around these hills, and these dark reddish brown, coarse, angular sand, angular gravel, and conglomerates are exposed in maximum thickness in the vicinity. The finest exposures of the contact between the Nambé Member and the crystalline rocks are in the short, steep washes along the east side of Santa Cruz Reservoir. The nonconformity can be traced for several hundred yards without interruption. At many points along the contact the conglomeratic sandstones crop out high on the shoulders of partially exhumed hills, showing that the sediments had been deposited across the edges of the granitic and gneissic rocks. A few patches remain as detached remnants that apparently occupied slight depressions on the surface of the crystalline rocks. These relations are shown in figure 11. A cross section (fig. 11A) illustrates the attitude of the beds near the mouth of a wash entering Medio (Frijoles) Creek south of the Santa Cruz Reservoir. Another example of the contact of the Nambé Member with the crystalline rocks is shown in figure 11C.

South of Nambé Creek, gray, light-colored, and comparatively fine-grained tuffaceous sediments of the Picuris Tuff underlie the Nambé deposits. In one small area the Picuris Tuff lies

[1]White Operation was a name given by Joseph Rak, one of the early collectors for the Frick Laboratory, to a large fossil quarry in this wash system. The quarry was a few feet below No. 4 White Ash stratum, which is more than 6 feet thick at this point.

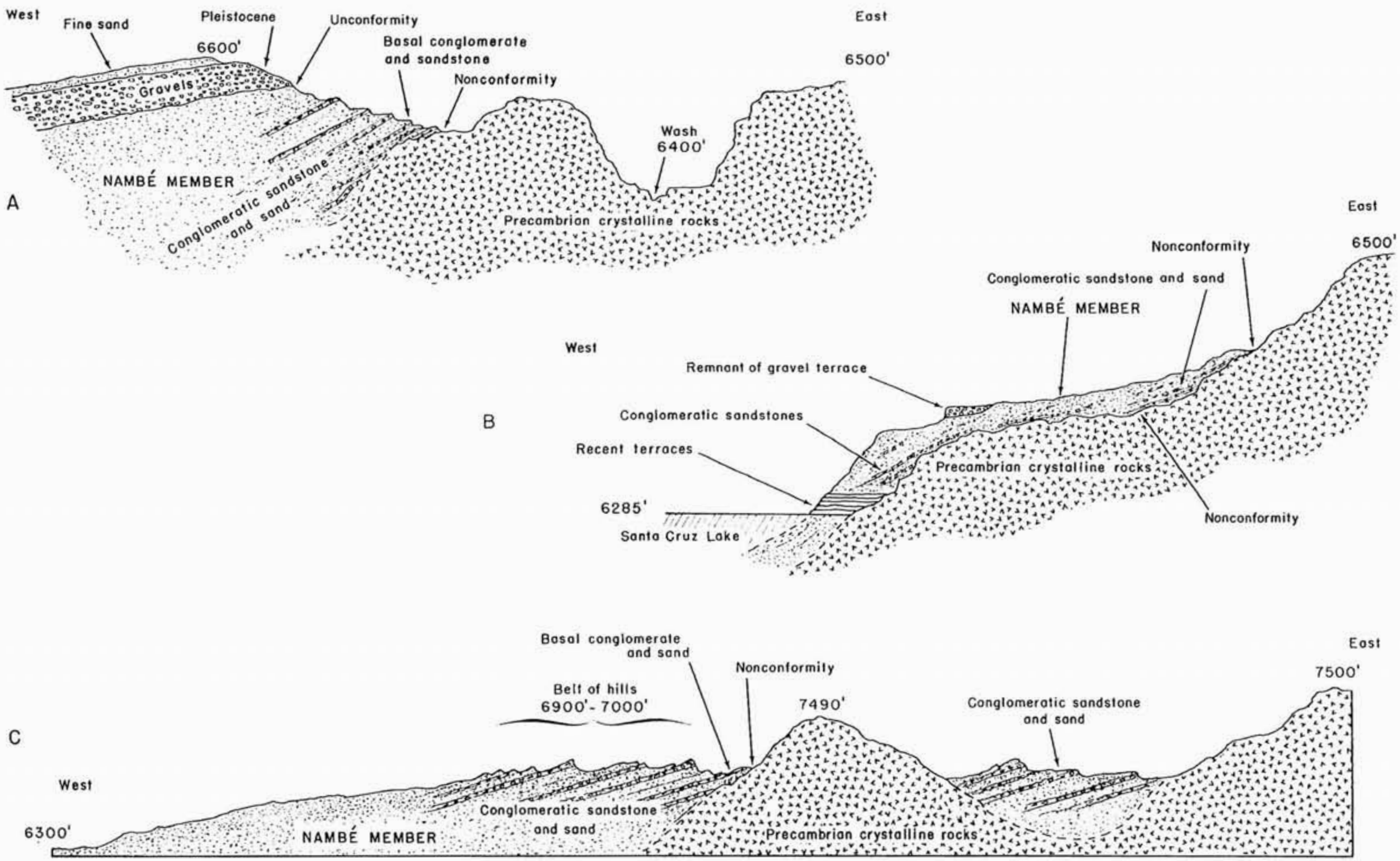


FIG. 11. Sedimentary contact of Nambé Member of Tesuque Formation with Precambrian crystalline rocks of Sangre de Cristo Range. A. Cross section near mouth of a wash entering Medio (Frijoles) Creek south of Santa Cruz Dam. B. Nonconformity of Nambé Member on Precambrian rocks along east side of Santa Cruz Lake. C. Sketch of a belt of hills of Nambé Member rocks south of Nambé–Cundiyo road, showing relation to crystalline rocks of Sangre de Cristo Range. Length of section, about 4 miles.

unconformably on a narrow belt of Pennsylvanian rocks of the Magdalena Formation. Along the base of Pinyon Mountain north of Nambé Creek the deposits of the Nambé Member lap unconformably across truncated Picuris Tuff deposits containing a weathered lava flow, and lie directly on the crystalline rocks. Fault contacts of the Nambé Member with the crystalline rocks are few. The predominantly depositional contact between beds of the Santa Fe Group and the crystalline rocks of the Sangre de Cristo Range compels radically different interpretations of the relations of the western border of the Sangre de Cristo Mountains north of Santa Fe from those presented by Cabot (1938, p. 88). These differences are examined in detail in this paper in the section on Structure, but at this point it is sufficient to mention that the fault traces are all observed to pass into the sedimentary sequence, and that the beds on each side of the fault are of the conglomeratic sandstone and sand of the Nambé Member. The faults have displacements of about 100 to 300 feet and are definitely a part of the post-Santa Fe period of deformation.

Nambé Member deposits were derived mainly, but not wholly, from granitic rocks; their source was in the Sangre de Cristo Range to the east, where granite, granite-gneiss, gneiss, and other rocks crop out over large areas. Bouldery gravel and breccia have been observed on many exposures immediately adjacent to the crystalline rocks, but these boulders are not of the large size and magnitude commonly associated with fanglomerates; but basinward and away from the mountains the deposits contain smaller rock fragments and a greater proportion of subangular and rounded pebbles. These observations were made of the same strata and are not a generalized analysis of gross relations of deposition in the Espanola Valley. The effect of changes in sedimentation resulting from progressive filling of the Espanola Valley is treated under the heading Pojoaque Member of the Tesuque Formation. Beds of red, coarse, sandy gravel crop out low in the section and can best be observed in exposures around the spur of hills near the Santa Cruz Dam. Farther south the reddish gravels crop out in a comparatively thin belt, and one good exposure can be studied conveniently along the east boundary of the Nambé Pueblo Grant northeast of the Nambé Pueblo about on the line between sects. 6 and 7, T. 19 N., R. 10 E., in Santa Fe County, New Mexico.

The conglomeratic sandstone and sand phase contains few pure volcanic ash or bentonitic strata of the kinds seen in the fossiliferous part of the Nambé Member, or in the excellent group of ash beds characteristic of the Skull Ridge Member. A few ash beds crop out in the conglomeratic part of the member; these are mostly local and are concentrated east of the Nambé Pueblo where they underlie beds assigned to the upper or fossiliferous portion of the Nambé Member.

Beds of the Tesuque Formation in general and the Nambé Member in particular have a distinctive light pinkish to light reddish color. The bulk of the sediments was derived from granitic rocks, and the unaltered pink microcline was of sufficient volume to impart the pinkish color to the beds. Technically some of the beds might qualify as arkose, but the 25 per cent of feldspar might, in some beds, vary significantly, or the 15 per cent matrix might be much higher. In general a more accurate description of the sediments would be arkosic conglomeratic sandstone.

The upper or fossiliferous part of the Nambé Member is 450 feet thick at the type locality (see fig. 13) and is estimated to be 500 feet thick on the Nambé Indian Pueblo Grant a few miles to the south. East of the Nambé Pueblo, lower beds of the fossiliferous portion crop out. They grade upward from alternating beds of sand and conglomerate into a fairly uniform group of strata of finer texture. These finer deposits include silt, bentonic and ashy strata, lenses of granitic conglomerate, and a thick series of cliff-forming sandy strata. This group, in turn, grades upward into another series of interfingering and alternating lenses of gravel and sand. The sequence of deposits grading from coarse sand and conglomerate through finer sediments back to coarse sand and conglomerate is interpreted as indicating shifting back and forth of the depositing channels on the coalescing alluvial fans that were building these deposits along the mountain front.

A prominent and well-exposed white ash bed is repeated by faults northeast of the Nambé Pueblo. This ash bed is capped laterally by a layer of hard sandstone, and this relation is well shown on the southernmost ridge southeast of the Nambé Day School in sects. 13 and 14, T. 19 N., R. 10 E., Santa Fe County, New Mexico, where the sandstone lies directly on the ash. Down the dip of the beds, sand and other sediments crop out between the sandstone and the ash, and the thickness of the sand tongue increases with distance. A few miles to the north, east of the Nambé–Cundiyo road, nearly 20 feet of the sediments separate the sandstone stratum and the white ash. South of Nambé Creek along the west side of Chupadero Creek the white ash is mixed with sand, and the bed passes beneath the land surface to the south. The upper 200 to 300 feet of the fossiliferous part of the Nambé Member in the locality east of the Nambé Pueblo is not well exposed. From the position of the white ash bed mentioned above westward to the No. 1 White Ash stratum, which crops out on the erosion escarpment at the fork of the Nambé–Cundiyo road, most of the fossiliferous part of the member has been eroded or has been buried by alluvium; this part of the section, however, is particularly well exposed in the type section (fig. 13) in White Operation Wash. (See also map of the contact between the Skull Ridge Member, and the Nambé Member, fig. 12).

The division between the Nambé Member and the overlying Skull Ridge Member has received intensive study in an effort to synchronize biostratigraphic and rock-stratigraphic data. The No. 1 White Ash stratum is arbitrarily selected as the contact between the two members because it is easily mapped. The base of the White Ash stratum is not a precise biostratigraphic division, because fossils referable to the Nambé fauna have been collected a few feet above it. The No. 1 White Ash stratum closely approximates, however, a biostratigraphic division and at the same time, owing to its mappability, fulfills the requirements of a rock-stratigraphic division. The map of the contact area between the Skull Ridge Member and the Nambé Member (fig. 12) shows the extent to which the beds have been broken by faults and illustrates how this deformation has affected the outcrop pattern of No. 1 White Ash stratum. This fault pattern is typical of other areas in the Tesuque Formation. The map also shows how the beds have been repeated or omitted, depending on the direction of the throw of the normal faults.

Sediments of the fossiliferous portion of the Nambé Member are finer-grained than those of the conglomeratic portion. Pinkish to buff sand, silt, or clay-filled sand forms the bulk of the member, although lenses of conglomerate are numerous in parts of the section. Calcareous ledges and small calcareous sand concretions are decidedly more plentiful in the locality north of Arroyo Seco than in the East Cuyamunque and Tesuque collecting localities (fig. 20), where fossils typical of the member have been collected east of Fault I. In the East Cuyamunque and Tesuque localities the sand and clays are soft, and the sediments are banded; at a few sites red clay and clay-filled sand merge laterally with channel sand and gravel. The zone of merging is very narrow and shows plainly the relation of the stream channel to the marginal flood plain areas on the Nambé alluvial fan. Thin bentonitic or ashy layers occur in the upper part of the member; one of these, about 100 feet below the top of the member, has been named the Nambé White Ash stratum (fig. 13) and has proved to be a useful horizon for local correlation.

At the crest of the divide between White Operation Wash and the drainage basins of the Santa Cruz River, the gravel and sandstones are observed to grade laterally to gray sandstones and gray sand. The sediments of the divide area are strongly granitic, conglomeratic, and lenticular in character, and their topographic expression resembles that of certain beds of the Pojoaque Member of the Tesuque Formation north of the Santa Cruz River. They are observed, however, to pass beneath Skull Ridge strata in an unbroken section along the ridge to the west.

Exposures of the upper part of the Nambé Member have been very fossiliferous in the Santa Cruz drainage basin south of the river, and in White Operation Wash and Arroyo Seco. Areas of the member in the East Cuyamunque and Tesuque localities, although small, have produced diagnostic specimens.

North of Nambé Creek, particularly in the vicinity of Pinyon Mountain, the conglomeratic sandstone and sand part of the section underlies a belt of fairly high but essentially rounded hills. The westward-dipping conglomeratic sandstones coupled with a mantle of gravel derived by deflation of the conglomeratic lenses have served to hold up the hills. Near Nambé Creek a subsequent drainage pattern has been cut deeply into the deposits by tributaries of Nambé Creek. The result is a bolder topography, for the hills appear higher and the slopes steeper. These hills, when viewed from a distance of several miles across the Espanola Valley, appear as a regular line along the mountain front and could

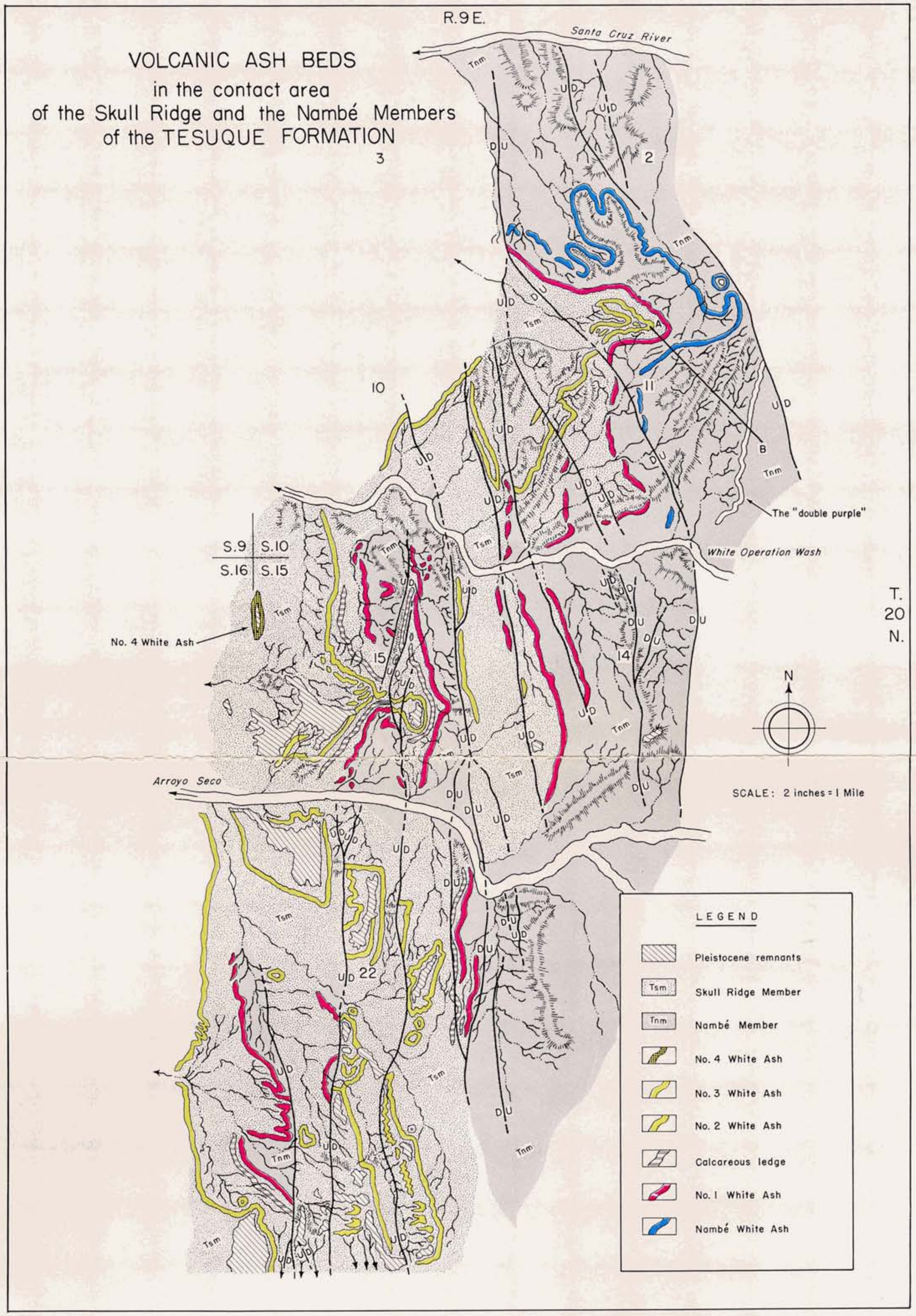


FIG. 12. Outcrop map of contact area between Nambé Member and Skull Ridge Member of Tesuque Formation, showing area underlying parts of sects. 2, 11, 14, 15, 22, 23, and 27, T. 20 N., R. 9 E., Santa Fe County, New Mexico. Outcrops of volcanic ash beds emphasized.

be mistaken for a little-dissected, sedimentary-igneous contact line. The high ridges conform to the general outcrop pattern of the conglomeratic sandstones. Farther north in the Arroyo Seco drainage basin the topography has been modified by long washes, with broad, gently sloping valleys and low, rounded divides leading down from the high belt of hills. Exposures in this area tend to be isolated and of small extent, which is in marked contrast to the rugged, finely dissected badlands topography north of Arroyo Seco.

The Nambé Member has produced a medial

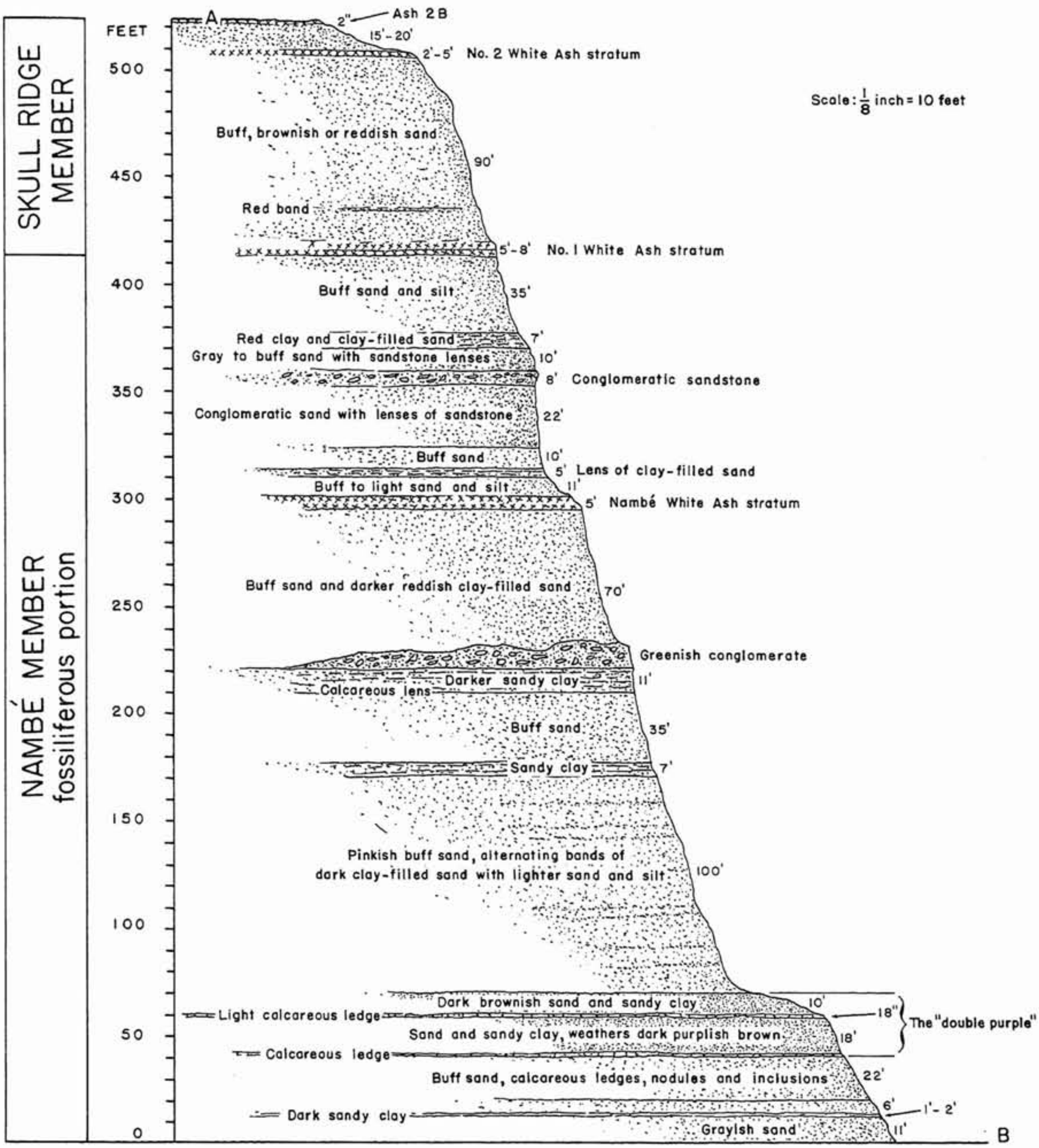


FIG. 13. Ideal section along A–B of figure 12, showing type section of fossiliferous portion of Nambé Member in sect. 11, T. 20 N., R. 9 E., Santa Fe County, New Mexico.

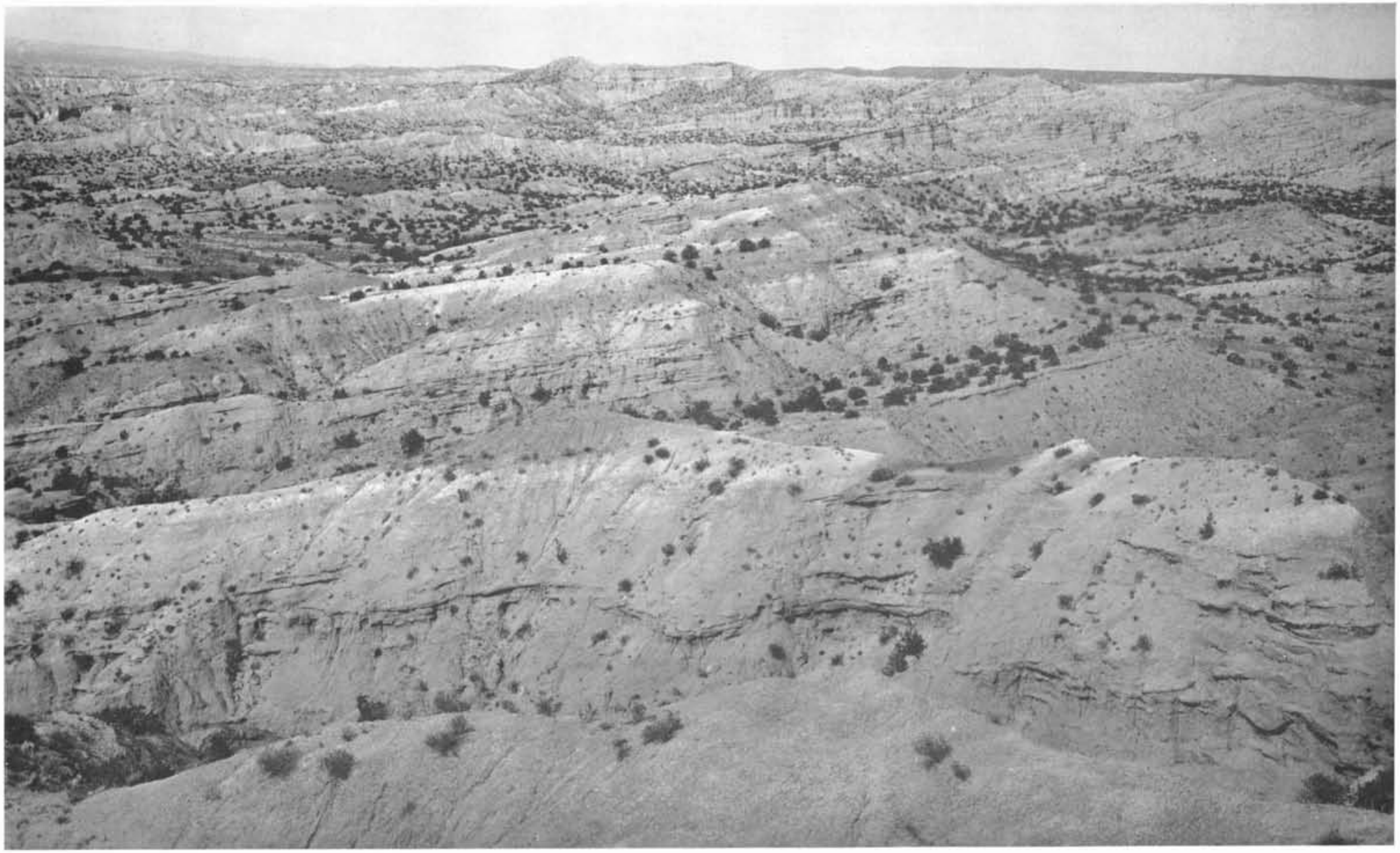

Fig. 14. Fossiliferous portion of Nambé Member of Tesuque Formation, looking north across White Operation Wash. Two purplish layers in low area along right edge of photograph are called informally "the double purple" and are a useful stratigraphic key horizon. Bluffs along upper left are deposits of Skull Ridge Member of Tesuque Formation. Note that conical hill on skyline at left center is also Skull Ridge. View is across unbroken fault block in which contact between Nambé Member and Skull Ridge Member is best shown. (Part of this area mapped in fig. 12; see also fig. 38.)


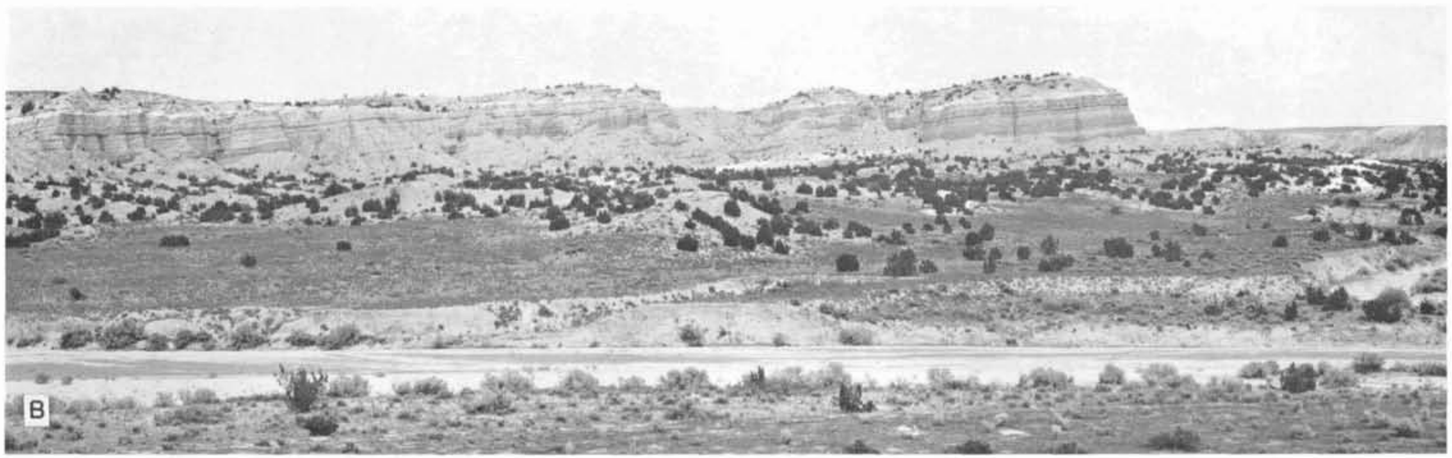


FIG. 15. A. Contact area of Nambé Member and Skull Ridge Member. High, conical hill on skyline at right center same as that in figure 14. View is to southeast. Nambé Member is exposed along base of hills at center and in rugged areas at left; Skull Ridge Member crops out along top of hills at center. White ash layers do not show well in photograph but in the field are effective marker beds. Santa Cruz River is just beyond fringe of trees in foreground. Snow-capped peaks of Sangre de Cristo Range show in left background. B. The Red Wall. Deposits of lower part of Skull Ridge Member, looking north across Arroyo Seco. Prominent cliffs are called the Red Wall. No. 1 White Ash Stratum at far right edge of photograph is faulted down from No. 1 White Ash at base of cliff at upper center. No. 2 White Ash stratum discernible along top of Red Wall.

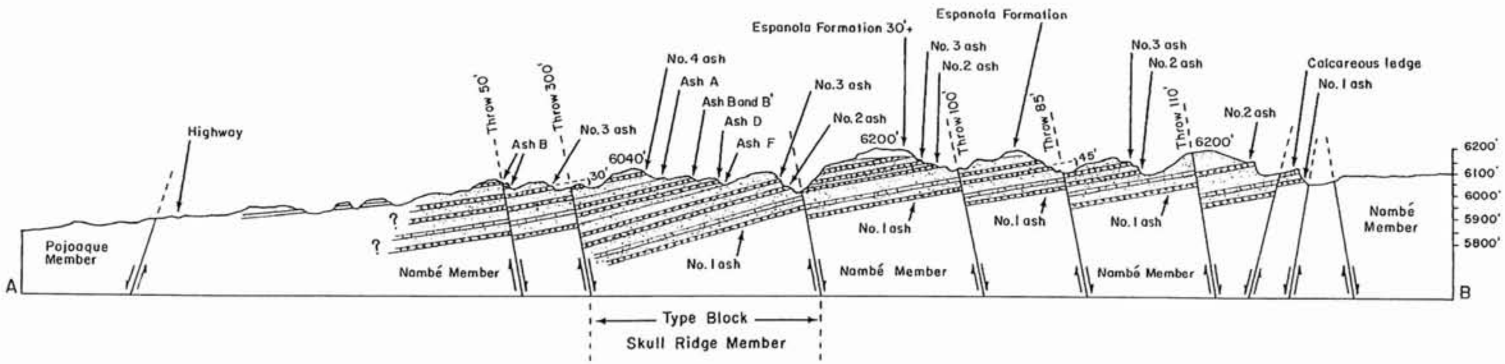


FIG. 16. Type section of Skull Ridge Member of Tesuque Formation shown as cross section A–B on the geologic map (fig. 38). The fault block designated as the type has the major ash beds in superposition and is situated in the N. ½ of sect. 21, T. 20 N., R. 9 E., Santa Fe County, New Mexico.

Miocene suite of fossils or, more specifically, in terms of North American Land-Mammal Ages, a Late Hemingfordian fauna (Sheep Creek local fauna equivalent; see section on the Age of the Santa Fe Group for extended discussion, p. 106). The Nambé Member thus provides, for the first time in the hundred-year history of the Santa Fe Formation (now Group), the stratigraphic position and age of the lowermost member of the beds of the type area.

### Skull Ridge Member, New Name

The name Skull Ridge Member is herein proposed as a new term to be applied to certain distinctive deposits in the Espanola Valley that overlie the Nambé Member and underlie the Pojoaque Member. The boundaries of the type locality of the Member are outlined approximately on the west by the road fault just west of United States Highways 64 and 285; on the east, by the line of cliffs capped by white volcanic-ash strata that lie west of the Nambé–Cundiyo road. The southern boundary of the type locality can be placed for convenience at Nambé Creek, but areas in the East Cuyamunque and Tesuque collecting localities are correlated as Skull Ridge equivalents by the comparison of the sequence of the ash beds, and by contained mammalian fossils. The northern limit lies north of the Santa Cruz River in the lower reaches of Third (United States Geological Survey: Arroyo de la Morada), Fourth (United States Geological Survey: Arroyo de las Martinez), and Fifth (United States Geological Survey: Arroyo de la Cuesta de los Vaqueros) Washes.

A type section of the Skull Ridge Member is a composite of two measured sections (fig. 17). The lower part of the Member represented by 500 feet of deposits between No. 1 White Ash stratum and No. 4 White Ash stratum is best exposed in a fault block south of Arroyo Seco in the N. ½ of sect. 21, T. 20 N., R. 9 E., in Santa Fe County, New Mexico (fig. 16). The upper part of the section lies along the divide between Arroyo Seco and White Operation Wash, approximately paralleling the boundary between sects. 8 and 17, T. 20 N., R. 9 E., in Santa Fe County. The upper part is composed of 150 to 250 feet of sediments above No. 4 White Ash stratum. Contact with the overlying Pojoaque Member of the Tesuque Formation can be observed in the SW. ¼ of sect. 8, T. 20 N., R. 9 E., in Santa Fe County.

The Skull Ridge section is 650 to 750 feet thick, depending on where the section is measured. The deposits are mainly pinkish, tan, or gray, fine to medium coarse sand and silt, some of which are slightly consolidated, but include interstratified beds of clay, conglomerate lenses, intraformational conglomerate lenses, and 37 distinct ash beds. The volcanic-ash beds are usually composed of fine particles or shards, and commonly are little mixed with other detritus except at points that were near the feeder channels of the depositing alluvial fans. Mixtures of ash and sediments are also observed in the upper part of the thicker ash beds. The ash layers vary in color, ranging from pure white to light gray, light blue, blue to dark green, dark gray, or black. Occasionally two colors appear in the same bed; for instance, a thin white ash streak may occur at the base of a light blue or gray ash bed. More rarely a gray ash may grade laterally to a white ash or to a blue one. Colors of ash beds, in a series of four or more used as a unit, have proved extremely useful for correlations.

Four of the thicker ash beds of the Skull Ridge Member are white ash. At some points thicknesses of as much as 10 feet or more can be observed, but commonly the white ash beds range in thickness from 18 inches to 4 feet. These white ash beds are repeated in several fault blocks and are the conspicuous white beds typical of the locality. They may resemble one another on some outcrops, and care must be taken to insure that a unit series is measured so that each can be properly identified. The use of a sequence of ash beds is the only way such identification can be assured at present. The ideal section of the Skull Ridge Member (fig. 17 shows such a sequence of ash beds.

Skull Ridge deposits in the section above No. 4 White Ash stratum are not areally extensive; partly because they are not very thick (maximum of 250 feet); partly because they are not greatly faulted; and mainly because they have yielded readily to erosion, and commonly only isolated remnants remain. The upper sediments of the Skull Ridge are much softer than those of the main body of the member, which tend to form cliffs. The upper beds are mostly fine-grained, reddish to salmon-pink sand and silt, with some clays, and occasional gravel lenses. Cylindrical spindle-shaped concretions commonly less than 6 inches long are found at several horizons, particularly just above Ash Gamma, but concretions and concretionary sandstones are not characteristic of the upper part of the Skull Ridge Member. The upper beds crop out in a narrow belt from Third Wash (United States Geological Survey: Arroyo de la Morada) north of the Santa Cruz River (fig. 38) southwestward to a point north of Pojoaque, New Mexico, where they are covered with alluvium. They crop out again south of Pojoaque along the west side of Arroyo Ancho, and on the Tesuque Pueblo Grant farther south are covered unconformably by gravel deposits.

The uppermost beds of the Skull Ridge Member can be observed best on either side of the road that crosses the drainage divide in a notch north of the Three Sisters Buttes (fig. 18). This road is the first one that runs north to the Santa Cruz River east of the junction of Arroyo Seco and United States Highway 64 (fig. 38). At this spot the basal sand bed of the Pojoaque Member lies disconformably upon a hard, blocky, red sandstone or mudstone that, at this point, is the uppermost stratum of the reddish or pinkish sediments of the Skull Ridge Member. The basal deposits of the overlying Pojoaque Member are predominantly gray friable sand, with small quantities of greenish pebbles that are numerous enough locally to impart a greenish color to the surface at those points where deflation has caused an erosional concentration of the pebbles. A strong gray conglomeratic sandstone, however, lies at the contact; from this site the basal sandy beds can be traced southwesterly along the base of the bluffs until they become covered with alluvium or dip below the surface. The contact between the Skull Ridge Member and the Pojoaque Member also can be observed on a few outcrops south of Arroyo Seco and east of the road fault (fig. 38) where remnants of the basal Pojoaque sand beds cap some of the ridges of Skull Ridge deposits.

The Skull Ridge Member is distinctive for the number and variety of the volcanic ash beds that it contains (fig. 17). These ash beds have been studied intensively as key markers, for they offer possibilities of detailed correlation that are inherent in no other member or formation of the Santa Fe Group. Selection of ash beds as one of the major criteria for correlation is based on the hypothesis that the ash from any specific volcanic eruption would fall indiscriminately upon the entire area, blanketing the highlands as well as the lowlands, but, most significantly, the ash would fall on each of the alluvial fans issuing from the Sangre de Cristo Range whether these fans were widely separated or were arranged as coalesced fans. The ash beds would tend to be present, therefore, in the same relative series on contemporaneous parts of the fans. It is axiomatic that ash falling on highlands or exposed positions would be immediately attacked by wind or water, or both, and would then be concentrated in the lowlands or protected areas, and especially in bodies of standing water, whether ephemeral or relatively permanent. It is important, therefore, to observe that any individual ash stratum may show a variety of characters along the strike, ranging from absence at originally exposed sites through probable normal occurrence of pure ash to a variety of mixtures of ash and sediments; moreover, there may be accumulations of ash showing faint to well-marked lamination as if laid down under water. In addition, irregular and lenticular masses of ash as much as three times the normal thickness of the bed have been observed; these are obviously the result of concentration, possibly by wind currents in protected spots, similar to dunes or snowdrifts. Differences in thickness, texture, and lithology of the sediments between the ash beds are to be expected, for the different alluvial fans probably arranged as a bajada or compound alluvial fans would have been of unequal size, would have had different sediment loads and transporting power, and may have derived their sediments from dissimilar rocks within the source area. Another factor influencing the general character of the sediments between the ash beds was the meandering of the depositing streams on the fans, thus contributing to the lateral variation of the sediments. Each alluvial fan would receive ash from each specific fall. Lateral changes of the ash beds would result from action by different geologic agencies or combination of agencies, and any program to use ash beds for correlation must recognize and use these changes.

The lower limit of the Skull Ridge Member was placed at the base of the No. 1 White Ash stratum for ease of mapping (fig. 12). The No. 1 White Ash stratum may be as much as 8 feet thick, but on most outcrops the thickness is 5 feet or less. A soapy, gray, impure bentonite occurs at the base of No. 1 White Ash on nearly all outcrops north of Arroyo Seco. The proportion of

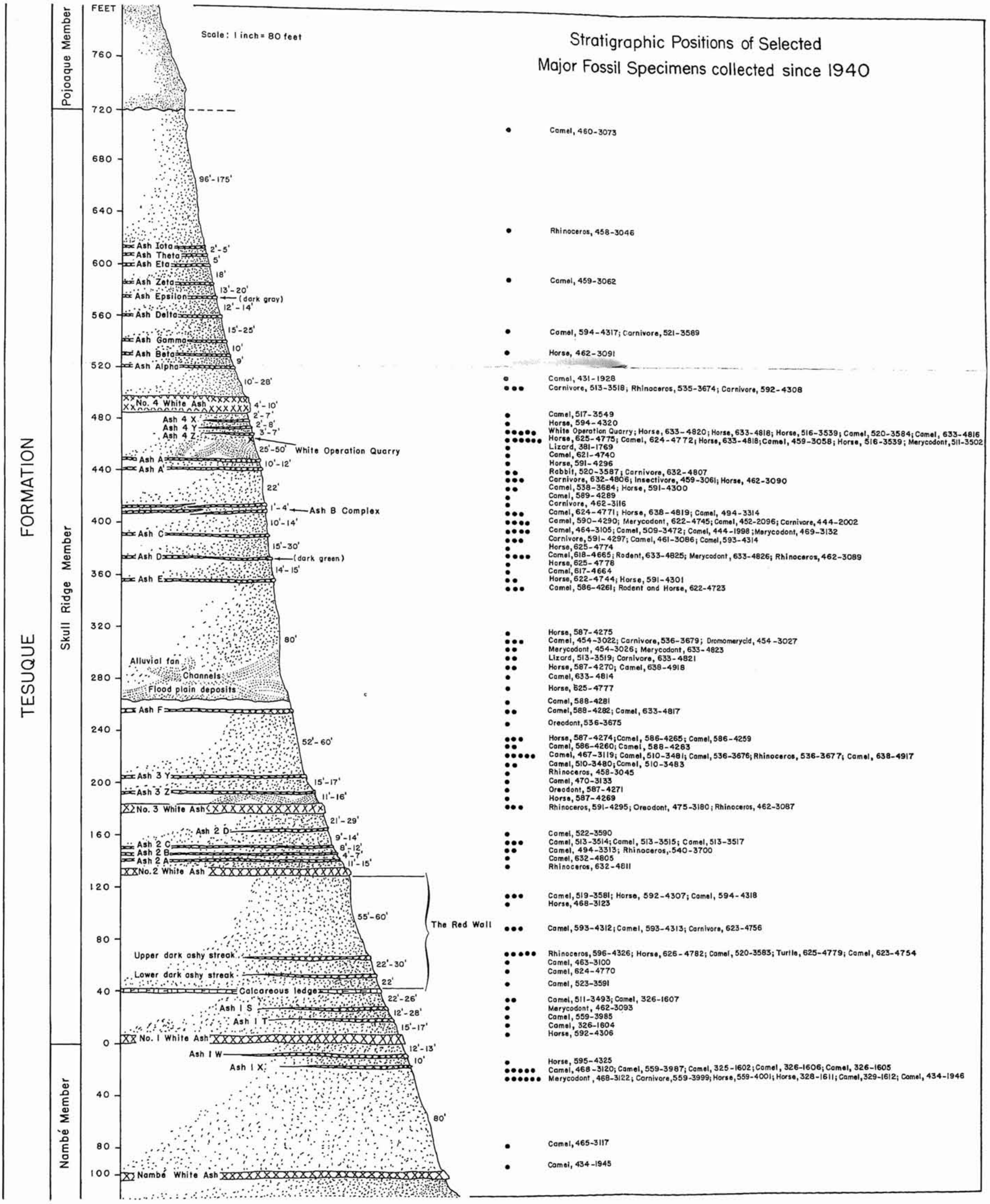


Fig. 17. Ideal section of Skull Ridge Member of Tesuque Formation, showing ash-bed sequence and stratigraphic positions of selected major fossil specimens collected since 1940.

FIG. 18. View looking north across Joe Rak Wash and tributaries toward Three Sisters Buttes (center of photograph). Arroyo Seco flows along north side of buttes. Bluffs in far distance are high levels of Pojoaque Member of Tesuque Formation. Some of sloping surfaces on right skyline have been cut on gravels of Picuris re-entrant fan (see section on Erosion Surfaces). Lowlands in photograph have been carved from uppermost 300 feet of Skull Ridge Member. Light-colored bluffs along left edge on skyline are Pojoaque Member beds. Contact area between Pojoaque Member of Tesuque Formation and underlying Skull Ridge Member of Tesuque Formation lies in low notch in the divide, slightly above and less than ½ inch to left of smallest butte of Three Sisters; contact also exposed along base of distant bluff at far left.

bentonite to unaltered white ash increases toward the north. Indeed, north of White Operation Wash, as well as on each side of the drainage divide between White Operation Wash and the Santa Cruz River, the No. 1 White Ash is mostly bentonite, with a few isolated patches of ash and bentonite cropping out on the horizon in the Santa Cruz drainage basin. South of Arroyo Seco the No. 1 White Ash averages 3 to 5 feet in thickness, and the bentonite at the base becomes very thin or disappears altogether. Northeast of the fork of the Nambé–Cundiyo road west of the Nambé Pueblo, No. 1 White Ash caps a cuesta-like erosion escarpment. A little farther north on the Nambé Pueblo Grant Ash 1S and Ash 1T crop out as distinctive horizons; two associated thin tuffaceous beds appear as dark streaks in the section. At the south end of the escarpment, at the road fork mentioned above, two thin ash beds underlie No. 1 White Ash. This sequence of ash beds was used in correlating the beds of the Skull Ridge collecting locality (fig. 2) with those of the East Cuyamunque collecting locality. The East Cuyamunque is separated from the Skull Ridge locality by nearly 3 miles of alluvium-mantled deposits across the valley of Nambé Creek. Isolated outcrops occur in linear groups that extend down from the north, where the main body of the Skull Ridge deposits is exposed, almost to the flood plain of the Nambé Creek. South of Nambé Creek, in a wash that heads against the drainage divide between Nambé Creek and East Cuyamunque Wash, Ash 1S and Ash 1T are well exposed, and southeastward toward the head of the wash where it crosses the old (now abandoned) Nambé–Santa Fe road, the No. 1 White Ash crops out. Ash 1S on some exposures may be completely eroded, but on adjacent outcrops it may be several inches thick. These ash beds crop out in a variety of combinations south and eastward until they pass under the pediment gravel in the southeast corner of East Cuyamunque Wash (fig. 19). In general, in the East Cuyamunque locality the sediments between the ash beds are finer-grained, with a higher silt and clay content, than in the Skull Ridge locality. Furthermore, the colors and textures of the outcrops are more suggestive of sedimentation in a low and probably muddy part of the area of deposition, as contrasted to the Skull Ridge locality where the sediments are coarser-grained on the average—all interpreted as suggesting that the East Cuyamunque locality may have been near, if not actually in, a low interfan area between two alluvial fans of a bajada.

Some beds are locally important in correlations. One of these is the calcareous ledge (fig. 17) shown as the base of the Red Wall. This ledge may be, locally, as much as 6 inches thick, but more commonly is less than 2 inches thick. The Red Wall is an informal term applied by Frick Laboratory collectors to the predominantly cliff-forming reddish sand and silt of the 100 feet of sediments underlying No. 2 White Ash stratum. The Red Wall (fig. 15B), with its capping of No. 2 White Ash, is a scenic topographic feature and is relatively easy to identify in adjacent fault blocks. Several distinctive ash beds (fig. 17) immediately overlie No. 2 White Ash stratum; these have been designated Ashes 2A, 2B, 2C, and 2D and are of unusual importance in correlations. No. 3 White Ash stratum is less well exposed than No. 2 White Ash and is often the most difficult of the major white ashes to map owing to the numerous lenses of granitic gravel that occur in the section from a point about 30 feet below No. 3 White Ash to a few feet above it.

A channel above Ash F (fig. 17) has been an important marker horizon and is interpreted as indicating an abrupt change in the sedimentation cycle. Unusual sedimentary structures are exposed in this part of the section, and some of the bedding and cross-bedding has been emphasized by the concentration of detrital micas, particularly muscovite on certain layers. Fortunately the outcrop area of the beds between Ash F and No. 4 White Ash (fig. 17) has comparatively wide lateral extension, as well as being repeated by faults in a series of fault blocks, which provide a fine opportunity for observations of changes across the strike. No. 4 White Ash stratum was used as the key stratum, from which measurements were made whenever possible, and from which the original naming and lettering of the various ash beds progressed as the sequence of the ash beds was established. Those beds below No. 4 White Ash were given letters of the English alphabet, or a name, and those above No. 4 were designated by letters of the Greek alphabet. Some of the ashes were named to show their proximity to the major White Ash strata (examples: Ash 3Z, Ash 2A, and Ash 1S). The thicknesses of the intervening

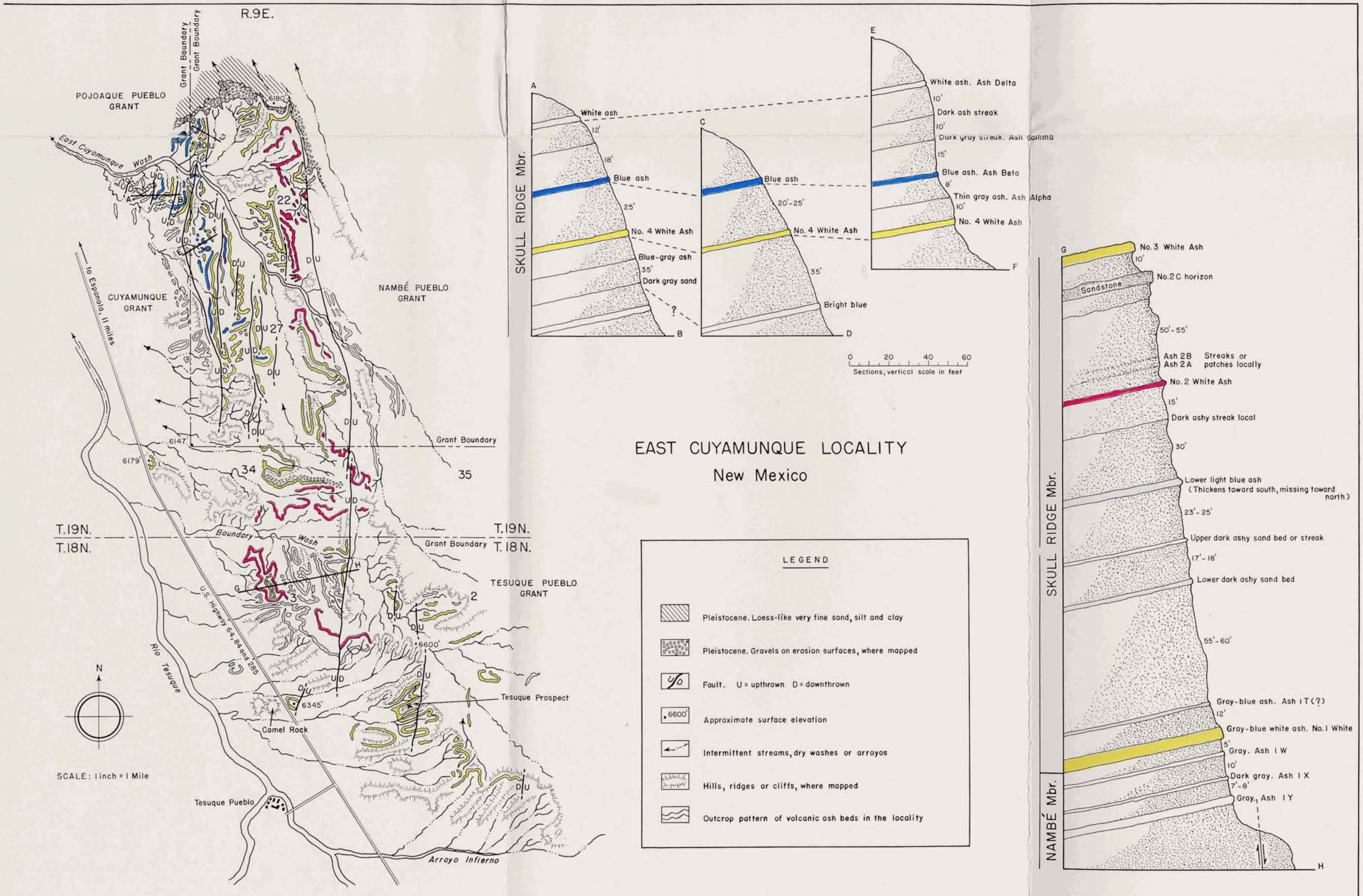


FIG. 19. Outcrop map of a part of East Cuyamunque collecting locality and part of Tesuque collecting locality. Base adapted from an aerial photograph. Sections show correlation details.

strata between the ash beds, as shown on the ideal section of the Skull Ridge Member (fig. 17), differ enough laterally in the equivalent deposits in East Cuyamunque, and also in the equivalent deposits north of the Santa Cruz River, to require separate evaluation. The relationships within the ash bed series in the several localities, however, remain essentially the same. The ash bed sequence is shown in figures 17 and 20, and this presents an ideal section of the Skull Ridge Member in which attention is directed primarily to the stratigraphic position of the various ash beds. The measured intervals between the ash beds show both the minimum and maximum observed thicknesses of the intervening sediments. A few selected fossil mammal specimens are listed on the section to illustrate the method of stratigraphic control used in the field. Many of the taxa are new, hence have not been named, but the field numbers can be cross-checked with forthcoming reports on the camels, horses, carnivores, rodents, and other groups, and the stratigraphic position of the fossil specimens can be readily determined. This chart (fig. 17) can be regarded as the stratigraphic framework for the very large collection of late Miocene (Barstovian) fossils in the Frick Collection from the Espanola area.

Fossils are extremely rare in the ash beds; this observation holds true not only for the Skull Ridge Member but for the ash beds of the entire Santa Fe Group. This fact suggests that the ash falls were not of sufficient density at the time of eruption to overwhelm and suffocate the animals living in the area. Much support can be adduced for the hypothesis that the animals living in the valley were driven temporarily from the area of deposition, possibly in several ways, but probably by the temporary accumulation of water over their grazing grounds, from an increase in the amount of rainfall coincident with the volcanic eruptions. Such ponding of grazing grounds, even for a few days, would drive the animals to higher grounds or adjacent areas. The approximate position of the standing bodies of water at the time of the ash falls can be inferred from the study of the ash strata, for volcanic ash falling into still water tends to settle as pure ash. The location of the various feeder streams can be determined by an observation of the position of the channel sand, gravel, and intraformational conglomerate beds that cut the ash beds. Admixtures of gravel, sand, and mud with the ash are seen adjacent to the postulated debouchures. A study of a large group of cross sections in the Skull Ridge member shows that the original surfaces on which the ash falls were deposited were remarkably regular. Differences of more than 4 feet in the original surfaces were rare, and generally that much inequality was compensated by the thinning or thickening of the immediately overlying sediments. Ponding must have been ephemeral, for no lacustrine features, such as lake deltaic deposits, wave-built cross-bedding, ripple marks, or other similar sedimentary structures, either primary or secondary in origin, have been recognized. Fish remains have not been collected from the Skull Ridge Member, nor have invertebrates. All these facts support a working hypothesis of ponding as opposed to a hypothesis of a lake of sufficient size or duration to be classed as a permanent feature. Fossil specimens are observed to be few immediately above the thicker ash beds, which is interpreted as support for the hypothesis that the animals returned to the area of deposition following the re-establishment of forage after a period of barrenness caused by the ash blanket. A few feet above the ash beds normal numbers of specimens occur. Some of the original ash falls must have been extremely heavy to have produced a bed 8 or 10 feet thick; the degree of compaction caused by several hundred feet of sediments on a bed of ash is difficult to estimate but is undoubtedly great. Robert L. Smith (1960, p. 825) showed that compactibility is related to bulk porosity, and that volcanic glass shards or crystals probably have a bulk porosity of about 50 per cent. It seems reasonable to assume, therefore, that the ash beds of the Santa Fe Group have been compacted to nearly half of their original thickness.

The Skull Ridge Member is admirably adapted for detailed study and sectioning. Close spacing of normal faults, with east side downthrown, has resulted in a repetition of the fault blocks, which, together with the average regional dip of about 9 degrees west, causes each ash stratum to be exposed in several places both across the strike and laterally along it. The sequence of ash beds between No. 1 and No. 4 White Ash strata is easier to use as a correlation unit than is the sequence above No. 4. Ashes above No. 4 are not so well exposed, because they are less faulted, more eroded, and the

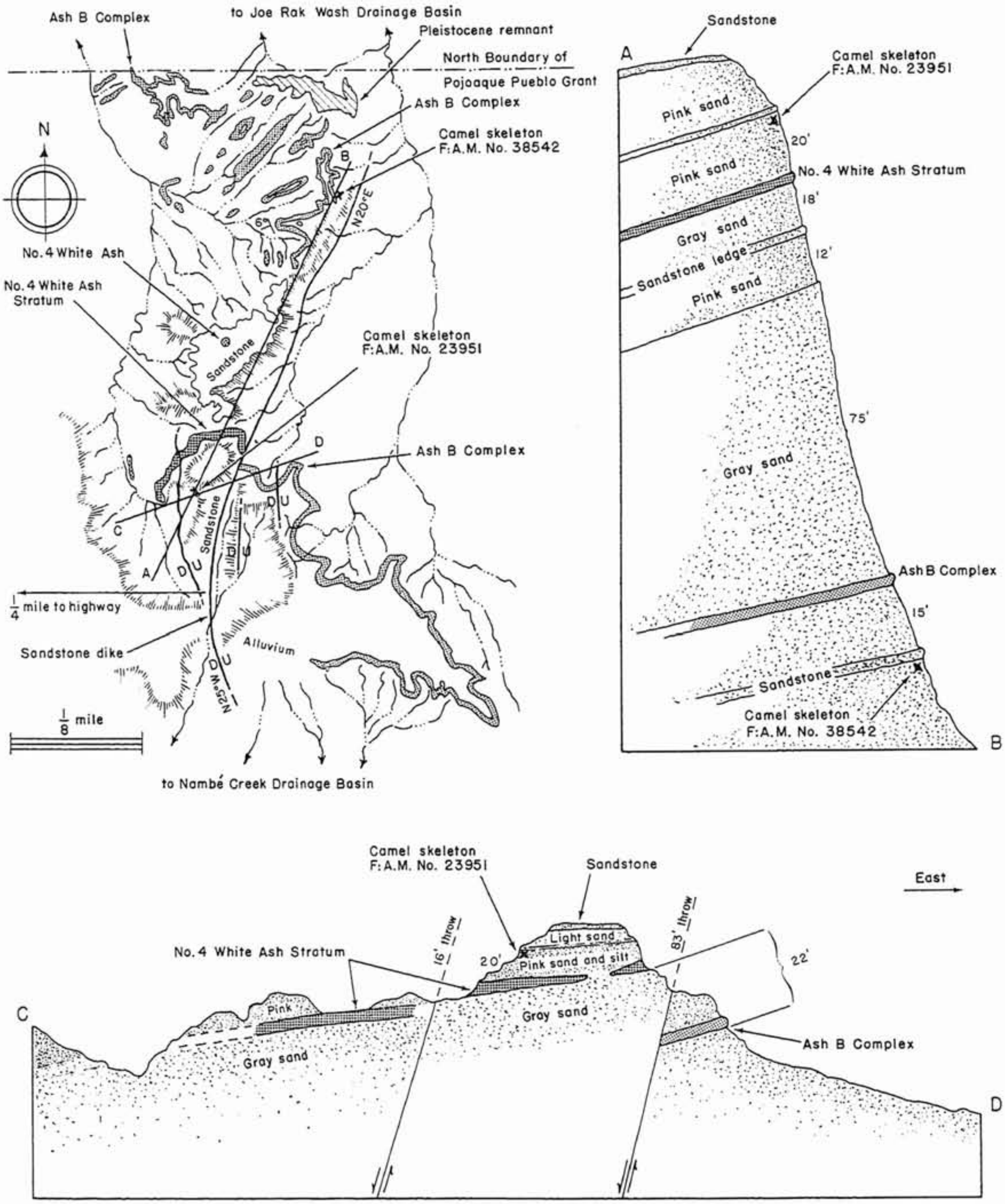


FIG. 20. Outcrop map of South Skull Ridge locality, showing location of two camel skeletons, and with associated cross sections illustrating usual method of correlation of field specimens. A–B. Ideal section. C–D. Profile section.

outcrops are arranged in isolated groups, compared with the section below No. 4.

### Pojoaque Member,[1] New Name

A new name, the Pojoaque Member of the Tesuque Formation, is herewith proposed for the predominantly pink to buff, or tan to gray, soft sandstones of granitic origin that disconformably overlie the Skull Ridge Member of the Tesuque Formation. The name Tesuque Formation of Spiegel and Baldwin (1963) is retained in a restricted sense for the larger grouping of strata, but, as noted in the section on the formation, several new members must be differentiated so that the beds can be recognized in the field and used by both geologists and paleontologists in a meaningful way for future research. The type area is in the Pojoaque Bluffs[2] on the Pojoaque Pueblo Grant. The type section (fig. 21) is situated just north of the south boundary in the SW. ¼ of SE. ¼ of sect. 36, T. 20 N., R. 8 E., in Santa Fe County, New Mexico. Five hundred fifty feet of beds are exposed at this point. The lowermost beds of the member are not exposed in this section. These can be observed on the west side of First Wash (United States Geological Survey: Arroyo del Llano) near the town of Santa Cruz in the SW. ¼ of sect. 31, T. 21 N., R. 9 E., in Rio Arriba County, New Mexico, and in Second Wash (United States Geological Survey: Arroyo Quarteles), and particularly in Third Wash (United States Geological Survey: Arroyo de la Morada), north of the Santa Cruz River in the SW. ¼ of SE. ¼ of sect. 33, T. 21 N., R. 9 E., in Rio Arriba County, New Mexico. Figure 22A is a photograph of the beds in the Santa Cruz locality. The upper part of the section is best exposed in several of the washes north of the Santa Cruz River where the washes head against the remnant of a great alluvial fan (fig. 38). Less well-exposed, but nonetheless important, outcrops of the upper contact can be observed in Santa Clara Canyon and on a few of the promontories held up by Puyé Conglomerate in the area between Santa Clara Creek and Guaje Creek.

The contact of the Pojoaque Member with the underlying Skull Ridge Member is discussed above (p. 54), and it is unfortunate that exposures are few on which the contact can be observed. At many places the actual contact was buried by the numerous faults or was left in the upthrown blocks and eroded. Some of the downthrown blocks were displaced only a few feet, but generally the amount was sufficient to bury the critical zone. The road fault (fig. 38) brought the beds of the Pojoaque Member down against those of the Skull Ridge, or against lower beds of the Pojoaque Member as exposed in the splinter blocks. No Skull Ridge strata have been recognized west of the road fault in the Espanola Valley.

A columnar ideal section across part of the Espanola Valley (fig. 23) shows the general stratigraphic relations of the Pojoaque Member. This, in particular, shows the stratigraphic position of the type section of the Pojoaque Member as exposed in the central Pojoaque Bluffs (United States Geological Survey: Los Barrancos).

The type section of the Pojoaque Member is shown as an ideal section (fig. 21). The structural relations in the Central Pojoaque Bluffs are shown in figure 38. An additional profile section for correlation is shown of beds in the North Pojoaque Bluffs (fig. 24) in the NW. ¼ of sect. 25, T. 20 N., R. 8 E., in Santa Fe County, New Mexico; this is in the southeast corner of the Santa Clara Pueblo Grant. The relative positions of the Pojoaque White Ash and the Blue-Gray Ash, both of which are key beds in this locality, are shown in these cross sections. A few fossil specimens that happened to have been collected from the line of section are listed to illustrate the method of field correlation of fossil collections made in the locality. The salmon-colored beds shown above the Pojoaque White Ash are distinctive and are useful for correlation. The 100 feet of beds cropping out above the Pojoaque White Ash are mostly faintly banded coarse to fine sand, with a few thin layers of siltstone and fine sandstone. Some gravel lenses crop out, but the pebbles in the lenses are small compared with those of the thick gravel lenses in the succeeding strata. The color is buff, tan, pinkish,

[1]Pojoaque is the Spanish pronunciation of the Tewa Indian word meaning "drinking water place." Harrington (1916), in his monumental work on the ethnogeography of the Tewa Indians, gave more than 40 different spellings for the word (p. 334). Pojuaque is the spelling used on Lt. G. M. Wheeler's map of north-central New Mexico, issued April 26, 1876, and this spelling was followed by Frick Laboratory parties. In order to conform to recent practice, however, the form Pojoaque is adopted.

[2]Shown as Los Barrancos on United States Geological Survey Espanola 7.5-minute Quadrangle, 1953.

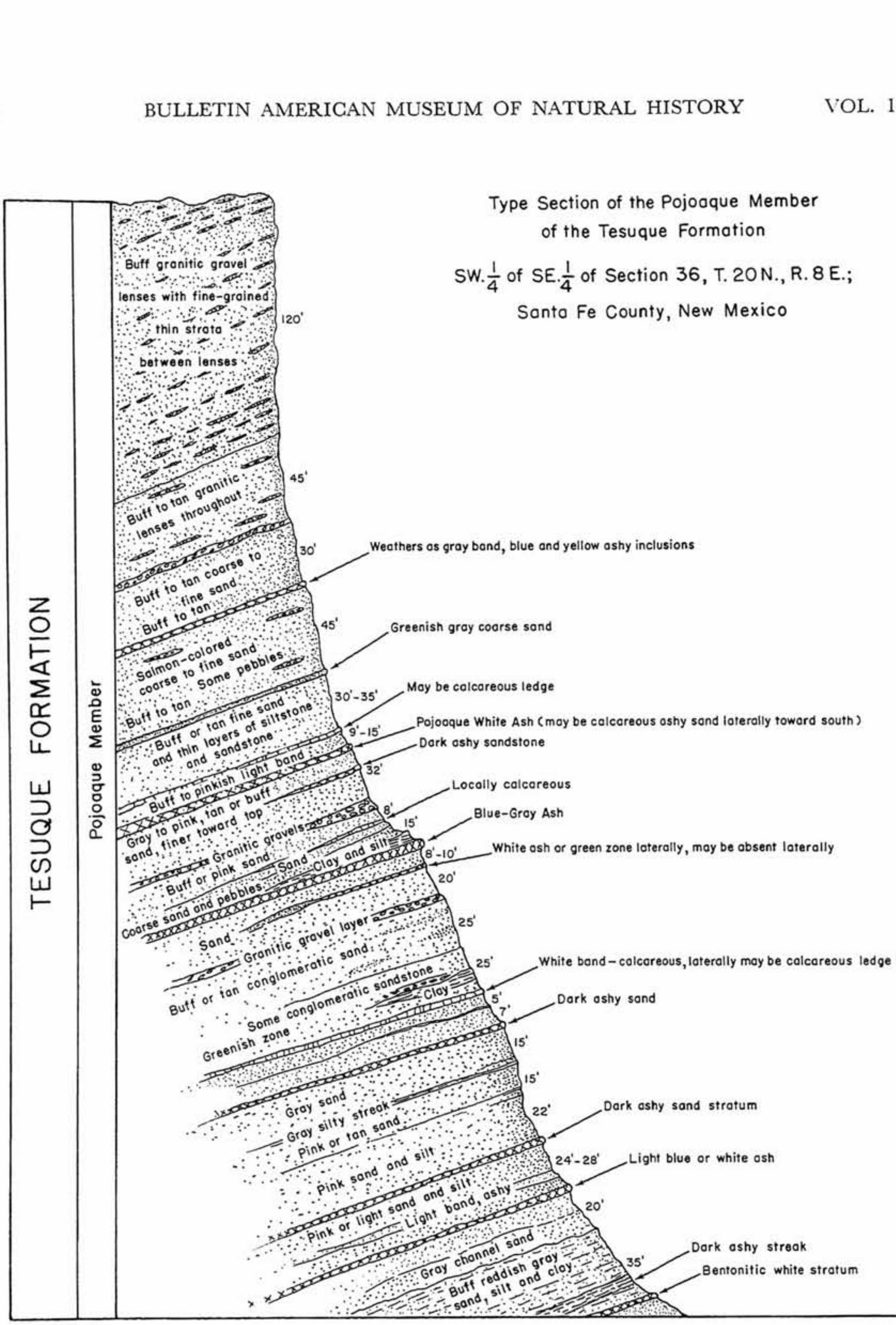


FIG. 21. Type section of Pojoaque Member of Tesuque Formation, SW. $\frac{1}{4}$ of SE. $\frac{1}{4}$ of sect. 36, T. 20 N., R. 8 E., Santa Fe County, New Mexico. These beds are exposed in central Pojoaque Bluffs, shown as Los Barrancos on United States Geological Survey, 1953, 7.5-minute series, Espanola, New Mexico, Quadrangle.


FIG. 22. A. First Wash in Santa Cruz collecting locality, view looking northeast across beds of Pojoaque Member of Tesuque Formation that have been unusually fossiliferous. First Wash shown as Arroyo del Llano on United States Geological Survey, 1953, 7.5-minute series, San Juan and Espanola, New Mexico, quadrangles. B. Pojoaque Bluffs, type locality of Pojoaque Member of Tesuque Formation, looking west from north of Pojoaque, New Mexico. Pojoaque Bluffs shown as Los Barrancos on United States Geological Survey, 1953, Espanola Quadrangle. Alluvial plains in foreground that extend to base of bluffs are being dissected by arroyos, which rarely cut deeply enough to expose the Pojoaque Member.

or salmon, and it often depends on the particular bed that is supplying most of the mantle rock. The same bed may show varying intensities of color on different outcrops; for instance, gentle slopes or north-facing slopes may show a marked color difference from those observed on steep slopes, cliffs, or on south-facing slopes. In the succeeding buff to pinkish, relatively thick, granitic gravel lenses that crop out in the higher parts of the Central Pojoaque Bluffs, and in the stratigraphically high portions of West Cuyamunque (fig. 25) and Santa Cruz localities, the color appears to be largely related to the abundance of feldspar in the gravel and in the fine-grained thin sandy strata between the gravel lenses. Pink microcline predominates in the granitic gravels north of Nambé Creek, which becomes known as Rio Pojoaque below the mouth of Tesuque Creek. In the higher gravel lenses south of Nambé Creek–Rio Pojoaque, particularly in the Arroyo Ancho and West Cuyamunque Wash (United States Geological Survey:

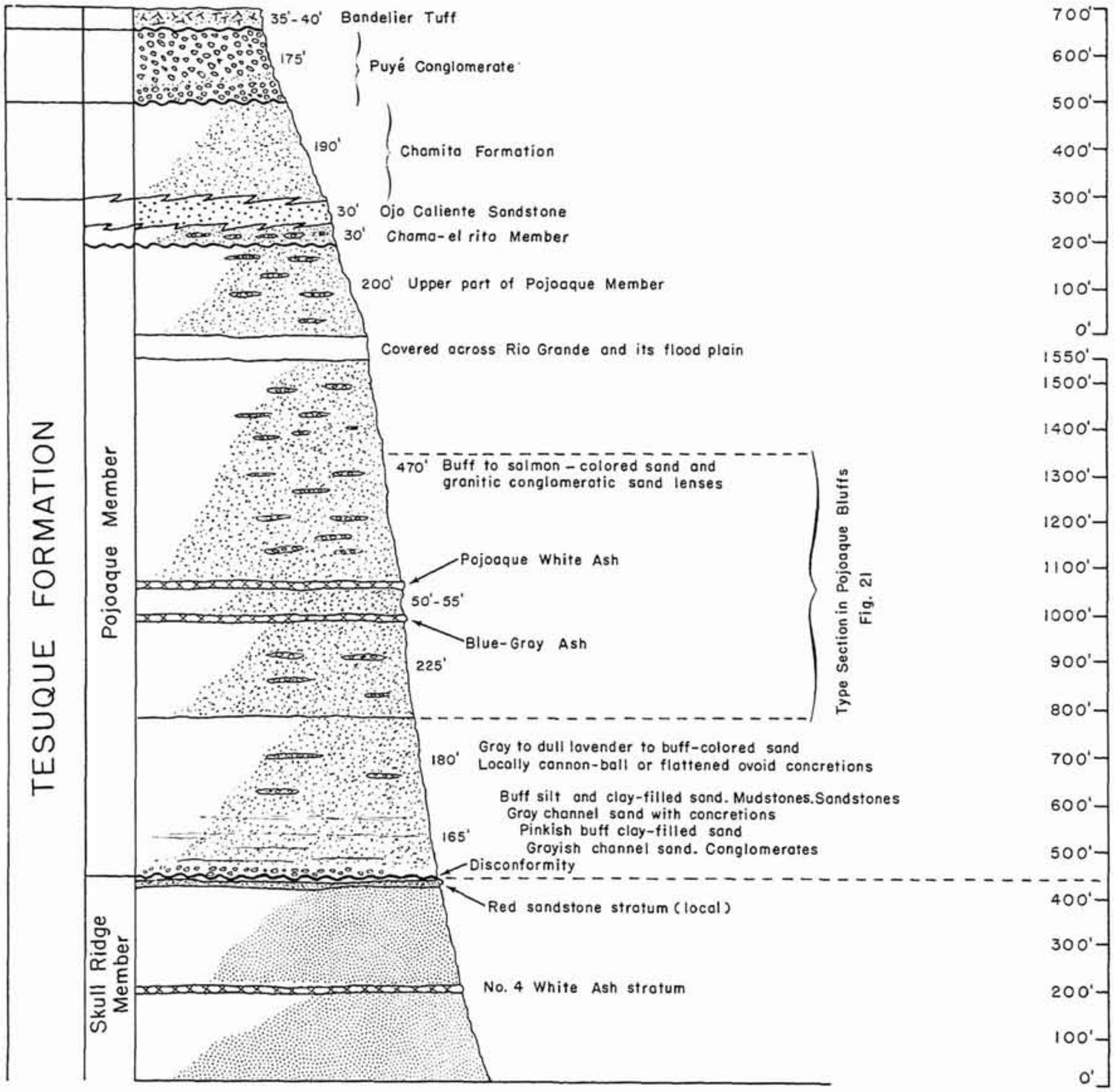


FIG. 23. Columnar ideal section across part of Espanola Valley, showing stratigraphic position of detailed type section of Pojoaque Member (fig. 21) in the central Pojoaque Bluffs (United States Geological Survey: Los Barrancos).

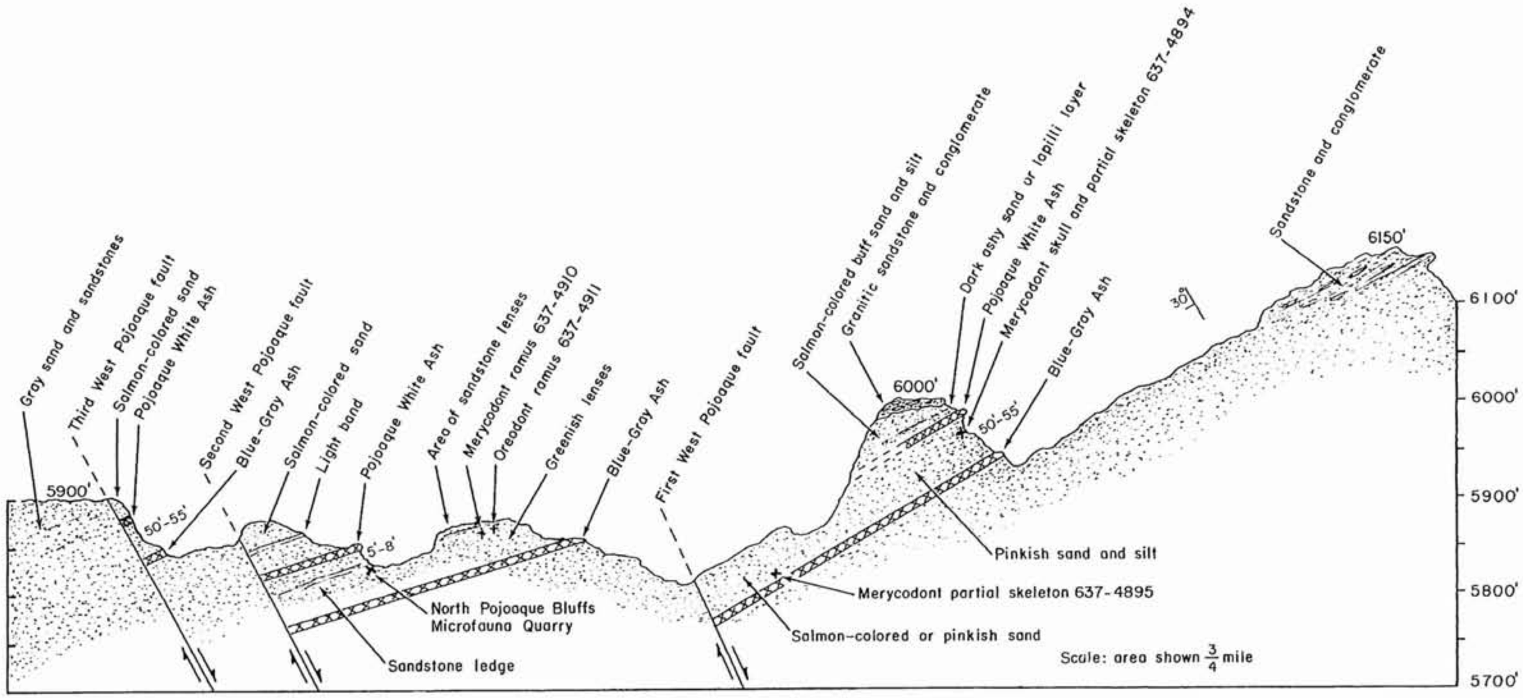


FIG. 24. Profile section in North Pojoaque Bluffs designed to show correlation details. Numbers are field numbers.

Arroyo Jacona), the deep reddish microcline becomes sufficiently abundant to give a distinctive reddish appearance to the outcrops. These reddish rocks are obviously derived from the southern part of the Sangre de Cristo Range and are a part of the alluvial-fan sequence that had a provenance in the Precambrian rocks of the range near the city of Santa Fe.

In general the Pojoaque Member crops out in a great semicircular belt or pattern of isolated groups of exposures from the vicinity of Chimayo, New Mexico, north of the Santa Cruz River, to Santa Cruz, through Espanola, San Ildefonso, Pojoaque, to the general locality west of the Tesuque Indian Pueblo. The outcrops are mapped in figure 38. Owing to faulting, several of the more fossiliferous horizons in the Pojoaque Member have been repeated, thereby providing excellent opportunities for obtaining extensive mammalian collections from the beds. The total exposed section in the various fault blocks is much greater than would be expected, because the topographic expression of the area, with its isolated groups of exposures, relatively narrow breadth of outcrop, and large covered areas, has given the illusion that the total exposed section is thinner than some of the other formations of the Santa Fe Group.

The rocks of the Pojoaque Member produced most, but not all, of the fossils described by Cope (1874a, 1874b, 1875a, 1875b) and also the bulk of the material described by Frick (1926a, 1926b, 1933, 1937). The fossils have proved to be forms currently assigned to approximately Valentine and Clarendon equivalents. The fossil taxa represented include many forms not commonly included in the Clarendonian, but the "fit" is better with a Valentinian (see above, p. 12) and Clarendonian concept of North American Land-Mammal Ages than with either the preceding Barstovian or the succeeding Hemphillian. We think it is worth noting that some of the strictly Clarendonian taxa have not been found in the Pojoaque Member, which does not, however, prevent an analysis of the forms collected and a subjective assignment of the taxa.

### Chama-el rito Member, New Name

Brief mention of the existence of beds in the Espanola area that differ lithologically from the Pojoaque Member but that were deposited at the same time is made above (pp. 7, 43). The recognition of the contemporaneous deposition of two great systems of alluvial fans in the Santa Fe area, the distal ends of which intertongued, is fundamental to the interpretation of the stratigraphy of the Tesuque Formation.

Fossils were collected at many localities in the beds of the Chama-el rito Member (fig. 26). One of the most prolific of these was the Chama-el rito collecting locality (fig. 2), which has been selected as the type locality of the Chama-el rito Member. The type section lies along the east border of the Juan J. Lobato Grant, in the two easternmost rincons at the head of Cañada de Tio Alfonso (see United States Geological Survey Medanales Quadrangle, 7.5-minute series, 1953). The area on that map designated as Rincon del Cuervo is underlain by Chama-el rito beds and the overlying Ojo Caliente Sandstone. The stratigraphic relations between the two members can be seen in the Cañada Honda where several faults have been mapped that bring the Ojo Caliente Sandstone down against the Chama-el rito as well as displaying the stratigraphic relations of the beds. The type section would have been in the W. $\frac{1}{2}$ of sect. 23, T. 23 N., R. 7 E., Rio Arriba County, New Mexico, had the Juan J. Lobato Grant been surveyed in the General Land Office Surveys of the area. This method of locating the type section is awkward but we hope will prove to be effective.

Beds of well-rounded-pebble- to cobble-sized clasts of volcanic rock, lenticular in outline and interbedded in buff to pinkish, coarse to fine, soft sandstones or siltstones, are characteristic of the Chama-el rito Member. The colors of the volcanic gravel lenses are commonly light purplish gray to medium brownish purple; not uncommonly, large areas underlain by the member have a somber purplish hue owing to the erosional concentration of volcanic clasts on slopes, particularly noticeable where the intercalated buff or pinkish sandstones or siltstones are thin and the gravel lenses are numerous. The volcanic clasts in hand specimens vary greatly in texture and composition and even in color. Some are glassy, some aphanitic, some crystalline, and others porphyritic, and this diversity of texture indicates that they were derived from several different kinds of rocks. The petrography and petrology of the volcanic debris that is characteristic of the Chama-el rito Member should provide some future investigator with an interesting and tremendously important

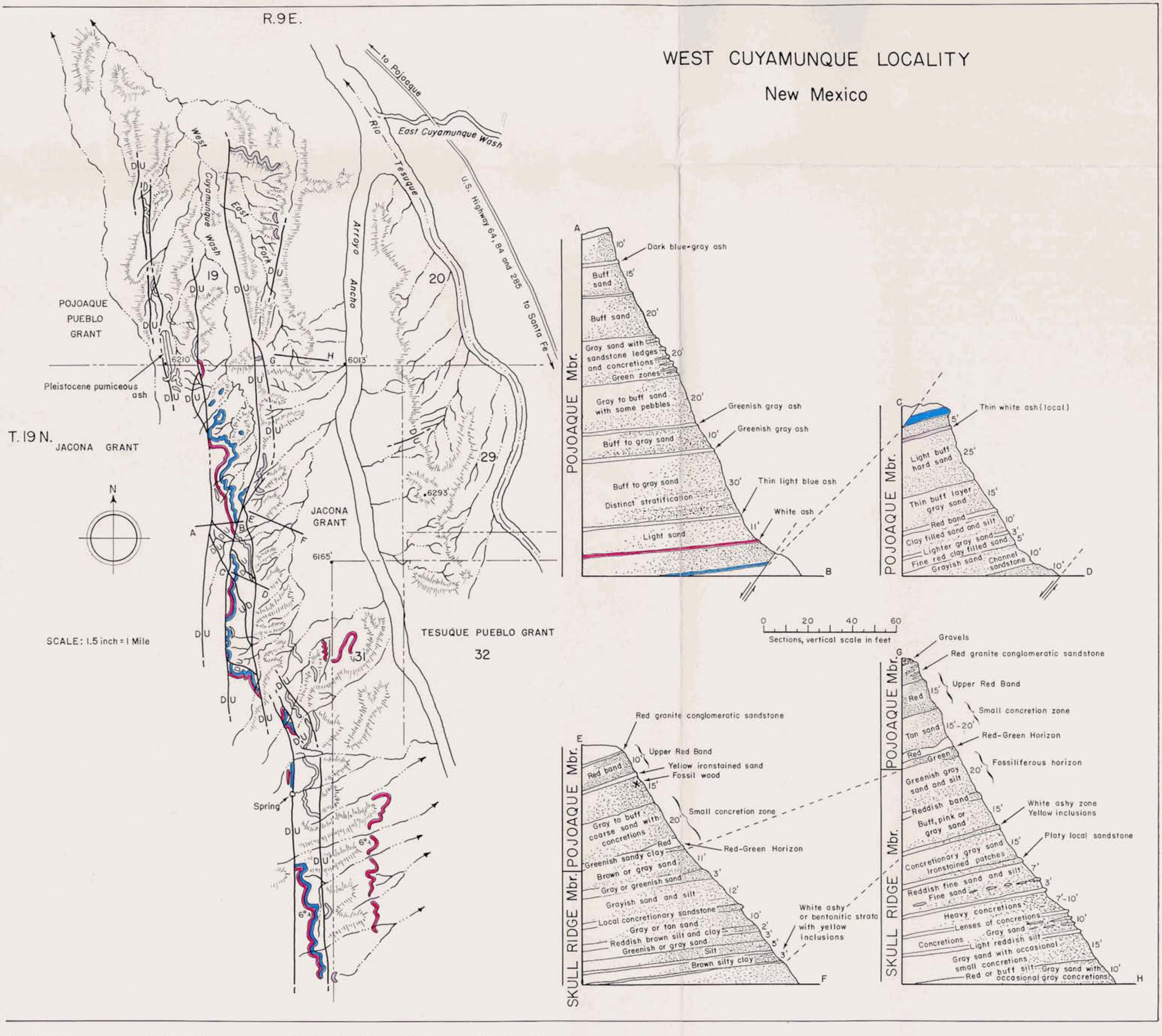


FIG. 25. Outcrop map of West Cuyamunque collecting locality, with four correlated sections.

project, particularly if comparable studies are made of the volcanic rocks of adjacent areas, and of the general San Juan Mountain or Taos Plateau regions, in an effort to establish firmly the provenance of the rocks of the Chama-el rito.

The San Juan Region of Colorado and northern New Mexico is here postulated as the source, either directly or indirectly by reworking, of the volcanic pebbles that are characteristic of the gravel lenses of the Chama-el rito Member. In this regard, we do not agree with Bryan (1938, p. 204) who suggested: ". . . the Sierra de los Valles area, in the eastern part of the Jemez Mountains, is similar in many respects to the San Juan region except for size. It includes a great thickness of older volcanic rocks, which have been much faulted and deformed." He considered the Jemez rocks as pre-Pliocene in age, and stated, "Many of the thin tuff beds of the Santa Fe doubtless had their origin in this volcanic center." Harold T. U. Smith (1938, pp. 939, 958) suggested that the Chicoma Volcanic Formation in the Valles Mountains represented "the much-eroded and partly buried remnants of an ancient volcanic field which dominated the ancestral Valles Mountains." Smith (p. 950) also wrote, "the Abiquiu tuff fan appears to have lapped against the Chicoma volcanic mass after active volcanism had ceased."

Still another origin for the Santa Fe beds was suggested by Atwood and Mather (1932, pp. 98, 99) who correlated the Conejos Formation volcanic beds, or material derived from these volcanic beds, with the Santa Fe Formation "up to the highest beds that contain andesite breccia." They speculated, moreover, that "Probably all the sand and gravel near La Madera, Ojo Caliente, and El Rito is of Conejos age." Several localities were discussed and conclusions drawn. Cross and Larsen (1935) refined the concept of the Conejos Formation and correlated many sets of rocks on petrographic similarity, while at the same time stressing that certain rocks changed from place to place. By 1956 Larsen and Cross had further expanded their subdivision of the rocks of the San Juan Region in Colorado, and, although they traced several sets of rocks of

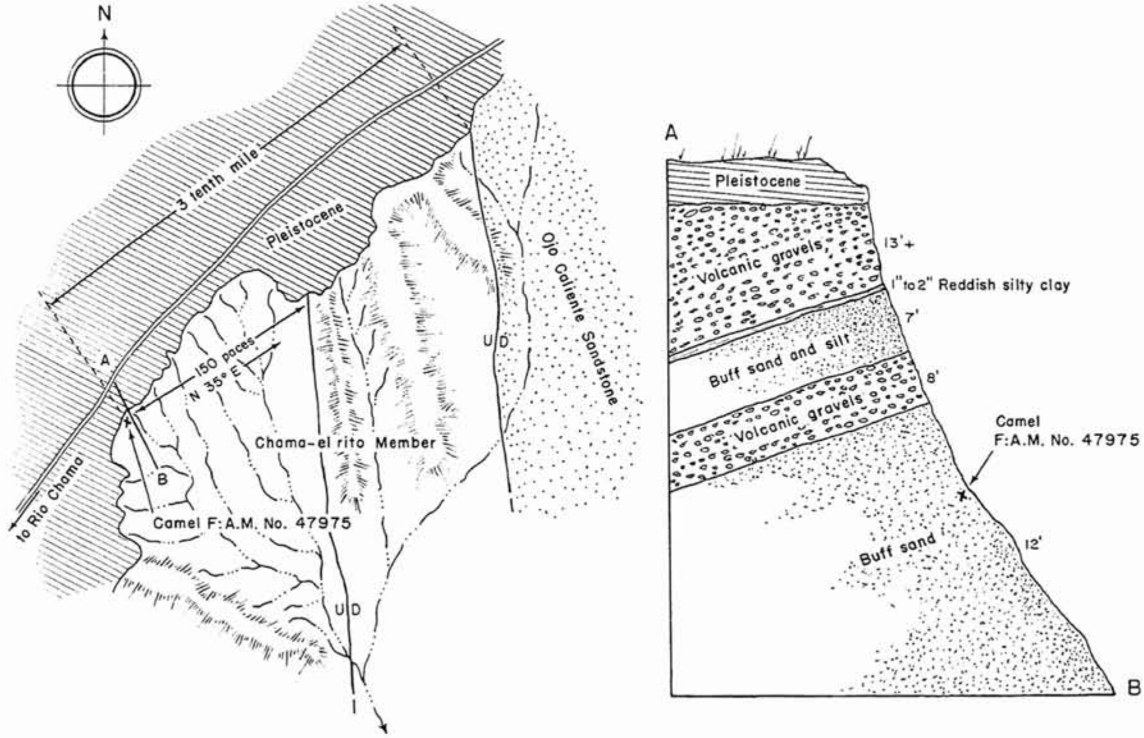


FIG. 26. Correlation detail in Chama-el rito collecting locality, showing location of one camel specimen (F: A.M. No. 47975) and a cross section at the site.

Conejos age into northern New Mexico, they did not postulate that these rocks extended into the Santa Fe area. They (Larsen and Cross, 1956, p. 186) reviewed the stratigraphic position of the Los Pinos Gravel, which previously had been considered a member of the Hinsdale volcanic series, and concluded that the rocks of the Los Pinos Gravel were correlative with the Fisher quartz latite. They quoted Butler as authority for the Los Pinos age of some of the gravels of the Tusas-Tres Piedras area, New Mexico, and they treated in great detail (p. 192) the extensions of the Hinsdale Formation into the type area of the Santa Fe Group.

Recent work by Bingler (1968, p. 35) introduced new data concerning the stratigraphic position of the Los Pinos Formation. He stated (pp. 36, 37): "On the basis of this work, it is the writer's opinion that the lower 300 feet of Precambrian clast gravel included in the Abiquiu Tuff are the lateral equivalent of the Ritito Conglomerate and that the upper 1000 feet of conglomerate represent the southwestern extension of the volcanic Los Piños Formation .... The Santa Fe Formation intertongues with Los Piños Formation over a large area from the badlands east of El Rito Creek through Ojo Caliente, La Madera, and Servilleta Plaza. In these areas, the pinkish purple sandstone and conglomerate beds of the Los Piños Formation are prominently intercalated with the buff siltstone of the Santa Fe. The contact zone represented by this interfingering appears to rise stratigraphically westward, although the absence of any key beds makes it very difficult to be certain of this conclusion." We believe that the buff siltstone that he cited as evidence for interfingering of the Santa Fe with the Los Pinos Formation is an integral part of his Los Pinos sequence and is not a part of the Santa Fe sequence. It is interesting to note that much of the area near El Rito, Ojo Caliente, and La Madera that was mapped as Los Pinos Formation by Bingler (1968, pl. 1b) was mapped by Harold T. U. Smith (1938, fig. 4) as part of the Abiquiu Tuff, and by Atwood and Mather (1932, p. 95) as the Conejos Formation. These differences emphasize the importance of a study of the provenance of the deposits of the general El Rito-Ojo Caliente-La Madera area to obtain an understanding of the stratigraphic position of the Chama-el rito Member.

Cross and Larsen (1935, p. 100) regarded Los Pinos Gravel as a member of the Hinsdale Formation and considered both the member and the formation to be Pliocene and probably late Pliocene in age. Bingler (1968, p. 36) estimated the age of the Los Pinos Formation "as Oligocene to Miocene, based on stratigraphic relationships" and, on a later page (p. 65), assigned a "Late Oligocene-Early Miocene age to the Los Pinos."

We have considered that at least some of the volcanic rocks in the conglomerate lenses in the Chama-el rito were derived from the reworking of clasts from part of the Abiquiu Tuff (see below, p. 115), but we believe that most of the volcanic rocks had a provenance in the general San Juan Region of Colorado and northern New Mexico. It will be a great advance when all these rocks have been dated by radiometric methods and the results made available.

These introductory paragraphs are written to provide a brief survey of published opinion regarding the volcanic rocks in the Chama-el rito Member of the Tesuque Formation, and to emphasize our support for the hypothesis that the volcanic rocks in the Chama-el rito Member were derived from the San Juan Region or contiguous areas to the northeast in the general Taos Plateau area rather than from the Valles (Jemez) Mountain region.

South of Santa Clara Canyon, and especially east of Battleship Mountain (fig. 38), the Chama-el rito Member interfingers at the base of, and is locally overlain by, part of the Ojo Caliente Sandstone. At a few spots between Battleship Mountain and the Sacred Springs (fig. 38) the Chama-el rito volcanic-pebble lenses interfinger with granitic beds of the Pojoaque Member. Indeed, it can be shown that the top of the Pojoaque Member at this locality clearly underlies part of the Chama-el rito Member which in turn underlies part of the Ojo Caliente Sandstone, which means not that the entire Chama-el rito Member is younger than the Pojoaque Member but only that a late part of the Chama-el rito is younger. This locality, then, is critical for establishing the stratigraphic sequence of at least parts of the various later members of the Tesuque Formation.

Extensive exposures of the Chama-el rito Member crop out in the area between Abiquiu and Rio del Oso near Chili, New Mexico. These deposits lie south and west of the Chama River in a belt extending to the edge of the high-level

Lobato basalt flows. Here, as elsewhere, the Ojo Caliente Sandstone can be observed overlying the Chama-el rito beds, and the contact displays a zone of interfingering. The interfingering seems to be the result of the overwhelming, by eolian sand, of relatively flat broad channels containing the characteristic volcanic pebbles. The channels are represented as lenses on most outcrops and in many places can be seen to have been shifted laterally. An occasional red clay or silt band indicates the presence for a significantly long time, probably for several years, of broad, flat, valley-like areas between sand hills. Finally the volcanic channels or lenses were completely cut off, and the eolian sand of the Ojo Caliente Sandstone was deposited as a genetically distinct unit.

Concretions in the Chama-el rito do not resemble those of the Ojo Caliente Sandstone and, furthermore, tend to be confined to certain levels. They are small, rarely more than 8 inches in diameter, unless they enclose or partially enclose fossil mammalian remains, in which event they commonly are larger. They weather to a light reddish brown color and typically have a rough exterior. They disintegrate fairly easily upon weathering, particularly if they contain fossils. The concretions are not abundant at any locality and are composed ordinarily of coarse sand or granule-size grains. The cement is calcium carbonate.

Although we recognize the provenance of most of the volcanic pebbles of the Chama-el rito to be the general San Juan and peripheral regions, we are aware of evidence of contemporaneous volcanism in the localities in which Chama-el rito rocks are exposed. One small, thin, interbedded lava flow crops out in the Rio del Oso-Abiquiu collecting locality (figs. 35, 38). This small flow was arched, but not breached, by one of the later Rio del Oso dikes; this occurrence is described in greater detail under the heading Rio del Oso Dikes (p. 90).

Tuffaceous sediments interbedded in the Chama-el rito Member are exposed along El Rito Creek just above the mouth of Cerro de las Minas Wash (United States Geological Survey: Arroyo del Perro). The presence of a nearby vent is indicated by volcanic bombs that lie in the tuff, many of them at the spots where they originally fell. The volume of tuff contributed to the adjacent deposits in the Chama-el rito is small. A third example of interbedded tuff crops out on the slopes of a small, unmapped, basalt-capped mesa about 3 miles northeast of the town of Ojo Caliente. The relations of this tuff are obscure, and the origin of it or its probable extension is unknown.

A series of multiple working hypotheses were tested in an attempt to decide whether the facies concept should be applied in differentiating the volcanic sediments of the Chama-el rito Member from the granitic sediments of the Pojoaque Member. Inasmuch as the two groups of sediments are genetically distinct, they are here treated as rock-stratigraphic members. Had they shown merely a contrast or change in conditions of deposition, they could be called the Pojoaque facies and the Chama-el rito facies of the Tesuque Formation with propriety. The fundamental differences are great, however, so they are separated as formal units.

### Ojo Caliente Sandstone, New Name

Ojo Caliente Sandstone[1] is a new member name proposed for the uppermost part of the Tesuque Formation. The new member is predominantly of eolian origin and is 450 feet thick at its greatest unbroken section. It is named for the Ojo Caliente River in Rio Arriba County, New Mexico, and the type locality is here designated as the triangular area that is bounded on the east by the Ojo Caliente River, on the southwest by the Chama River, and on the west by El Rito Creek (figs. 27B, 27C, 38). The Ojo Caliente Sandstone overlies beds of both the Pojoaque Member and the Chama-el rito Member of the Tesuque Formation and interfingers at the base with each. The upper boundary is the unconformity at the base of the Chamita Formation (see below, p. 74). It is exposed in an unbroken section along the southwest flank of Black Mesa (figs. 28B, 30B); also in the Dixon sub-basin to the southeast where it has been beveled by the Truchas pediment, and where three red clay bands are locally useful for correlations (fig. 28C; see section on Erosion Surfaces, p. 95). A small area of the sandstone (fig. 27A) also crops out parallel to the west face of the Precambrian crystalline rocks of the low

[1]With equal propriety these beds could have been called the Ojo Caliente Sands owing to the slight amount of compaction or consolidation of the sand, but the term sandstone was used advisedly to imply broader generic relationships.

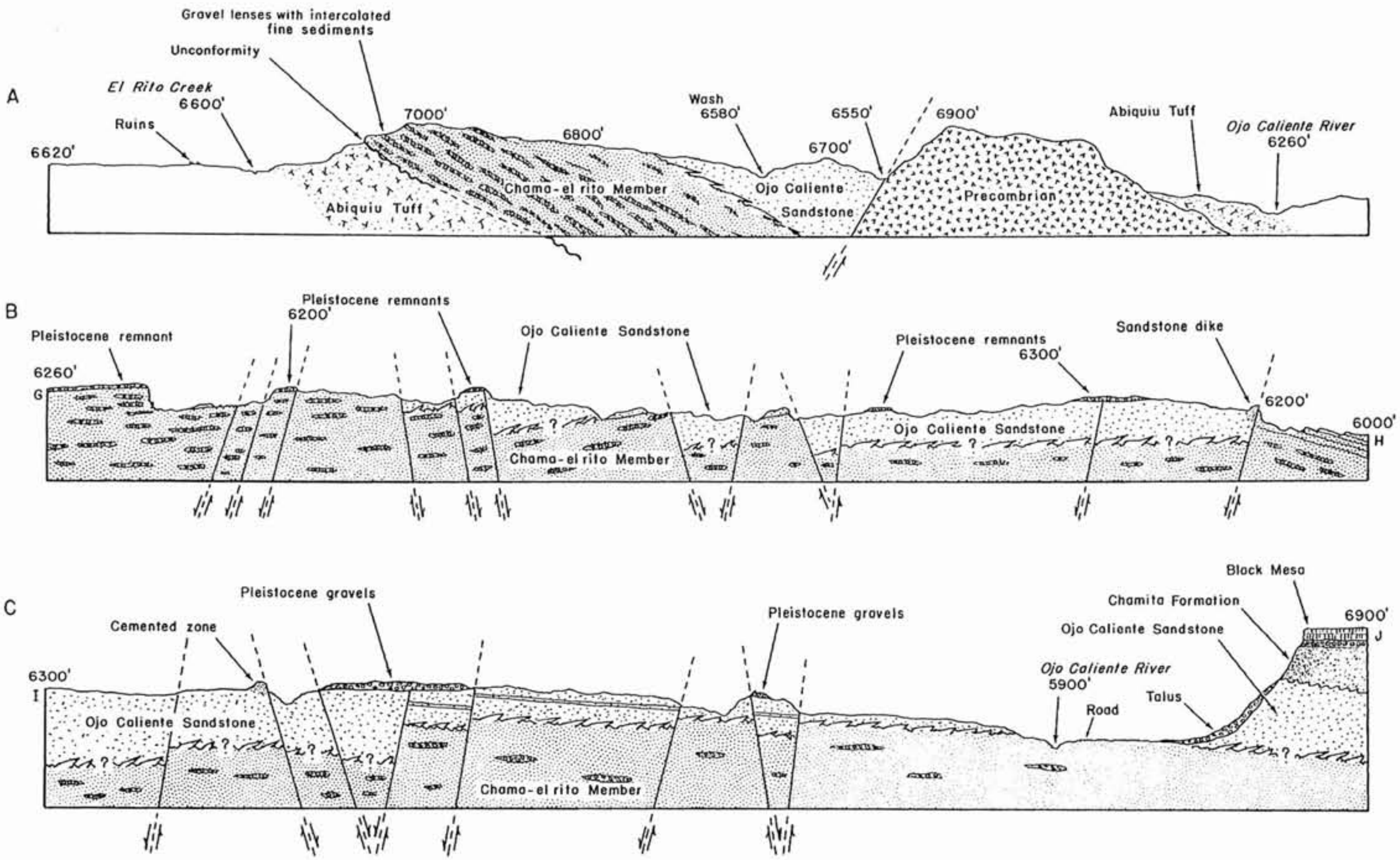


FIG. 27. Cross sections of deposits of Chama-el rito Member and Ojo Caliente Sandstone of Tesuque Formation north of Black Mesa. A. Geologic section across divide between El Rito Creek and Ojo Caliente River. Length of section, about 8 miles. B. Geologic section from Chama-el rito locality through middle Ojo Caliente locality, showing relation of Ojo Caliente Sandstone to underlying Chama-el rito Member of Tesuque Formation. C. Type section of Ojo Caliente Sandstone in north fork of Middle Ojo Caliente Wash, sects. 28, 34, and Black Mesa Grant, T. 23 N., R. 8 E., Rio Arriba County, New Mexico. Length of section, about 2 miles.

mountains immediately west of Ojo Caliente, New Mexico. West of the Chama River between Kunya Ruins Wash and South Wash (United States Geological Survey: Arroyo de la Presa) in the Rio del Oso-Abiquiu locality (fig. 38) the Ojo Caliente Sandstone and the underlying fossiliferous beds of the Chama-el rito Member are broken by many faults, and excellent exposures are available for study. Some of the high hills that rise as monadnocks above the several erosion surfaces of the locality are part of the Ojo Caliente Sandstone. The Ojo Caliente Sandstone thins rapidly toward the south, and the exposures in Santa Clara Canyon probably represent original thicknesses rather than remnants of post-Ojo Caliente erosion. Still farther south near Battleship Mountain (fig. 38) the member is only a few feet thick. It is less variable lithologically than any other member or formation of the Santa Fe Group and has been extremely useful in the correlation of widely separated exposures.

Several hundred feet of little-consolidated, well-sorted, fine- to coarse-grained, pinkish to white quartz sand characterizes the Ojo Caliente Sandstone. The individual sand grains are commonly well rounded, with a dull, frosted appearance. Eolian cross-bedding on a large scale is typical of most, but by no means all, of the strata and is present over wide areas. A few of the larger observed foresets are more than 80 feet long; most of them, however, measure less than 25 feet. An easily accessible example of eolian cross-bedding is shown in figure 36B, a photograph taken along the highway south of the town of Ojo Caliente. Concretionary sandstones may or may not occur throughout, and individual concretions may range in length from a few inches to many feet and in thickness from a few inches to 4 feet. These concretionary sandstones are clearly epigenetic and normally occur in a horizontal position often incorporating the steeply inclined lamina of the cross-bedded sand. On steep slopes, and when viewed from a distance, the concretionary sandstones commonly cause the outcrops to have a distinctive ribbed appearance. The ribbed feature is especially noticeable along the western flanks of Black Mesa.

The lower part of the Ojo Caliente Sandstone in the type locality, particularly west of the fault zone (fig. 38), contains great numbers of concretions that are very irregular in form and distribution. They range from very small, individual, ball-like masses to great flattened tubes of sandstone, some of which are more than 40 feet in length, 6 to 10 feet wide, and usually not more than 3 feet thick. The outer shells of the tubelike concretions are only a few inches thick, homogeneous, and harder than the interiors, which are often friable masses of sandy, ball-like concretions, with loose sand filling the interstices. The cementing material is calcium carbonate. Concretionary sandstones may cap columns in much-dissected localities, and along cliffs may protect the underlying sand so that vertical or smooth-walled surfaces as high as 30 feet are formed. Large areas underlain by the Ojo Caliente Sandstone have no concretions, or only a few, and some of these areas have a subdued, rounded topography modified by loose sand, which is shifted back and forth by the winds. Other areas of soft sand are being strongly dissected by small, finely branching gullies which often cause the sandstone to become sculptured into an intricate system of vertical columns that become pointed and spirelike toward the top.

At several horizons, and especially near the middle of the member, small, round, sand-blasted, and light-colored sandstone balls were observed. The origin of these sand-blasted balls is not clear, although they appear to have been reworked from lower beds of the member. Commonly they are between $\frac{1}{2}$ inch and 1 inch in diameter.

Fossils are rare in the Ojo Caliente Sandstone; only in the Rio del Oso collecting locality (fig. 2) were significant numbers of specimens found. These fossils came from the lowermost 200 feet of the member in this locality.

Strong arguments could be presented for separating the Ojo Caliente Sandstone as a new formation, for it is certainly a distinctive lithologic unit, easily recognizable, mappable, and with an unmistakable, although interfingering, lower boundary. We prefer to consider it a member of the Tesuque Formation, for the rocks of which it is composed were obviously winnowed from the Pojoaque and Chama-el rito members of the Tesuque and were the response to an environmental change that brought Tesuque deposition to a close. At many points in the areas in which the Chama-el rito Member and the Ojo Caliente Sandstone are in interfingering contact, the dune sands of the Ojo

Caliente appear to have encroached upon, displaced, and finally overwhelmed (above, p. 67) the broad channels of gravel of volcanic origin that are characteristic of the Chama-el rito Member.

Some lithologic similarities exist between the Ojo Caliente Sandstone and the Zia Sand Formation (Galusha, 1966), which is treated briefly in this report in the section on pre-Santa Fe Group formations. Despite the general gray or whitish or pinkish color of each, the eolian cross-bedding, the similarity of concretions, the weathering characteristics, and the similarity of topographic expression, these beds are vastly different in age. The Zia Sand Formation is Arikareean to Hemingfordian in age, and the Ojo Caliente Sandstone is Clarendonian. They each represent, obviously, a response to a similar set of environmental conditions that occurred millions of years apart, and these lithologic and other similarities emphasize the danger of relying solely on lithology for correlation.

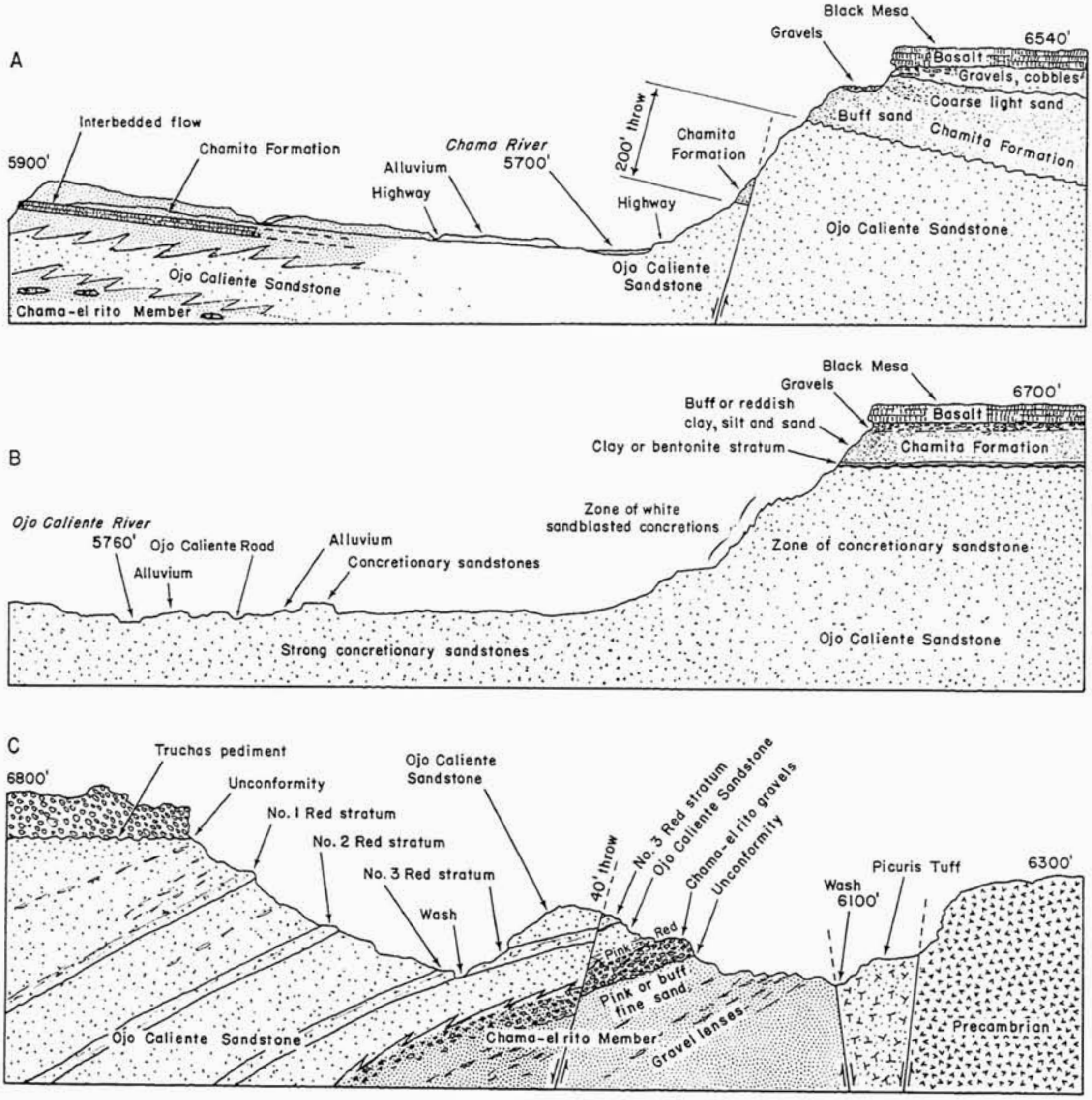


FIG. 28. Relations of Ojo Caliente Sandstone at three sites. A. Southwest tip of Black Mesa. B. Unbroken section on west side of Black Mesa. C. Cross section in Dixon sub-basin on Embudo Creek.

## CHAMITA FORMATION, NEW NAME

Strata of the Santa Fe Group in the type area that are stratigraphically above and are unconformably in contact with the Ojo Caliente Sandstone, which is the uppermost member of the Tesuque Formation, are here proposed as a new formation. The term Chamita Formation is used for these rocks, which are here distinguished and described for the first time. The uppermost boundary of the Chamita Formation commonly is marked by an unconformity, and it is overlain by later formations at several different localities. These later formations include the Puyé Conglomerate, Los Pinos Gravel, and beds questionably assigned to the Ancha Formation, to the Servilleta Formation, to unnamed beds of the Picuris re-entrant, and to constructional deposits on late erosion surfaces. These occurrences are discussed later in this section. The Chamita Formation, in addition to being lithologically distinct, has produced an extensive fauna that is appreciably different from that previously reported from the Santa Fe type area. These deposits are shown by the fossils to have been deposited during a segment of Hemphillian time. This is discussed in detail in the section on the age of the Santa Fe Group.

The San Juan collecting locality (fig. 2) is selected as the type locality of the Chamita Formation because it contains a large part of the stratigraphic section referred to the formation. The formation takes its name from the nearby village of Chamita. The type section is shown as an ideal section in figure 29, and is situated in a small, triangular area lying south of Black Mesa between the Chama River and the Rio Grand (figs. 30A, 38). The apex of the triangle is near the mouth of the Chama, and the greater part of the type section lies within the boundaries of the San Juan Pueblo Grant. The type section is further designated as underlying the NW. $\frac{1}{4}$ of sect. 10 and the W. $\frac{1}{2}$ of sect. 3, T. 21 N., R. 8 E., in Rio Arriba County, New Mexico.

One of the distinctive features of the type locality is the presence of two zones of white to pinkish tuffaceous beds (fig. 29). The Lower Tuffaceous zone comprises about 80 feet of moderately coarse sand and gravelly layers, with four or more white tuff layers and some dark ashy sand strata interspersed throughout the zone. The Upper Tuffaceous zone is composed of 100 feet of white, light-colored or pinkish, tuffaceous beds. The white tuff layers or bands of the Upper Tuffaceous zone are commonly several feet thick, but the generally light color of the zone results from the dissemination throughout the zone of the white pumiceous or ashy particles. In the lower portion of the Upper Tuffaceous zone the sands are mostly quartzitic and range in size from coarse sand to granules, with some fine sand, silt, and reworked tuff present. Quartzitic gravels are abundant and are lithologically different from either the volcanic gravels of the Chama-el rito Member or the granitic gravels of the Pojoaque Member of the Tesuque Formation. Obviously the Chamita Formation marks a profound change in the sedimentary regimen of the type area of the Santa Fe Group. A few cobble beds and occasional isolated boulders have been observed in the section. Cross-bedding is neither extensive nor well developed. The upper portion of the Upper Tuffaceous zone is fine-grained and may have many reddish, fine-sand zones and patches. The Lower and Upper Tuffaceous zones are separated by about 260 feet of light brown or gray bands of fine to coarse sand in which lenses of conglomeratic sand and gravel crop out. Thick beds of rounded to subangular pebbles of quartzite crop out on the Black Mesa side or base of the triangle, and the beds at that point are different in appearance from those on the same horizon at the south end of the locality in the apex of the triangle. Breadth of outcrop of the two tuffaceous zones is vastly different. The lower zone is exposed at only a few places, but, on the other hand, the Upper Tuffaceous beds crop out in a broadly saucer-shaped pattern along the north, southeast, and south sides of the Chamita Formation type locality, and less distinctly on the southwest and west. Dips are low except along the foot of Black Mesa.

The Upper Tuffaceous beds are moderately resistant and characteristically erode to smoothly rounded convex surfaces on which very little weathered mantle rock remains. Occasional sandstone or conglomerate lenses form ledges or benches. These benches and the smoothly rounded surfaces combine to give the zone a distinctive appearance quite apart from the more obvious one of color. Thin clayey layers may be present locally, and thin limey or marly strata also may crop out. Not uncommonly these clayey and limey beds have been associated with concentrations of fossils. The San Juan Quarry

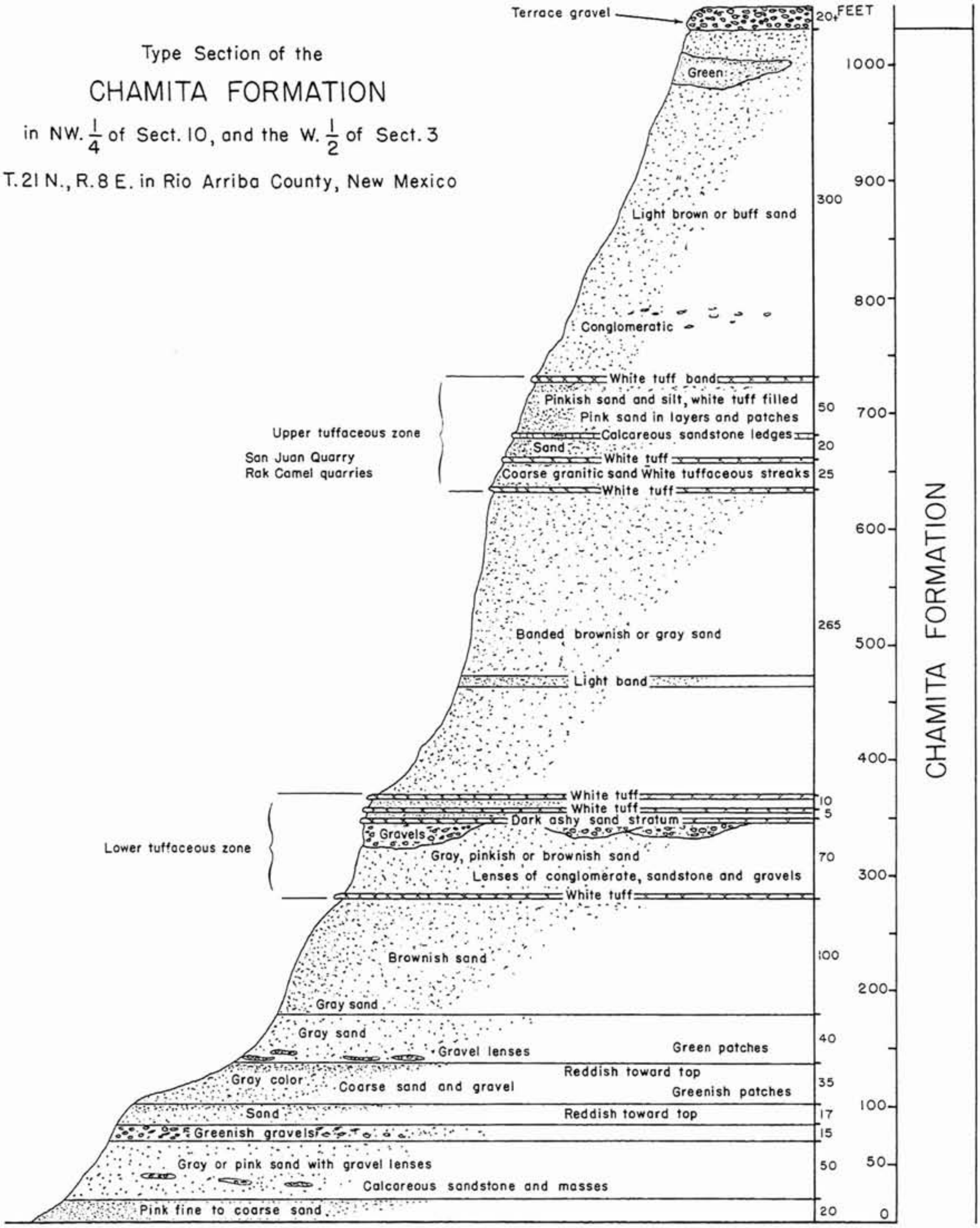


FIG. 29. Type section of Chamita Formation in NW. 1/4 of sect. 10, and W. 1/2 of sect. 3, T. 21 N., R. 8 E., Rio Arriba County, New Mexico.

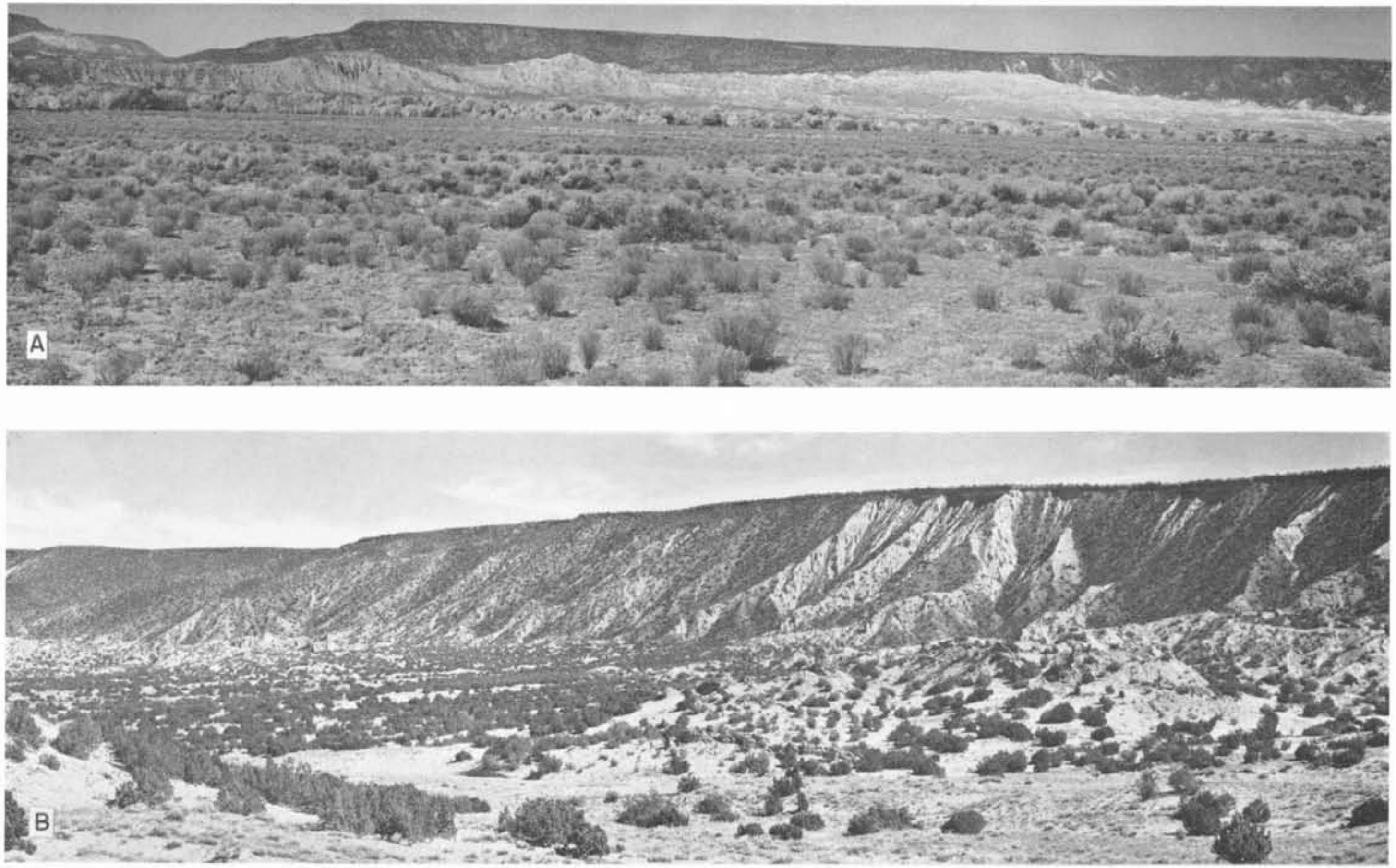


Fig. 30. A. Type locality of Chamita Formation, showing relationship to southern tip of Black Mesa, view looking northwest from east of San Juan Pueblo, New Mexico. Line of trees in middle distance is along Rio Grande. Chama River flows through notch left of top of Black Mesa. At left edge of photograph, white hill in distance is "Conical Hill" in Rio del Oso-Abiquiu locality. Dark hills above and beyond it on skyline are remnants of high-level Lobato basalt flows. B. Part of northwest-facing wall of Black Mesa taken in easterly direction from high cemented zone (Cerrito de la Baca: United States Geological Survey, 1953, 7.5-minute series, San Juan Pueblo, New Mexico, Quadrangle) on east bank of Ojo Caliente River about 2 miles above mouth. Chamita Formation deposits crop out below basalt near top of steep exposures at right center. Several hundred feet of Ojo Caliente Sandstone are exposed on lower slopes of Black Mesa and on low hills in foreground.

and several small quarries have been worked in the Upper Tuffaceous zone.

The topmost tuffaceous stratum in the Upper Tuffaceous zone grades upward into 300 feet of pinkish, brownish, or gray sand, silt, and conglomeratic sand. The general color is light brown or buff. The sediments are coarse in the lower part of the 300 feet, and conglomeratic lenses are numerous. These sediments are much softer than the beds of the underlying Upper Tuffaceous zone and are protected from rapid erosion by remnants of a high, late Pleistocene or Recent, river-gravel terrace 20 or more feet thick which cap high points in the Chamita type locality. The light brown strata dip at a lower angle than those of the Upper Tuffaceous zone. In the center of the saucer-shaped basin the dip is 2 to 3 degrees. The deposits of the Chamita Formation unconformably overlie the uppermost beds of the Ojo Caliente Sandstone of the Tesuque Formation along the northwest side of Black Mesa where the 200 to 300 feet of the Chamita are exposed below the rim. The beds along the northwest side of Black Mesa are a somewhat different facies from those of the type locality, but the fossils collected from them show that they are equivalent.

Additional exposures of the Chamita Formation crop out as isolated patches along the flanks of Black Mesa from El Guique to the vicinity of Velarde. These lie within the Black Mesa Grant and closely approximate the southeastern boundary of the grant. West of the Rio Grande and south of South Wash (United States Geological Survey: Arroyo de la Presa) is a much-faulted area of scattered and ill-exposed outcrops of the Chamita Formation. The area is known as the Hernandez locality, and the topography has been controlled by an erosion surface and the constructional gravels lying thereon. South of Black Mesa the Chamita Formation lies mostly on granitic gravel beds of the Tesuque Formation. The Chamita, however, can be observed overlying a thin wedge of Ojo Caliente Sandstone along the lower slopes of the bold promontories west of the Rio Grande from Santa Clara Canyon south to the Sacred Springs of the Tewa Indians near Guaje Canyon (figs. 31B, 38). These deposits are the most fossiliferous, but also the thinnest, part of the Chamita Formation, for they have been planed off to form the erosion surface on which the Puyé Conglomerate was deposited and are now no more than 200 feet thick. The extremely prolific Round Mountain Quarry is in the Chamita Formation in a small canyon just north of the road to the Puyé Ruins in the NW. ¼ of sect. 20, T. 20 N., R. 8 E., in Rio Arriba County. The quarry is on the Santa Clara Pueblo Grant. (See photographs showing early work in the quarry, fig. 8A, B). Chamita beds in Santa Clara Canyon have yielded characteristic fossils, as have the beds south of Battleship Mountain on the San Ildefonso Pueblo Grant.

Beds of several localities were correlated with, and included in, the Chamita Formation on lithologic similarity, but often it was possible to use both lithology and fossils in making the determination.

The contact of the Chamita Formation with the underlying Ojo Caliente Sandstone is a special variety of unconformity in which the dune sand of the Ojo Caliente was leveled and reworked over the areas in the type locality of the Santa Fe Group in which the Chamita Formation was deposited. At those localities in which the contact can be observed readily, such as the southwest side of Black Mesa, in Santa Clara Canyon, and in the vicinity of Battleship Mountain (fig. 38), the basal beds of the Chamita were heavily overloaded with sand reworked from the Ojo Caliente. Care must be exercised in determining the contact, because the reworked sand beds above the contact often resemble those commonly interpreted as interfingering.

Great variation in thickness of the Chamita Formation is commonplace owing to the unknown, but surely extensive, amount of erosion of the upper beds of the Chamita. These thicknesses may range from more than 700 feet at the type locality (figs. 29, 30A) to 300 feet along Black Mesa (fig. 30B) to a near minimum of 30 feet at Battleship Mountain (fig. 31A).

The Puyé Conglomerate (Griggs, 1964) overlies the Chamita in the area west of the Rio Grande, but along the northwestern side of Black Mesa the Chamita Formation is unconformably overlain by a gravel bed assigned to the Los Pinos Gravel by Atwood and Mather (1932, p. 99), which is in turn unconformably overlain by Black Mesa basalt, which was assigned to the Hinsdale Formation by Atwood and Mather (1932, p. 98), Larsen and Cross (1956, p. 197), Harold T. U. Smith (1938,

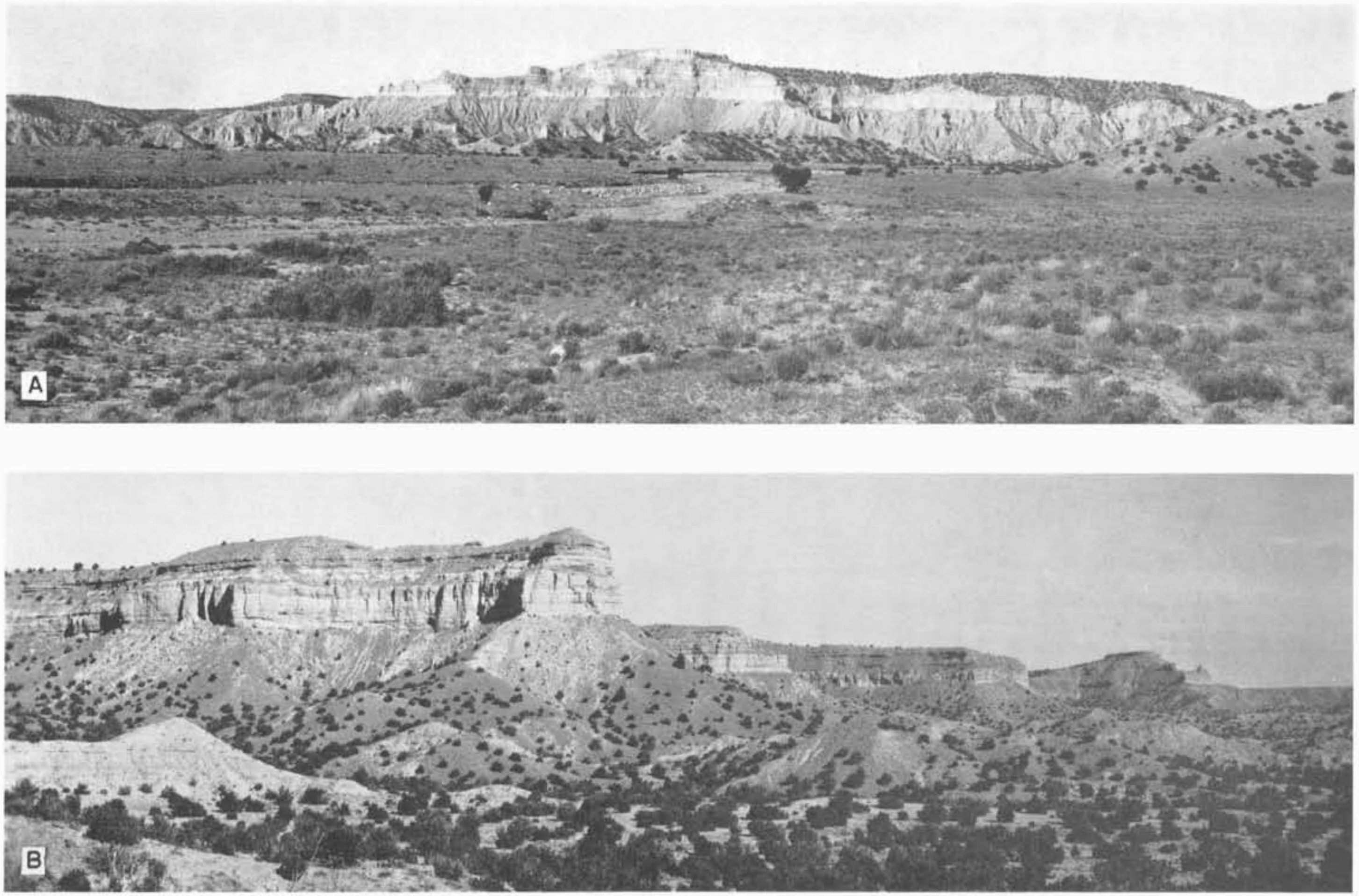


FIG. 31. A. Contact of Chamita Formation of Santa Fe Group with overlying Puyé Conglomerate at prominent white horizontal line across face of Battleship Mountain. Remnant of Bandelier Tuff forms highest point in photograph and weathers with characteristic columnar jointing. Contact with underlying Puyé Conglomerate lies just below white zone below columns. Low cliffs along base of left half of Battleship Mountain are Ojo Caliente Sandstone, underlain by thin wedge of Chama-el rito Member, in turn underlain here by Pojoaque Member. B. Contact of Chamita Formation and Puyé Conglomerate, view of bold promontories held up by Puyé Conglomerate south of Battleship Mountain. Cliffs are Puyé Conglomerate; slopes, Chamita Formation. Contact between the two formations is well exposed in this locality. Battleship Mountain, surmounted by remnant of Bandelier Tuff, at far right.

p. 959), and others. These relations are discussed below (p. 87).

A particularly fossiliferous outcrop of the Chamita Formation occurs near the head of a short steep canyon on the slope of Black Mesa near the settlement of Lyden. Some of the upper sediments in this canyon suggest those of the Upper Tuffaceous zone in the type locality, but near the main fossiliferous concentration the pumiceous particles are concentrated in a distinct stratum and are not diffused through the section. In this respect the mode of occurrence is very similar to that observed near the Round Mountain Quarry. Across the Rio Grande and almost directly opposite the Lyden locality is a small fault block containing a fossil quarry from which was collected the first known remains of *Osbornoceros osborni* Frick (1937, p. 490). The quarry is associated with a channel deposit, that is, the channel deposits lie beneath the quarry horizon and are typically greenish or gray. The quarry and channel sand contain concretionary lenses locally. Concentrations of pebbles occur in the channel deposits but are not extensive. The green-colored sand is observed to grade laterally to gray sand. At this spot a direct relationship seems to exist between the presence of the underlying green channel deposits and the occurrence of fossils. The quarry horizon crops out only a few feet above the level of the wash at this point, and it is extremely fortuitous that the quarry concentration was exposed. The sediments in the Osbornoceros fault block stratigraphically above the quarry horizon have a banded appearance, with colors that are soft tones of brown or red. The beds are fine-grained, for the most part, but lenses of conglomeratic material do occur, and concretions are moderately abundant.

The Osbornoceros fault, which cuts off the Osbornoceros fault block on the east, strikes N. 15°W., 66°E. It is a high-angle normal fault, and the amount of throw was not determined. The beds lying to the east are younger than those of the quarry fault block and are characteristically cliff forming. Thin and quite diffused lenses of sandstone and granitic conglomeratic sandstone grade toward the east to a strong conglomeratic sandstone ledge, several feet in thickness, which tends to cap cliffs in the locality. The cliffs are brown or buff and may display dark brown or reddish streaks locally.

We regard the Chamita Formation as having been deposited as a response to a major geologic event in the type area of the Santa Fe. This event brought to an end the deposition of the Ojo Caliente Sandstone, which in itself was the final stage of deposition of the Tesuque Formation. The contact between the Ojo Caliente Sandstone and the overlying Chamita Formation marks the change from eolian deposition of the Ojo Caliente to one of predominantly fluviatile origin of the Chamita, which culminated in the introduction of a different suite of rocks from a different source into the type area of the Santa Fe. These rocks are easily separable from those of any of the members of the Tesuque Formation, and it is on this criterion that the new term, Chamita Formation, is proposed.

## POST-SANTA FE GROUP FORMATIONS

Post-Santa Fe Group formations discussed in this report are: (1) Puyé Conglomerate, formerly the Puyé Gravel; (2) Ancha Formation; (3) deposits on erosion surfaces; (4) Zia Marl; (5) Servilleta Formation; (6) Espanola Formation; (7) varved or rhythmical sediments; (8) Otowi Lava Flow; (9) Bandelier Tuff; (10) Cerros del Rio lava flows; (11) high level basalts; (12) volcanic rocks; (13) Rio del Oso dikes; and (14) Round Mountain. Most of the above formations were at one time included in the Santa Fe Formation; later, as work progressed, they were separated as distinct formations. A few of them in recent years have been reassigned to the Santa Fe Group, with the remaining formations arbitrarily separated. A few comments on the Pleistocene and Recent formations of the type area of the Santa Fe Group are included in the section on Stratigraphy (above, p. 33).

### PUYÉ CONGLOMERATE

The Puyé (pronounced Poo-yaý) Gravel was first mapped by Harold T. U. Smith (1938, p. 937), and a small area of the formation was later mapped by Denny (1940b, pl. 1). We have mapped additional areas (fig. 38). Working in the Los Alamos area, Griggs (1964, p. 28) described the Puyé Conglomerate as a term to replace Puyé Gravel; he recognized two members: a lower or Totovi Lentil, and an overlying Fanglomerate Member, which represents the main body of Puyé Conglomerate.

The formation consists mainly of gray sand and smaller pebbles, but cobbles and boulders, and in a few places large boulders, are conspicuous sediments. Most of the pebbles are derived from andesitic, latitic, basaltic, and rhyolitic rocks. Some of the pebbles near the base of the formation are quartzitic and granitic, but these form only a small part of the deposits.

Puyé Conglomerates unconformably and continuously overlie beds of the Chamita Formation of the Santa Fe Group from South Wash in the Rio del Oso-Abiquiu locality (fig. 38) southward to Guaje and Los Alamos canyons. South of Guaje Canyon the contact is covered by basaltic talus from the overlying Otowi lava flows. The Puyé Conglomerate is confined to the west side of the Rio Grande where the deposits form high, terrace-like escarpments that are deeply trenched by long, dry washes heading along the base of the Jemez Mountains. The Puyé Conglomerate reaches its maximum exposed thickness northwest of Round Mountain in the vicinity of Santa Clara Canyon. The thickest known section was given by Griggs (1964, p. 28) as 726 feet in a test hole in Pueblo Canyon, which is a northern branch of Los Alamos Canyon, which in turn is a southern tributary of Guaje Canyon. At Guaje Canyon and Los Alamos Canyon the Puyé maintains a thickness of 150 to 200 feet, but it thins abruptly toward the east and southeast, and only 60 feet of the gravels are preserved beneath the northern tip of the Otowi (pronounced Oh-toh-wee) lava flow just west of the Otowi bridge. Across the Rio Grande to the east the Puyé is not present beneath the part of the Otowi lava flow known as the Mesa de los Ortizes, which is surmounted by a dissected volcanic cone.

The contact between the Puyé Conglomerate and the Chamita Formation of the Santa Fe Group is best exposed on promontories south of Santa Clara Canyon. Considerable variation in size and texture and lithology of the Puyé along the contact makes detailed description beyond the scope of this report; in general, however, the sediments can be said to be gray sand, medium-sized gravel, or flattened, smoothly rounded to ovoid cobbles. The large boulders in the Puyé, for the most part, crop out rather high in the section. About 150 to 175 feet of Puyé is exposed on Battleship Mountain (fig. 31), south of Santa Clara Canyon, and is overlain by a remnant about 40 feet thick of the Bandelier Tuff.

The Puyé Conglomerate was apparently named for the Puyé ruins (Tewa Indian: "Where the cottontail rabbits assemble"), which is situated on the Pajarito Plateau (pronounced Pah-hah-reeto) about 10 miles west of the village of Espanola, and 30 miles northwest of Santa Fe. The Puyé Conglomerates were deposited on an erosion surface originating in the Jemez Mountains. The overlying Bandelier Tuff has been stripped from several square miles of the gravel, and a long sloping plateau has resulted. The surface of the plateau probably closely approximates the original constructional surface of the conglomerate. Ancient Indian ruins on the ridges and cliffs of Bandelier Tuff that lie on the constructional surface have been an important archeological study region known collectively as the Pajarito (Little Bird) Plateau.

The Puyé Conglomerate was deposited later than the post-Santa Fe deformation, which brought the deposition of the Santa Fe Group to a close. Although three faults are known to cut Puyé Conglomerates, they are well developed in the Chamita deposits and were traced into the Puyé just west of Battleship Mountain (fig. 38). We believe that these faults represent subsequent adjustment or, more probably, late stages of adjustment to the regional deformation.

A thick veneer of volcanic gravel derived from the Puyé Conglomerate buries the Chamita Formation north of Espanola on the west side of the Rio Grande. The gravel veneer lies on erosion surfaces graded to a series of terraces along the Rio Grande. The relations to the higher, terrace-like escarpment of Puyé Conglomerate can be seen readily, for the long washes trenching the escarpment have supplied the materials as well as provided the agent for lateral corrasion to cut the erosion surfaces. Remnants of Puyé Conglomerate occur north of Rio del Oso, but the main thickness lies south of the igneous spur that extends eastward from the Jemez Mountains on the south side of Rio del Oso.

The age of the Puyé Conglomerate is in doubt. A thick section of the Chamita Formation, however, was eroded prior to the deposition of the Puyé, which would place the Puyé as younger than Hemphillian (mid-Pliocene). A provisional assignment of the Puyé Conglomerate as equivalent to the Gila Conglomerate in age seems feasible. Regional correlations of thick gravel and conglomerate deposits in Colorado, New Mexico, and Arizona have not been made, but some of these deposits are latest Pliocene or early Pleistocene and might well have been laid down during a period of widespread and excessive precipitation, perhaps in conjunction with volcanic activity and regional uplift.

A bed of diatomite in the Puyé Conglomerate has been prospected commercially in South Wash (United States Geological Survey: Arroyo de la Presa) south of Rio del Oso (fig. 38). This is the only diatomite bed so far reported from the entire region. Farther south, in the region between Santa Clara Canyon and Los Alamos Canyon, lake deposits were observed at several sites in the Puyé Conglomerate. Some of these lake deposits have been called Santa Fe beds mistakenly, in popular articles on scenic points of interest that have appeared from time to time in newspapers and magazines.

## ANCHA FORMATION

The term Ancha Formation was applied by Spiegel and Baldwin (1963, p. 45) to detrital materials lying with angular unconformity upon the Tesuque Formation (the Pojoaque Member of the Tesuque Formation of the present report). They pointed out that the rocks of the Ancha Formation lie on an erosion surface (p. 49), but they had difficulty in determining the contact between the Ancha and the Tesuque in the Santa Fe area.

We consider the rocks included in the Ancha as Pleistocene, approximately equivalent to or slightly post-Bandelier Tuff in age. One outcrop of pumice lithologically similar to that characteristic of the Otowi Member of the Bandelier Tuff was observed near the base of the Ancha in the West Cuyamunque Wash (United States Geological Survey: Arroyo Jacona) (fig. 25). The Ancha is readily distinguishable from the Pojoaque Member in the West Cuyamunque general area where it lies with angular unconformity on the Pojoaque; this is shown particularly well in the ramifying gullies in the head of West Cuyamunque Wash and in the heads of some of the washes that parallel it on the west.

Spiegel and Baldwin (1963, pp. 54, 56) recognized three or more graded surfaces as having been developed prior to and during deposition of the Ancha Formation. They named and discussed three of these: (1) the Plains surface, (2) the Airport surface, and (3) the Divide surface. In our opinion the beds underlying the Plains surface should be separated at least on the member level from those underlying the Divide surface. The "marls" and sands underlying the area described as the Plains surface were part of Hayden's (1869, p. 166) original description of the Santa Fe marls. Obviously the beds underlying the Plains surface are younger than those of the Divide surface; moreover, they are of quite different lithology.

The relations of the Ancha Formation to the conglomeratic and detrital materials lying on the Truchas pediment of the Picuris re-entrant of Cabot (1938, p. 98) or the Penasco Embayment, as mapped by Kelley (1956, p. 110), remain to be worked out. The geomorphology of the type area of the Santa Fe Group is a major research project that would add immeasurably to the knowledge of the Santa Fe area and awaits only the attention of an interested investigator.

## DEPOSITS ON EROSION SURFACES

Remnants of erosion surfaces and the constructional deposits preserved thereon are conspicuous parts of the geomorphology of the Santa Fe region. The erosion surfaces are all of post-Santa Fe age, and the interpretation of the sequence of events during which the various surfaces were cut might well provide future investigators with problems of monumental proportions and solutions of great significance.

The deposits lying on the various erosion surfaces are of many kinds. Some are basaltic or andesitic lava flows and associated tuff deposits. Others, such as the Puyé Conglomerate and the deposits on the Truchas pediment (see discussions of pediments and erosion surfaces, p. 95), are thick gravel accumulations derived from the mountains. Still others are a thin veneer of gravel partly covered with a coating of caliche. At other places a thin layer of gravel and a greater or less thickness of buff or yellowish brown or reddish brown fine sand cover the surfaces. At some localities only buff or brownish wind-blown sand is present. Other special deposits are related to the disruption of adjacent terraces or erosion surfaces. Two such deposits are: (1) extensive deposits of subangular blocks of lava boulders, cobbles, and pebbles derived from the Lobato lava flows that cover many erosion surfaces in the Rio del Oso-Abiquiu locality; (2) some gravel deposits derived secondarily from the Puyé Conglomerate, or other gravel beds, and preserved on lower and later erosion surfaces.

Pond deposits, on one of the lower erosion surfaces in Kunya Ruins Wash, 2½ miles southeast of Abiquiu, have produced fragments of mammoth teeth and other fragmentary late Pleistocene fossils, and also several kinds of very small invertebrates. The pond deposits are greenish or brownish in color and are commonly less than 4 feet thick. Similar appearing invertebrates occur at several sites in the Espanola Formation, suggesting contemporaneity of these deposits with the Espanola Formation but not necessarily proving it.

## ZIA MARL

The Pleistocene deposits that lie on the Llano de Albuquerque were named the Zia Marl by Reagan (1903, p. 84) who believed them to be Eocene in age. He discussed at some length his reason for allocating them to the Eocene, and mapped (pl. 4) them as underlying the Zia Mesa (his name for the Llano de Albuquerque). Earlier Herrick (1898, p. 29, pl. 13) called these deposits the Albuquerque Marl, but his attention had been directed primarily to the caliche. He determined the age of the marl as (?)Pleistocene—a remarkably accurate estimate for his day. Bryan and McCann (1938, pp. 3, 5) described the Llano de Albuquerque at length and cited the "marl" of Herrick (which was also Reagan's Zia Marl) as caliche, and used it to support their conclusion that a great erosion surface beveled the Santa Fe beds. This they (p. 8) identified as a part of the Ortiz surface of Ogilvie (1905).

The Zia Marl was listed by Wilmarth (1938, p. 2394) and by Keroher and others (1966, p. 4338) as questionably Eocene. Wilmarth further noted that Herrick (1898) called the beds Pleistocene. It is clear that the term Zia Marl should be abandoned, for it is preoccupied by Albuquerque Marl and, furthermore, is not an Eocene formation. It should be noted that the term Albuquerque Marl was applied to deposits occurring on several erosion surfaces besides that of the Llano de Albuquerque. Bryan and McCann (1938, p. 14) named two such later surfaces. Reagan (1903, p. 86) did not recognize that his Zia Marl was the same as Herrick's Albuquerque Marl, but used the term Albuquerque Marl as follows: "The Pliocene rocks in the Rio Grande embayment which are identical with the Jemez marls, just described, will be here called the Albuquerque marls. These marls are a continuation of the Santa Fe marls of Cope, a part of which was identified by him when at Algodones in the seventies."

In the interest of stability of stratigraphic nomenclature, we believe that the terms Jemez Marl and Zia Marl should be abandoned. Neither of these has been published since originally proposed (Reagan, 1903), and in each case the names were applied to beds with prior names. Moreover, the ages allocated by the original authors give an erroneous stratigraphic position to the formations, which probably accounts for the disuse of the terms.

## SERVILLETA FORMATION

The Servilleta Formation was described by Montgomery (1953, p. 53, pl. 1) as unconformably overlying both Picuris Tuff and Santa Fe beds in the Picuris Range and vicinity. He mapped gravel and basalt flows in the Dixon and the Rinconada localities as part of the Servilleta, and this concept was expanded by Lambert (1966, p. 45) in his report on the Taos-Questa area. These beds have been regarded as part of the Hinsdale Formation and the Los Pinos Gravel (Atwood and Mather, 1932, p. 99; Harold T. U. Smith, 1938, p. 964) and have included also the lava beds of the Taos Plateau as delineated by Upson (1939). Black Mesa (fig. 28) is a remnant of a lava tongue from the Taos Plateau. Lambert's (1966) study of the Servilleta has contributed greatly to the understanding of the Servilleta and the series of Pleistocene beds of which it is a part. Much still remains to be done in interregional correlations of the Servilleta units with those of the type area of the Santa Fe farther south, especially correlations with the beds lying on the Truchas erosion surface, and with the Ancha Formation.

Miller, Montgomery, and Sutherland (1963, p. 50) pointed out that the Servilleta is possibly equivalent to the Ancha Formation, but, if not equivalent to the Ancha, then is younger than the Tesuque but older than the Ancha. They mapped Black Mesa, Dixon Mesa, and underlying gravels as part of the Servilleta Formation.

## ESPANOLA FORMATION, NEW NAME

Near the town of Santa Cruz are some Pleistocene remnants from which Frick (1926c, p. 444) reported a fine specimen of *Canis dirus*. The Pleistocene deposits cap the ridge along the west side of First Wash (United States Geological Survey: Arroyo del Llano) for several hundred yards and range from only a few feet to 30 or 35 feet in thickness. The southernmost edge of the Pleistocene remnant (fig. 32) is about 240 feet north of the General Land Office survey stake MC7, SCG; sect. 31, T. 21 N., R. 9 E., Rio Arriba County, New Mexico. This locality is here designated as the type locality of the Espanola Formation, a new name proposed for a series of Pleistocene remnants in the general Espanola Valley area. The new formation takes its name from the town of Espanola near which some of the best exposures of the Espanola Formation crop out. Frick (1926c, p. 444) published a photograph which shows a typical outcrop of the formation. The sediments are wind-blown sand or silt, with a distinctly brownish color. They are easily distinguished from the underlying Pojoaque Member of the Tesuque Formation, for the Pleistocene sediments lack the light pink, buff, or flesh color of the beds of the Santa Fe Group. The Pleistocene remnants are loess-like in that they tend to stand with vertical faces, except where weathering is advanced. Several kinds of small invertebrates have been collected in the deposits of the type locality.

Erosion of the beds of the Santa Fe Group produced surfaces of considerable relief prior to the deposition of the Pleistocene Espanola Formation. Field relations at the type locality suggest that the Espanola Formation accumulated in a small valley that had been cut in the Pojoaque Member. Similar deposits occur at widely separated points from El Rito to Santa Fe; they occur at many elevations, and, although commonly not so thick elsewhere, there is reason to believe that many of them can be considered essentially equivalent to the First Wash (United States Geological Survey: Arroyo del Llano) remnants. A sketch of the type locality and the type section is given in figure 32. A few remnants of the Espanola Formation are mapped in figure 38.

A good example of the Espanola Formation crops out on the hill just west of United States Highway 64 about 1 mile southeast of Espanola, New Mexico. At this point the remnants are scattered over the slope of the hill, with differences in altitude of as much as 100 feet. The strong unconformity at the base shows that the area had been well dissected before the Espanola Formation was deposited.

Fragments of fossils testifying to the presence of *Equus*, *Bison*, ?*Camelops*, and other forms in the scattered Pleistocene remnants capping some of the hills in the Skull Ridge collecting locality (fig. 2) give additional support to the idea that the definitely recognizable Pleistocene deposits in the type area of the Santa Fe Group are extensive enough to warrant being accorded the rank of formation.

The Espanola Formation once must have been very extensive and probably formed a mantle of wind-blown sand and loess over the entire area. Eventual correlation of the Espanola Formation with the loess and loess-like deposits of the Great Plains east of the Sangre de Cristo Range seems likely when a thorough study of the subject has been made. Winds strong enough to build the great beds and associated eolian deposits of the Great Plains would surely have carried vast quantities of dust over the Sangre de Cristo Range and would have whipped large quantities of sand and finer particles from the beds of the Santa Fe Group.

## VARVED OR RHYTHMICAL SEDIMENTS

A small deposit of varved clay or rhythmically deposited sediments crops out on the east side of the Rio Grande in White Rock Canyon just south of the mouth of Canyada Ancha approximately on the west boundary of the Caja del Rio Grant about 3½ miles southwest of Otowi Bridge. The varved clay fills most of the lower part of a small valley that had been cut in the Santa Fe beds. The outline of part of the floor of the valley and the contact with the underlying Pojoaque Member of the Tesuque Formation is excellently exposed, and several feet of river-channel conglomerate lie at the contact. The varved clays overlie the conglomerate and grade upward into a fairly thick series of yellowish to cream-colored beds of laminated silt, sand, and clay, which typically have small ironstone concretions or limonite plates along the bedding planes.

Rhythmical sedimentation took place in this small lake for a period of more than 200 years, with the eventual dissolution of the glacier

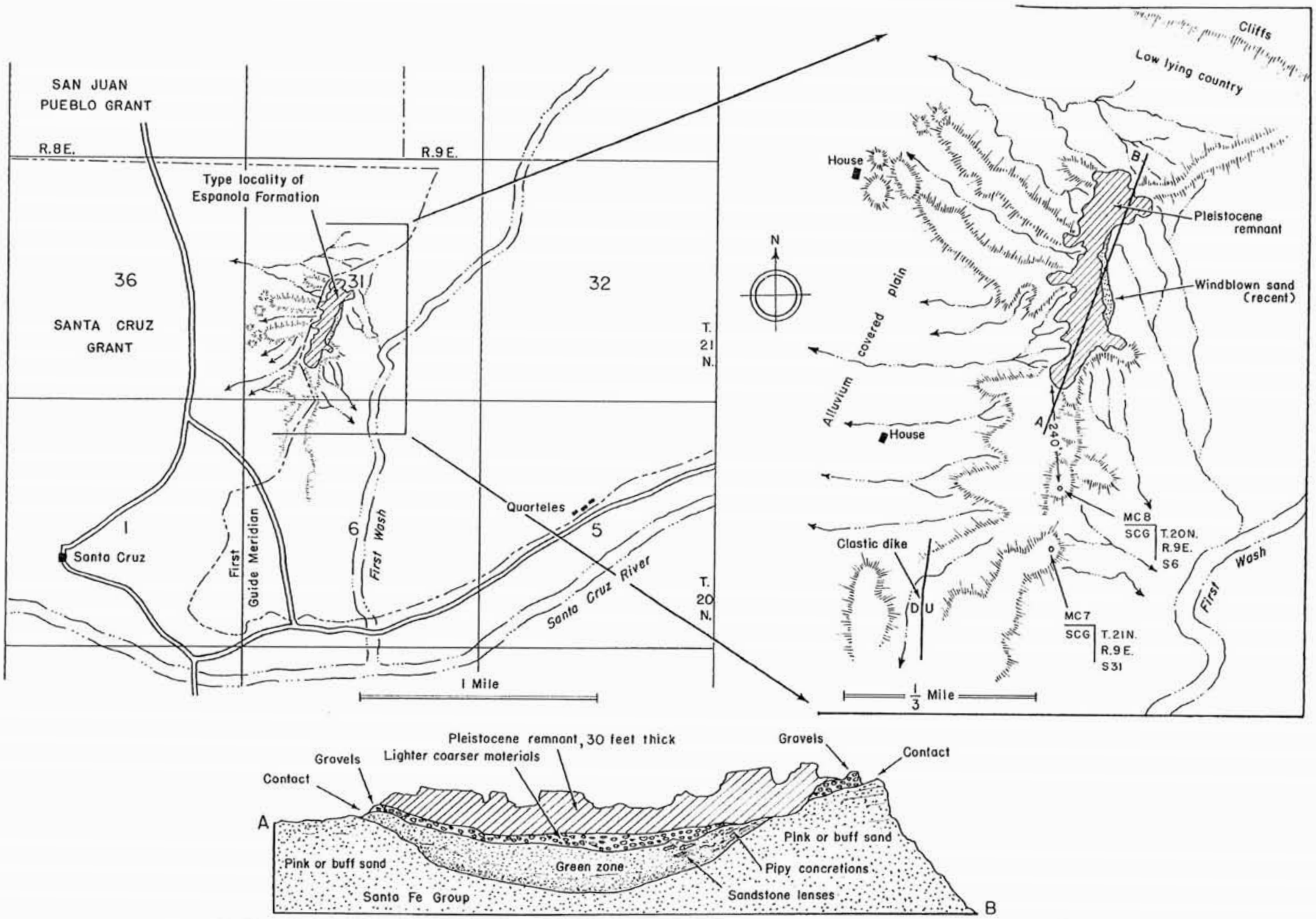


FIG. 32. Type locality of Espanola Formation in sect. 31, T. 21 N., R. 9 E., Rio Arriba County, New Mexico.

supplying the sediments indicated by a gradual change from varved to laminated deposits. The glacial lake was apparently formed by the damming of White Rock Canyon at some point downstream, after the Rio Grande had cut the canyon almost to its present depth, for the bed of the river is not more than 20 feet below the floor of the old varve-filled valley.

Disruption of the Cerros del Rio flow was active prior to the deposition of the varves, because a large block of lava 4 feet by 3 feet by 2 feet was caught along the south side of the basin of varve deposition. Two photographs of the varves appear in figure 33.

A laminated deposit similar in many respects to that overlying the varves was observed along the west bank of the Rio Grande about half a mile below the Otowi bridge.

## OTOWI LAVA FLOW

The name Otowi lava flow is here applied to a basaltic lava flow that crops out on each side of the Rio Grande in the vicinity of the Otowi bridge. The type section is at the northern tip of the flow about half a mile west of the Otowi bridge (fig. 34C) and a few hundred yards south of Guaje Creek. The Otowi flow slopes westward and southwestward, and its northern limit is the south border of Los Alamos Canyon. At no point does the Otowi flow cross Los Alamos Canyon, but black stratified tuff and laminated, greenish, silty clays, fine gravel, and sand occupy its position north of the canyon.

The Otowi flow can be traced continuously to the south past the old Buckman Bridge road to a point where it passes beneath the lava of a higher, later flow. From that point south in White Rock Canyon the identity of the Otowi flow is lost beneath the thick cover of talus formed by the disruption of the very thick upper flow that forms the rim rock of White Rock Canyon. The Otowi flow crops out westward from the type section for about 2 miles along Guaje and Los Alamos canyons, and a fine section of the underlying Puyé Conglomerate can be studied along most of the distance. Chamita Formation beds are also exposed at a few places along the lower ends of the canyons, and the relation of the three formations to one another is well shown.

The Otowi lava flow laps marginally over the southeastern corner of the Puyé Conglomerate and is later, therefore, than the Puyé. East of the Rio Grande the Puyé Conglomerate is not present beneath the flow on Mesa de los Ortizes (fig. 34B).

West of the Rio Grande the Bandelier Tuff is observed to overlie the Otowi lava flow at nearly all exposed contacts; at a few small outcrops bluish gray laminated clays and silt were observed to be locally intercalated. One such outcrop is at the base of the small, isolated, cone-shaped hill of Bandelier Tuff resting on the Otowi flow west of Otowi bridge (fig. 34C).

Mesa de los Ortizes, an extension of the Otowi lava flow, east of the Rio Grande is surmounted by a dissected volcanic cone. The cone was probably the source of the Otowi flow. Thick deposits of tuff, cinders, agglomerate, basaltic dikes, sills, and irregular intrusive masses have been exposed by the Rio Grande along the west side of the cone, which is shown in the sketch of Mesa de los Ortizes (fig. 34B).

## BANDELIER TUFF

The Bandelier Rhyolite Tuff was mentioned by Harold T. U. Smith (1938, p. 959) in his study of the Abiquiu quadrangle, and several isolated outcrops were mapped by him (p. 937, fig. 4). Although the Bandelier Tuff is not observed to be in contact with beds of the Santa Fe Group, yet the Bandelier forms a distinctive and scenic part of the geologic section. Denny (1940b, pl. 1) mapped a small area of Bandelier Rhyolite Tuff along the west side of White Rock Canyon but did not discuss the formation other than to include it with Quaternary rocks of the locality (p. 686). Ross, Smith, and Bailey (1961, p. 140) mapped and described the Bandelier Rhyolite Tuff in some detail, and Ross and Smith (1961) the same year described in great detail the lithology of the ash flows of the Jemez Mountains and particularly the welded tuffs of the Bandelier. Spiegel and Baldwin (1963, p. 64) discussed deposits of pumice in the Santa Fe area that overlie a basalt flow and noted a similarity to pumice near the junction of the Los Alamos and Bandelier National Monument highways. Griggs (1964, p. 46) redescribed and redefined the formation as the Bandelier Tuff, naming three new members: (1) Guaje Member, composed mostly of pumice; (2) Otowi Member, light buff to pinkish pumiceous tuff; and (3) Tshirege Member, ash-flow and ashfall pumice and tuff. This last member apparently

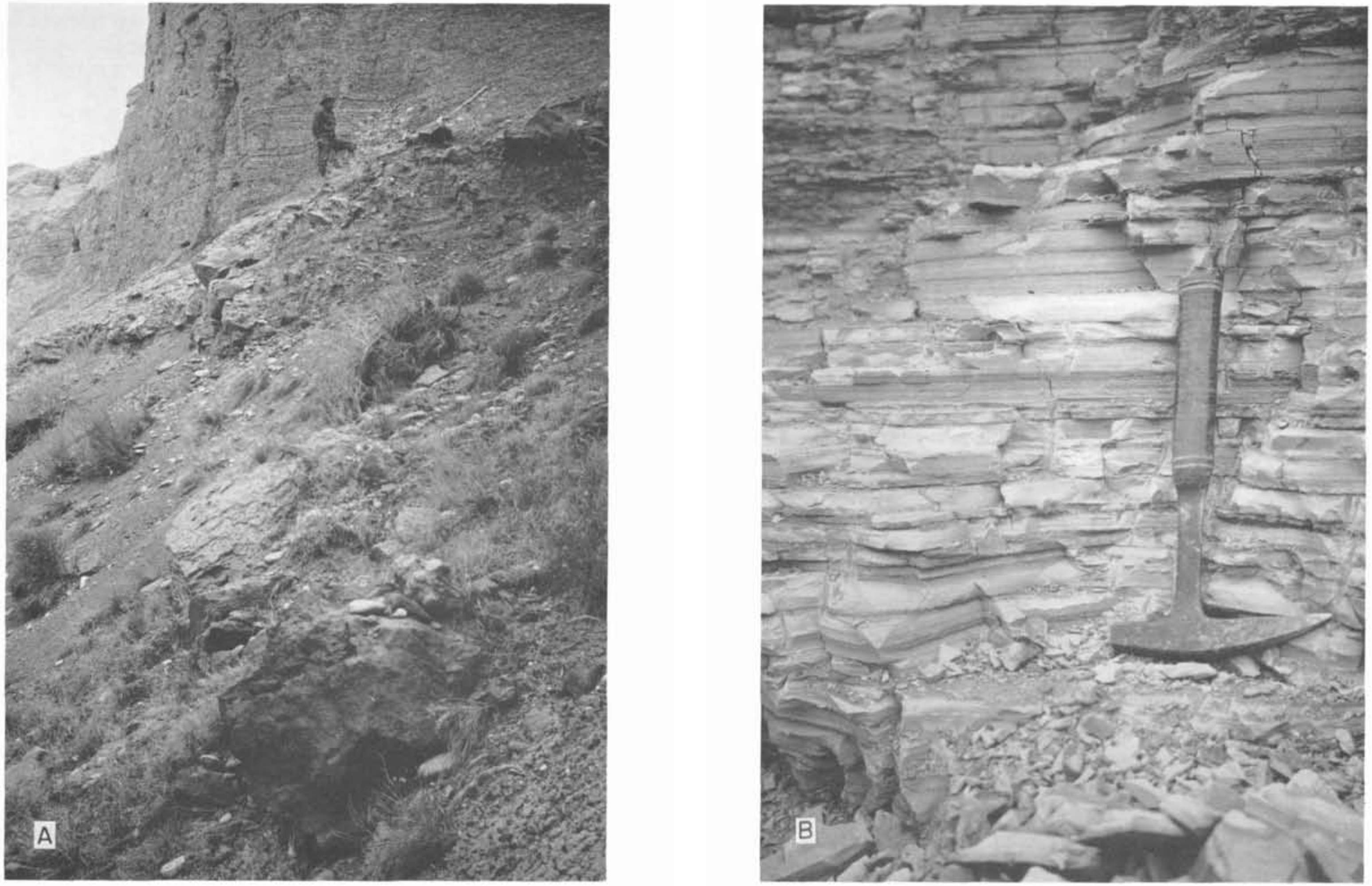


FIG. 33. A. View, looking north, of varved or rhythmically deposited sediments on east side of Rio Grande south of mouth of Canyada Ancha. Man is standing on lens of conglomerate that underlies varves. B. Close-up of varves exposed in cliff wall to right of man in A.

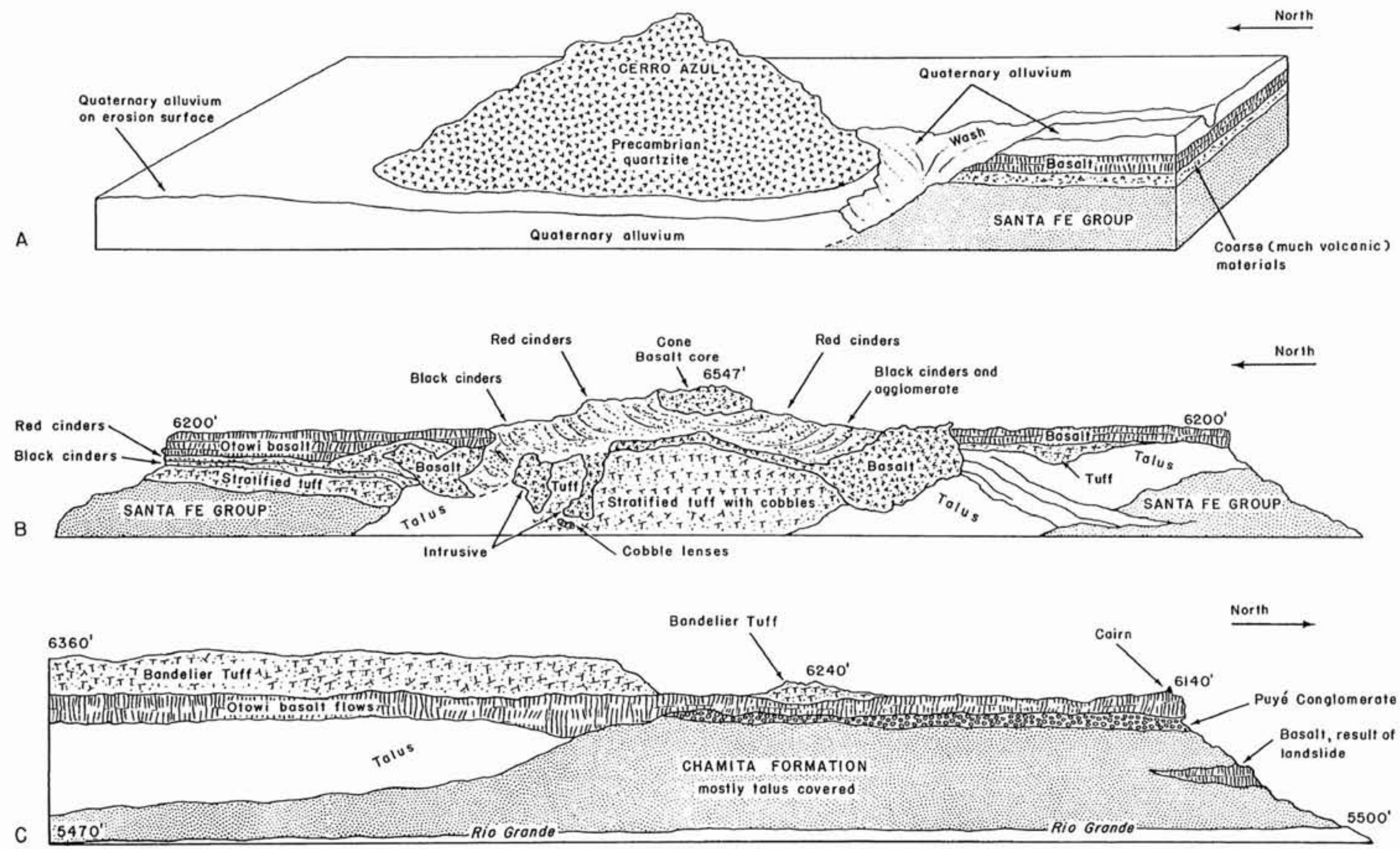


Fig. 34. Diagrams of geologic relations at Cerro Azul, Mesa de los Ortizes, and Otowi lava flow. A. Cerro Azul, Precambrian inlier completely surrounded by Quaternary alluvium. Small exposure of beds of Santa Fe Group crop out in wash at southeast corner. Basalt is edge of distal end of one of flows of Taos Plateau. B. Mesa de los Ortizes, cliff face, showing volcanic cone and Otowi basalt flow and relations to beds of Santa Fe Group. Area shown is 2 to 3 miles long and is east of Rio Grande and south and no more than ½ mile west of Otowi bridge. C. Correlation detail west of Rio Grande, west and south of Otowi bridge, showing cliff-face view of about 2 miles. Otowi basalt is intercalated between Bandelier Tuff and Puyé Conglomerate.

comprises most, but by no means all, of the welded tuffs of the area.

The Bandelier Tuff, as now exposed, is a remnant of a thick mantle of hot ash flows that welled from vents in the Jemez Mountains. Some of the pumiceous portions may have originated in explosive eruptions and represent true ash falls rather than cascading ash flows, but the bulk of the formation seems to have been of ash-flow origin. These distinctive pinkish, buff, or whitish tuffs crop out in isolated groups around the entire Jemez Mountains except along the northeast corner from Rio del Oso to a point near Cañones, New Mexico, and, at the south end of the mountains, in the general Borrego Mesa area. These and intervening areas once may have been covered completely by the mantle. Renick (1931, p. 69) discussed the Bandelier Tuff as rhyolite and rhyolite tuff, and described a few localities along Jemez Creek and its tributaries where he found the rhyolite tuff resting on Poleo Sandstone, Chupadero Formation, Abo Sandstone, and even on beds of the Magdalena Group. In the type area of the Santa Fe Group, however, the Bandelier Tuff is in contact with three formations: (1) the Puyé Conglomerate, (2) the Otowi lava flow, and (3) the Cerros del Rio flows. Several other volcanic rocks of the Jemez Mountains have been differentiated, but these are not discussed in this report.

The base of the Bandelier Tuff is mostly, although by no means everywhere, comprised of beds of white to gray or yellowish ash or pumice. The great bulk of the formation, however, is a fairly compact yellowish, cream-colored, pinkish, or brownish tuff. The formation has been incised deeply by streams that have cut across it from the mountains, and the topographic expression commonly is one of deep canyons with high, narrow, intervening ridges or mesas forming steep escarpments. The south slopes of the escarpments are usually very precipitous, and many ancient Indian talus and cliff villages were built along them. Large and very numerous pueblo ruins occupy the summits of some of the ridges. The rhyolite tuff in many parts of the area is columnar, particularly the welded ash-flow portions of the Bandelier. These were broken and readily shaped by the Indians to form building blocks for their pueblos. Tuff that was not welded could be worked easily by stone tools, and hundreds of rooms and caves were excavated in the cliff walls. Cliffs of some of the strata of the Bandelier Tuff have a well-marked joint set; huge blocks break off and form steep talus slopes. Rock falls must have been an ever-present danger to the Indians of the cliff villages.

Slopes are smoother and cliffs are commonly lower on north-facing hillsides, and this feature is definitely correlated with the tendency of snow to accumulate on north slopes in this region, and for moisture to remain longer from the summer rains. The greater moisture content supports a much greater vegetation density, and the two factors work together to weather the bedrock to soil and to retain the soil when it is formed. On the south slopes less moisture falls or is retained, less vegetation grows, and as a result erosion is comparatively rapid.

Phenocrysts of quartz and sanidine are often numerous in the ash-flow tuff, and on some benches or mesa-like areas hundreds of anthills made up of piles of predominantly quartz crystals have been observed. Some of the anthills are as high as 2 feet.

Some of the strata of the unwelded ash flow or pumice ash flow have a tendency to weather, with a surface pockmarked with natural holes and caves, and many of these cavities were utilized as dwellings by the ancient Indians. Flakes and chips of obsidian and fragments and blocks of fibrous pumice are numerous in some beds.

The Bandelier Tuff increases in thickness toward the south; this general relation is shown in figure 4. Only isolated mesas of the formation crop out north of Santa Clara Canyon, for example, Shupinna Mesa, but south of Santa Clara Canyon the formation is continuous and the thickness is as much as 1200 feet. (Griggs, 1964, p. 47, wrote that 1050 feet of Bandelier was penetrated in a drill hole in Los Alamos Canyon.) One of the best-exposed and most accessible sections of the Bandelier is in the canyon of El Rito de los Frijoles in the Bandelier National Monument.

## CERROS DEL RIO LAVA FLOWS

The Cerros del Rio were described by Bryan (1938, p. 208) and regarded by him as interbedded in the Santa Fe Formation. We have failed to confirm his correlation, and regard the Cerros del Rio flows as slightly later than the Otowi lava flow and in part contemporaneous with the Bandelier Tuff. The evidence for this correlation follows: The rim of White Rock Canyon, as far south as the Rito de los Frijoles, consists of very thick, andesite-basalt flows that are stratigraphically higher than the Otowi lava flow; this relation is well shown in the canyons west of the site of Buckman Bridge. At least four separate flows, including the Otowi flow, are exposed in the canyon up which the old Buckman Bridge road winds. The lowermost flow has a general north-south trend and apparently developed a high wall where it was in contact with sedimentary rocks, for fine-grained sediments are plastered on the surface of the lava. Buff tuffaceous sediments 30 to 35 feet thick separate the lower flow from the overlying Otowi flow. These sediments are very tuffaceous and unlike Santa Fe deposits in color, texture, and weathering characteristics, although some formation of the Santa Fe Group was probably the source of much of the included sand. Above the Otowi flow are several feet of stratified tuff and sand, and above this sequence are two or more lava flows, one of which forms the rim of White Rock Canyon.

At many points where one lava flow of the Cerros del Rio is in contact with another, the lava above the contact is often highly fragmented and contains much yellowish or brownish earthlike material, which may be palagonite. In a short canyon leading north-northwest from the "white-rock" on the Buckman Bridge road a small tongue of the upper flow is interbedded in the white pumiceous tuff as though it had flowed into a small canyon in the tuff and solidified. The tongue is overlain by pink tuff, gray tuff, and columnar tuff, all of which are part of the Bandelier Tuff.

South of the Buckman Bridge road, on the west side of White Rock Canyon, a long narrow ridge of Bandelier Tuff extends down to the rim of the lava. South of this ridge the entire area for several miles has been eroded to a much lower level. The area has been stripped almost to the underlying lava, which forms the rim of White Rock Canyon. Soil and debris from the decomposition and mechanical disruption of the Bandelier Tuff have been deposited on the truncated beds. The present topography is that of a gently rolling, sloping plain on which the streams are not incised, although Pajarito Canyon has cut a trench into the lava no more than 20 feet deep. The plain increases gradually in elevation toward the south, rising to the top of a ridge of rhyolite tuff on the north rim of Potrillo Canyon. The rim rock of lava on the west side of White Rock Canyon has maintained a temporary base-level for the surface of erosion represented by this plain.

On the east side of White Rock Canyon, less than a mile above the mouth of Pajarito Canyon, is a group of permanent springs. A white efflorescence of salts covers an acre or two of the area around the springs, and several small rivulets enter the Rio Grande from them. These springs are adjacent to the base of a cinder cone on the east rim of the canyon. The sides of the cone have been breached by two small ravines. These small ravines have removed large quantities of red cinders and have formed a secondary or erosional crater about a quarter of a mile in diameter. A conical hill of red cinders remains in the center of the crater. A basalt flow forms a rim around the crater, except on the west where it has been removed by erosion. At the north end of the cone the lava flowed down the slope of the cone for a short distance.

The Cerros del Rio lava flows deserve closer study than they have received. Intensive study of the Cerros del Rio conceivably could provide important new interpretations of the geologic history of the Santa Fe area. It is hoped that some investigators of the future will give the Cerros special attention.

## HIGH-LEVEL BASALTS

Basaltic lava flows, which were extruded on erosion surfaces and were originally of greater extent, now stand as high, steep-walled mesas in the northern part of the type area of the Santa Fe Group. The mesas are at different altitudes, and are difficult to correlate because they are isolated. Some evidence of relative age is available, however, and such recorded evidence may eventually be useful in geomorphological studies of the area.

The high Lobato basaltic lavas were mentioned by Harold T. U. Smith (1938, p. 959, fig. 4) and mapped as high-level basalt. The Lobato flows crop out mainly in the J. J. Lobato Grant and apparently were named for the grant. The flows are continuous from Rio del Oso northward to Abiquiu Creek and form a bold escarpment west of the Chama River.

An idea of the stratigraphic position of the high-level Lobato flows can be inferred from their relations to outcrops of Puyé Conglomerate and the Chamita Formation in the Rio del Oso-Abiquiu locality (fig. 2). Several remnants of the Puyé Conglomerate occur in the area north of Rio del Oso. The Puyé remnants are observed to issue from some canyons cut in the edge of the Lobato flows, and at other places they abut against the steep slopes. A few isolated patches of beds of the Chamita Formation crop out along the talus slopes below the Lobato flows. Physically these isolated Chamita exposures are at elevations higher than the Puyé gravel remnants. Stratigraphically the Chamita beds underlie the Puyé gravels (see Puyé Conglomerate, p. 76).

Cerro de las Minas (United States Geological Survey: Sierra Negra) is a high, basalt-capped mesa of small extent a few miles northeast of Abiquiu, New Mexico. The Abiquiu Tuff crops out very high on the mesa, and the Santa Fe beds are faulted down against the Abiquiu Tuff along the south side.

Cerro Pedernal, another high, basalt-capped mesa near Cañones, New Mexico, is also a remnant of a lava flow. A correlation of Cerro Pedernal and Cerro de las Minas would be purely conjectural. Harold T. U. Smith (1938, p. 954) stated that the structural position of the basalt flows on Cerro de las Minas suggests that they are interbedded in the Santa Fe. We interpret the evidence differently and believe the basalt of Cerro de las Minas to be not earlier than that of the Lobato flows and therefore later than the Santa Fe Group.

Black Mesa is a canoe-shaped tongue of basalt about 10 miles long and at no point more than 3½ miles wide. Along most of its length it is more than 700 feet high. It lies along the northwest side of the Rio Grande from Embudo to Chamita, New Mexico, and is probably best described as a remnant of a valley tongue. Near Embudo (Spanish: the funnel) erosion has cut through the basalt, and Black Mesa is separated for nearly 2 miles from the much larger area of lava flows, which are apparently a part of the vast lava plateau that fills the Rio Grande Valley west of Taos, New Mexico, and extends northward to the San Luis Valley of Colorado. Velarde Mesa is an isolated part of the flow lying east of the Rio Grande near Embudo and Dixon, New Mexico.

Atwood and Mather (1932, pp. 98, 99) were the first to suggest that Black Mesa is capped by Hinsdale basalt, and later Harold T. U. Smith (1938, pp. 958, 964) discussed the age relations of the Black Mesa basalt. Larsen and Cross (1956, p. 193) subdivided the Hinsdale Formation into two members on the basis of origin and petrographic character of the material. The lower member was called the rhyolite unit; and the upper, the latite basalt. They speculated concerning the extent of both members into New Mexico, and stated (p. 193) regarding the Hinsdale rhyolite, "Rocks that are almost identical form the regular flows and tuff beds of the Valles Mountains of New Mexico and similar rocks form many of the central Valles Mountains." The latite basalt of the Hinsdale was recognized as reaching as far south in New Mexico as "the south end of Black Mesa near the junction of the Chama River and the Rio Grande" (p. 196).

Recent work by Steven, Mehnert, and Obradovich (1967, p. D50) on the age of the volcanic activity in the San Juan Mountains of Colorado showed that the Hinsdale Formation is much older than previously had been supposed. Potassium-argon dating of the Hinsdale rhyolite gave an age of 22.4 million years. Dates on Hinsdale basalt in the area of Spring Creek Pass of the San Juan Mountains ranged from 12.4 to 15.6 million years. They (p. D55) questioned whether the dated basalt can be grouped with the other basalts in the San Juan region into a single formation fitting the concept of the originally proposed Hinsdale Formation. Their question raises some doubt concerning the feasibility of correlating the lava beds of the Taos Plateau with the Hinsdale.

Ozima et al. (1967) dated a series of lava flows in the Rio Grande Gorge near Taos, New Mexico; the base of the upper, normal-polarity lava flow gave a potassium-argon date of 3.7 million years. The exact relation of this part of the Taos Plateau basalt flow is unknown, but Black Mesa appears to be a valley tongue belonging to the general Taos Plateau sequence. This radiometric age assignment for the Taos Plateau would coincide most nearly with that of the Blancan North American Land-Mammal Age.

Miller, Montgomery, and Sutherland (1963, p. 50) mapped Black Mesa and adjacent remnants of basalt flows as a part of the Servilleta Formation, which commonly has been assigned to late Pliocene or early Pleistocene age. We believe that the basalt lavas of Black Mesa will prove to be Pleistocene in age.

Ross, Smith, and Bailey (1961, p. 139) stated: "The earliest basaltic lavas of the Jemez Mountains erupted from numerous centers over a wide area. They formed a field of low coalesced shields, the remnants of which now form Borrego Mesa in the south and Lobato Mesa and Mesa de la Grulla in the north."

It is interesting to note that the Lobato Mesa basalt overlies the Chama-el rito Member, the Ojo Caliente Sandstone, and some beds, not well exposed, that are here correlated as Chamita Formation, indicating at least post-Hemphillian (post-middle Pliocene) age or possibly Blancan (late Pliocene) age for the Lobato flows. More significant than the probable age of the Lobato flows is the inference that can be drawn regarding the source of the well-rounded volcanic pebbles and cobbles that form the thick lenses that are characteristic of the Chama-el rito Member. Ross, Smith, and Bailey (p. 142) pointed out that "nowhere are the older sediments of the Santa Fe group known to contain volcanic rocks of the Jemez Mountains." In a footnote they added, "Pebbles of volcanic rocks do occur in Santa Fe beds on the east and north beneath the basalts of Lobato Mesa and the Puyé Gravel, but these rocks are unlike those in the Jemez volcanic pile and appear to have come from a more distant source." These are the rocks that we believe belong in the great Vallecitos fan, had their source in the San Juan region of Colorado, and are typical of the Chama-el rito Member of the Tesuque Formation.

The age of the several occurrences of high-level basalt is clearly post-Santa Fe Group.

## VOLCANIC ROCKS

Extrusive rocks are widely distributed around the outcrop area of the Santa Fe Group. The greatest outpourings of lava or other volcanic rocks in the type area of the Santa Fe Group are late Pliocene and Pleistocene in age. Volcanic rocks of the age of the restricted Santa Fe Group are relatively few in number and small in area. Other large areas of volcanic sediments form parts of the Abiquiu Tuff, Picuris Tuff, and Espinaso Volcanics formations and underlie the Santa Fe Group.

Direct evidence of volcanic activity during Santa Fe time is provided by the numerous beds of fine volcanic ash that crop out in the upper part of the Nambé Member and in the Skull Ridge Member of the Tesuque Formation. Volcanism on a smaller scale is indicated by a few ash beds in the Pojoaque Member of the Tesuque, and thick zones of pumiceous tuff are characteristic of the Chamita Formation and suggest that volcanism in the area had undergone a distinct change of pattern during Chamita time. The presence of ash beds, even thick ash beds, however, is not proof of proximity to the source of the eruption. Martin (1913, p. 167), describing the eruption of Mt. Katmai in Alaska, reported that ash from the eruption spread over many thousands of square miles and ranged in thickness from 4½ feet, 15 miles from the crater, to almost 1 foot, 100 miles away, to a fraction of an inch, 150 miles away. Too many unknown factors exist to draw even an approximate comparison between the eruption of the Miocene and Pliocene volcanoes and those of Katmai, Tomboro, Krakatao, or other great historic eruptions. The ancient volcanoes could have been smaller, equal, or vastly greater in magnitude, violence of eruption, and amount of material ejected. The ejected material may have been carried great distances, depending on the strength of the winds.

Late Tertiary volcanic eruptions, some of which may have spread ash over tens of thousands of square miles, have great potential possibilities for interregional correlations, not only of the beds of the Rio Grande Valley but of the Great Plains formations as well. Close synchronization of rock-stratigraphic data, particularly of ash beds, with biostratigraphic data, as shown by the study of the very large collections of mammalian fossils that are available, may lead to correlations quite beyond the expectations of geologists and paleontologists working with the disjointed, often fragmentary, and in some cases erroneous information now available on late Tertiary deposits. Who can say, for example, that the dark ash bed of the Sheep Creek-Snake Creek beds of Nebraska is not equivalent to Ash D of the Skull Ridge Member of the Tesuque Formation of the Santa Fe Group? Who can say that the ash beds of the Valentine-Burge-Ash Hollow sequence of the Great Plains of Nebraska are not represented by ash beds of the Pojoaque Member? What better chance has a geologist to correlate widely separated late Tertiary deposits derived from dissimilar rocks than to work with large collections of fossils and to tie the time information thereby obtained to the volcanic ash beds in each section? Such ash beds are the only late Tertiary stratigraphic layers that conceivably could have been contemporaneously deposited over many thousands of square miles.

Tuffaceous materials, as contrasted to volcanic-ash layers, are present in the beds of the Santa Fe Group but are confined mostly to the Chamita Formation. The Chamita Formation also contains an interbedded lava flow that is one of the few for which conclusive evidence of Santa Fe age is available. This flow is faulted and crops out as low remnants south of Rio del Oso, and here and there along the south side of South Wash where the dips are about 20 degrees east. Locally the flow is amygdaloidal and has burned a fairly thick, red, indurated zone at the base; the maximum thickness of the flow is about 40 feet, but in most places it is less than half of that thickness. The eastern edge of the dipping interbedded flow south of Rio del Oso extends to the west bank of the Chama River about half a mile south of the settlement of Chili. Terrace gravels are preserved on the surface of the lava flow near the river, and these terraces conform closely to the projected planes of erosion surfaces in the Rio del Oso locality. The lava flow deflected the Chama River to the left nearly a quarter of a mile. The west abutment of a proposed Chamita dam was to be set on the lower end of this lava flow. Exploratory holes that were drilled in an attempt to reach the lava where it supposedly had dipped below the surface of the river bed penetrated about 200 feet of sediments without striking a trace of the flow. Probably the end of the flow was originally in the area now a part of the stream bed of the Chama River.

Quaternary basaltic and andesitic flows that cap many of the mesas and buttes of the area were extruded on broad erosion surfaces that had been cut on Santa Fe or older rocks. The basaltic or andesitic-basaltic flows resist erosion, and they commonly cap mesas, many of which are several square miles in extent and several hundred feet high. Even the mesa remnants probably long since would have been removed by erosion had not their slopes been defended by an armor-like talus of lava blocks. Erosion of the soft Santa Fe beds undercuts the flows and hastens the disruption of the mesa borders. Steep talus slopes are formed which consist of extensive interlocking masses of lava blocks that move downward as a result of a process akin to deflation. As the underlying soft sands are gradually removed, principally by running water, the blocks tend to wedge tightly together and form a resistant cover on the steep slopes of the mesas. The talus cover has been cut through at some points where a few steep canyons head against the borders of the mesas.

The Otowi, Lobato, and Cerros del Rio lava flows, the Puyé Conglomerate, and the Bandelier Tuff each has been described as a formation of the post-Santa Fe Group in this report.

Tuffaceous materials of the age of the Chamael rito Member crop out along El Rito Creek just above the mouth of Cerros de las Minas Wash (United States Geological Survey: Arroyo del Perro). That a vent was nearby, but not exposed, is proved by the presence of volcanic bombs that still lie in the tuff at the spots where they originally fell.

Two thin beds of coarse-grained tuff crop out in the Pojoaque Member in the North Pojoaque Bluffs. The clasts are commonly smaller than the lower range (4 mm.) of lapilli, although a few may be as much as 20 mm. in diameter. The range in size of the particles suggests that they came from a vent that was, at most, only a few miles distant. No suggestion of the probable site of the vent can be deduced owing to the small area over which the coarse-grained tuff is exposed.

The Cerros del Rio lava flows, which were considered by Bryan (1938, p. 208) as "probably the area of most intense eruption in Santa Fe time," are regarded by us as post-Puyé Conglomerate in time, hence Pleistocene, and definitely not a part of the restricted Santa Fe Group. The basalt lapilli tuff that underlies the Cerros del Rio basalt flows in Canyada Ancha northwest of Santa Fe along the old Buckman Bridge road is later than the Pojoaque Member of the Tesuque Formation. The lapilli tuff also is interpreted by us as overlying the Ancha Formation. Spiegel and Baldwin (1963, p. 50) excluded both the basalt lapilli tuff and the overlying lava flows from the Ancha Formation, but stated that the basalt flows interfinger with the Ancha Formation, a statement with which we cannot concur.

### Rio del Oso Dikes

Basaltic dikes are numerous in the western part of the Rio del Oso-Abiquiu locality where they have been injected along fault planes of the post-Santa Fe deformation and also into unfractured strata. These relations can be observed in Dike Wash and also in the second and third tributaries on the north side of Rio del Oso (see geologic map, fig. 38). The first basalt dike crossed on the way up Dike Wash (United States Geological Survey: Arroyo del Palacio) has a sinuous trend, and the wash has cut a narrow gash through it (figs. 35, 36). Many of the dikes form sharp, narrow ridges more than a mile in length; these dike ridges resemble hogbacks and are prominent local topographic features at those points where the soft Ojo Caliente Sandstone has been eroded from around them. The dikes are narrow; few of them exceed a dozen feet in thickness and most of them average 4 to 8 feet. Most of the dikes dip to the east, but a few dip to the west. They always dip at a high angle, conforming in this respect to the regional fault pattern.

Narrow contact zones of indurated sand, commonly less than 1 inch wide, occur along the dike walls. The contact zone may be reddened and is much wider where silty clay or clay is mixed with the sand.

The second dike at Dike Wash shows clearly that these dikes have been injected along fault planes; the evidence is shown on the south slope of the wash (figs. 35, 36). The sediments east of the dike have been faulted down into contact, and the dike itself has split into two adjacent walls. The westernmost of the two is a small accessory fault, and the injected material does not extend to the surface but pinches out in the sand. The easternmost wall of the dike is well exposed up to the base of the small lava flow, but it does not break through it, although it arches the flow at one place. The lava flow is thin and of small extent and cannot be shown to be surely equivalent to any other flow in the locality. The flow is interbedded in the Chamael rito Member, because a small hill of fossiliferous sediments rests upon it. The evidence, therefore, points to a Santa Fe age for the small lava flow, and a much later age for the dikes. The dikes are older than the erosion surfaces in the locality, because the deposits lying on the surfaces cross and cover the dikes at many places. Pleistocene fossils have been collected from deposits lying on lower and later erosion surfaces in Kunya Ruins Wash, and the relation suggests early Pleistocene age for the dikes.

South of Dike Wash some of the dikes crop out in closely spaced groups, particularly in tributaries north of Rio del Oso. At one point a dozen parallel dikes were counted in less than half a mile. The arrangement of these dikes, and others in the locality, suggests that they were injected into *en echelon* fault planes.

Dikes were observed as far north as Kunya Ruins Wash, but in that locality they are small. They are of the same lithology as those farther south in the Rio del Oso-Abiquiu locality, that is, predominantly high-density, dark green to dark greenish brown olivine basalt.

### Round Mountain

Round Mountain (United States Geological Survey: Black Mesa; fig. 37) is a very prominent black basaltic mesa situated on the east bank of the Rio Grande between Espanola, New Mexico and the San Ildefonso Indian Pueblo. The Tewa Indians call it *Tunyo Piñ*, which means "very spotted mountain." According to Harrington (1916, p. 293) it had many Spanish names, including La Mesa, Mesita, Mesilla, and Huérfano (orphan). English names have been even more diverse, such as Black Mesa, San Ildefonso Mesa, Mesita, Mesilla, Sacred Fire Mountain, Orphan Mountain, Beach Mesa, Round Mesa, and Round Mountain. Our field parties have consistently used the name Round Mountain for more than 40 years, in order to differentiate the mesa from the large Black Mesa mapped by Wheeler (1876) along the northwest side of the Rio Grande between Embudo and Chamita, New Mexico. We consider it unfortunate that the United States Geological Survey, on adjoining 7.5-minute quadrangles, used the term "Black Mesa" for two prominent geographic features no more than 12 miles apart, especially because of the many names that have been applied to the mesa that we call Round Mountain.

Round Mountain is a small, gravel-capped, denuded, composite cinder cone and volcanic neck, with a small extrusion of basalt. It rises about 500 feet above the river, and on its flanks undisturbed Santa Fe beds that vary 2 or 3 degrees from the horizontal are exposed. That beds so close to a conduit are so little disturbed is probably owing to the fact that the conduit,


Fig. 35. A. Breach in Rio del Oso Basaltic dike, made by Dike Wash (United States Geological Survey: Arroyo del Palacio). This is first dike crossed as one goes up Dike Wash from its mouth on Chama River. B. View looking south, showing second dike crossed as one goes upstream in Dike Wash; main part of dike on left (east). Split or apophysis (see fig. 36A) in left center pinches out in overlying sediments. Lava flow at right skyline is mapped in figure 38.

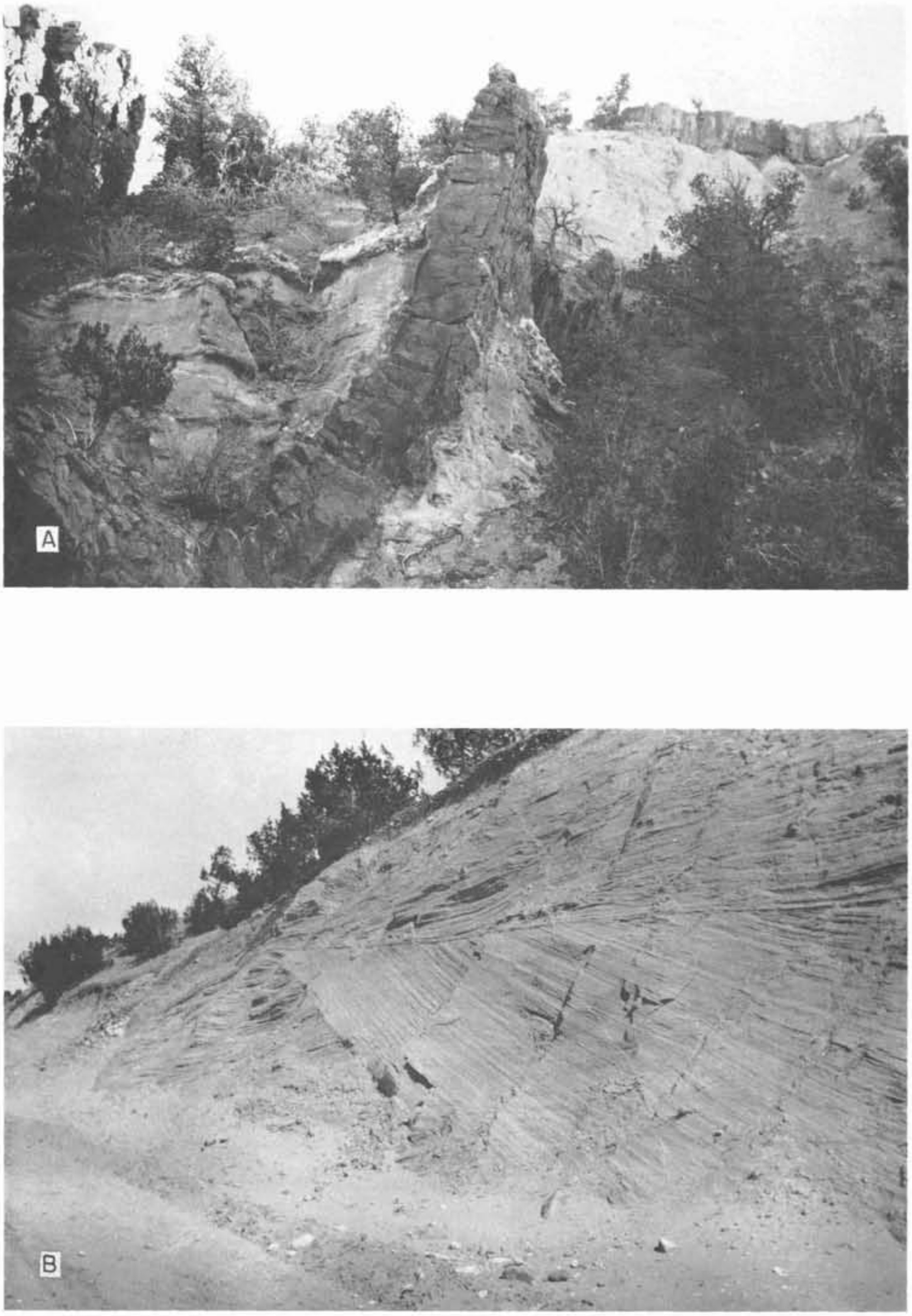


FIG. 36. A. Close-up of apophysis of second Rio del Oso dike (fig. 35B). A narrow indurated zone occurs on each side of dike. B. Cross-bedding in Ojo Caliente Sandstone, view taken in road cut on east side of United States Highway 285 about 6 miles south of Ojo Caliente, New Mexico. Several road cuts in vicinity display comparable gigantic cross-bedding, except where slopes are covered by slump or talus.

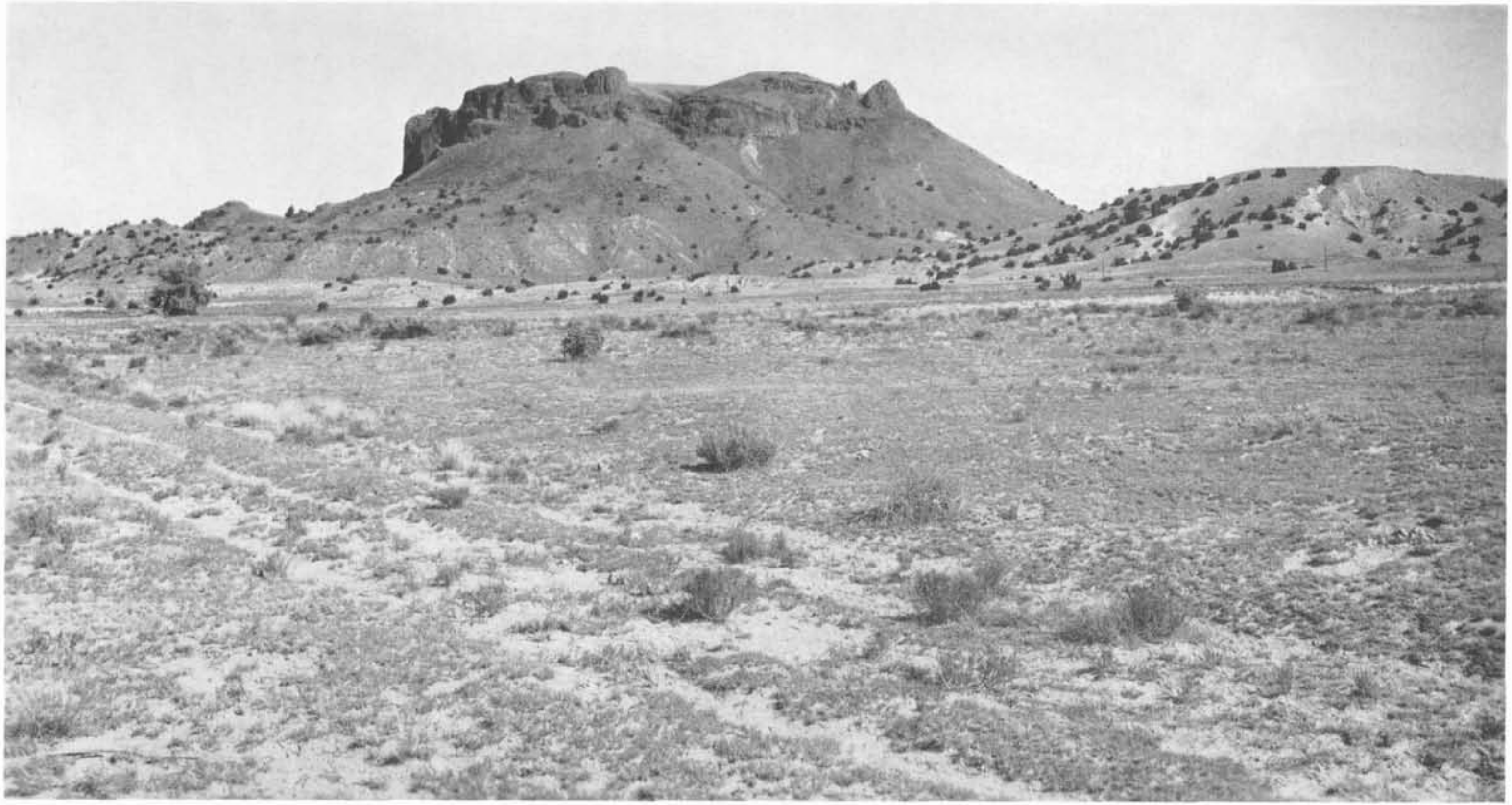

Fig. 37. Prominent landmark known locally as Round Mountain, San Ildefonso Mesa, Black Mesa, Huerfano, Mesa Negra, and, by Tewa Indians, as *Tunyo piñ* (Tewa: very spotted mountain). View looking northeast from north of San Ildefonso Pueblo and showing contact of Santa Fe Group with basalt. Light spots on slopes and one just under basalt at center of photograph are Santa Fe sediments. Rounded surface on skyline in notch near middle of Round Mountain is thick gravel cover on top of Mesa. This side of Round Mountain has many cinders in addition to columnar basalt.

initially small, later became enlarged through stoping, by the outpouring lava, of the soft sediments that formed the walls.

The basalt is essentially columnar, and much of it is vertical, but on the west side of the cone the columnar part lies almost horizontal and is eroding only on the ends of the hexagonal columns. Such a horizontal position indicates that this mass of basalt cooled along the wall in the upper part of the conduit. The west side also contains about 50 feet of agglomerate. Cinders and agglomerate are separate from the columnar basalt and occur below it, intercalated with it, and in a vertical position toward the interior of the mass.

The presence of red cinders along the southwest side of Round Mountain is further evidence of local eruptive action. We observed a similar red lava to be the last extrusion in the crater of Mt. Pisgah, a young and almost undissected extinct volcano near Lavic, California.

A bed as much as 10 feet thick, of river gravel of cobble size or smaller, caps part of Round Mountain. Perched on these gravels is one large boulder of typical Puyé Conglomerate lithology measuring 3 feet by 3 feet by 2 feet; this is reputedly a sacred fire shrine of the Tewa Indians. These gravels attest to the tremendous erosive power of the Rio Grande and its tributaries in the Espanola Valley. Round Mountain is obviously pre-Puyé Conglomerate in age, and the gravels on the summit are post-Puyé, with the large boulder having been reworked from the Puyé. Round Mountain is probably the same age as the volcano on the Mesa de los Ortizes southeast of Otowi Bridge. These two and several other cones in the general Cerros del Rio area are arranged in a line along what may be a deep-seated fissure or line of weakness in the rocks underlying the Santa Fe deposits.

# GEOMORPHOLOGY

## EROSION SURFACES

A COMPLEX SYSTEM of erosion surfaces has been cut across the type area of the Santa Fe Group. The erosion surfaces have beveled older rocks as well as those of the Santa Fe Group. Tremendous thicknesses of sediments have been planed away, and the resulting erosion surfaces have had a profound effect on the topography of the Rio Grande Valley north of Santa Fe. Because of the extensive planation associated with the forming of these erosion surfaces, no beds are now preserved in the type area that can be referred to the absolutely uppermost levels of the original deposits filling the valley.

The erosion surfaces have been cut across the inclined beds. In many places the surfaces have remnants of thick gravel preserved on them; at other places thin gravel beds remain; and still others have thin gravel and a few inches to a few feet of buff or yellowish brown or reddish brown, mostly wind-blown sand on them (see discussion of the Espanola Formation, p. 80). At some localities only the buff or brownish wind-blown sand covers the erosion surfaces. Some of the upper surfaces of the constructional gravel deposits that were laid down on the erosion planes have been neatly beveled, suggesting that they, in turn, were subjected to erosional planation. The cutting of the upper surfaces appears to have been about parallel to that of the base of the gravels, but the relation of one to the other is becoming increasingly obscure as the gravel deposits are dissected. Technically the erosion surface lies at the base of the constructional deposits, but in the field the recognition, projection, and interpretation of the surface are greatly simplified by the use of the top of the constructional deposits rather than the base as the datum plane.

The term erosion surface is used advisedly for the planes of denudation in this area. The evidence is not conclusive for the application of the terms piedmont, pediment, or rock pediment to all the various types of surfaces in the area, nor does the term planes of lateral corrasion have universal applicability. The use of the term pediment, if used at all, must be in the broadest general sense, for few of the surfaces conform to a restricted definition of a pediment. Most of them bevel sedimentary rocks and were not cut on crystalline rocks.

Southwest of the Santa Cruz Dam near Chimayo, New Mexico, are remnants of a prominent, gravel-capped, erosion surface. Cabot (1938, p. 95) described and figured this surface and others in the vicinity of the Santa Cruz Dam. The deposits of cobbles and boulders on the erosion surface may be 50 feet thick at some points, and the remnants end on the high hills along the drainage divide of the Santa Cruz River and White Operation Wash. Against the side of the westernmost of these hills, and at a much lower level, another erosion surface can be detected; on this lower surface the buff or yellowish brown sand has been deposited, and at some places a thin layer of gravel crops out at the base of the sand. Sand that is lithologically similar to that on the lower surface also lies on the bouldery gravel cap of the higher remnants south of the Santa Cruz Dam. The field evidence indicates that the main erosion remnants are early Pleistocene. The lower remnants, although definitely Pleistocene, must be regarded as sediments deposited during a later stage, because the higher remnants had been dissected extensively before the lower were laid down. In those localities where only the wind-blown sand of the Espanola Formation is preserved, the higher, gravel-covered erosion surfaces have been eroded strongly, and much of the gravel on the basinward end of the surfaces has been removed completely, prior to the deposition of the sand. The buff and light sand deposits of the Espanola Formation were laid down across the uneven surfaces and are now preserved as scattered remnants of small area capping many of the hills of the Skull Ridge and Nambé members of the Tesuque Formation, and also a few isolated exposures in the outcrop belt of the Pojoaque Member.

A divide separated the drainage system of the Arroyo Seco and Joe Rak Wash from the Nambé Creek system at the time of the deposition of the Espanola Formation. This relation is illustrated by the attitude of the Espanola Formation remnant that is preserved a few feet south of the north boundary of the Pojoaque Pueblo Grant and about a quarter of a mile east of United States Highway 64. The remnant is about 100 to 125 feet lower than the present divide, which is a few hundred yards to the south. The remnant was deposited on the wide erosion surface that truncated the beds of the Skull Ridge collecting locality.

The name Truchas surface is proposed for the particularly well-exposed and extensively gravel-capped erosion surface in the valley of Embudo Creek, south of the town of Dixon. The Truchas surface extends westward from the base of the Sangre de Cristo Range in the vicinity of the town of Truchas to a point near the Rio Grande southwest of Velarde. The gravels are thick near the mountains but thin to less than 100 feet near the Rio Grande. The boulders near the mountains are large; the size of the clasts decreases rapidly basinward until, near Velarde, pebbles and small cobbles are typical. Precambrian rocks, and limestone from the Magdalena Group of the Pennsylvanian, have supplied most of the bouldery material preserved on the Truchas surface. The Truchas surface is younger than the deposits of the Picuris re-entrant fan, and the gravel deposits preserved on the Truchas surface and those of the Picuris fan were derived from dissimilar rocks within the range. The relation of the Truchas surface and the deposits thereon to the deposits of the Santa Fe Group in the Dixon sub-basin is shown diagrammatically in figure 28C.

The Picuris re-entrant was originally described by Cabot (1938, pp. 91, 92, 98), and the deposits of the Dixon sub-basin were treated briefly in the same paper. The great fan filling this re-entrant is called the Picuris re-entrant fan in the present report. The Picuris re-entrant fan was formed by the issuance of coalescing alluvial fans from several mountain valleys. Moreover, good evidence can be adduced that the sources of various fans could be established by detailed sedimentation studies, but these would be a major task. The Picuris re-entrant fan is in the process of being dissected from all sides, and also by long washes that cross it diagonally; Embudo Creek has carved the Dixon sub-basin on the north side, and the Santa Cruz River and its tributaries have dissected the southern side. Many erosion surfaces are observed in the Picuris re-entrant, and they have affected the re-entrant fan at many different levels and obviously reflect a complex series of events. The correlation of erosion surfaces in various parts of the type area should be done with utmost caution.

The area lying east of the Ojo Caliente River, east of the town of Ojo Caliente and extending to the base of Black Mesa, is for the most part a series of remnants of at least two gently sloping erosion surfaces. During the cutting of these surfaces, vast amounts of Santa Fe deposits were removed. Over most of the locality the Santa Fe deposits are now covered by alluvium or other sediments. The Santa Fe beds have been re-exposed in the lower reaches of the washes along Ojo Caliente River. Cerro Azul, an Ortega quartzite inlier of Precambrian rocks (Just, 1937, p. 43), is being exposed in the locality; its relation to the erosion surfaces, to the basalt flows, and to the beds of the Santa Fe Group is shown in figure 34A. The lower erosion surface in this locality covers most of the area, and in addition to its normal gravel mantle it is also covered by several feet of reddish brown to buff, fine, wind-blown sand and soil. Except for the area along Ojo Caliente River, the deposits of the lower surface have been little dissected. The erosion surface slopes gently to about the height of the lower of the Ojo Caliente River terrace remnants. This erosion surface has been a prime factor in the determining of the topographic expression of the locality.

A great erosion surface slopes outward from the Ortega Mountains; it once swept around the Precambrian crystalline rocks of Ojo Caliente Mountain and can be studied on large numbers of isolated remnants in the locality. The surface has a thick gravel cap on many of the remnants and narrows greatly between Ojo Caliente Mountain and La Madera Mountain; Ojo Caliente River, or Vallecitos Creek as it is sometimes known above the town of La Madera, has cut deeply through it. Tributaries of Ojo Caliente River are dissecting it strongly but have not reached the point at which the continuity of the surface of the remnants is obliterated, and these, when projected, give an idea of the size and contour of the surface. This surface is here named the Vallecitos erosion surface. It can best be observed from the summit of the small, isolated, basalt-capped mesa east of the town of Ojo Caliente. An exposure of the Vallecitos erosion surface still remains along the west flank of that mesa. A large remnant of the surface is represented by the heavily gravel-covered tablelands east of Ojo Caliente. Tentatively correlated remnants of the Vallecitos surface are prominent features along each side of El Rito Creek above the town of El Rito.

A series of erosion surfaces and terraces are exposed along El Rito Creek. Near the Northern New Mexico Normal School at El Rito an erosion surface starts against the distal end of an older surface. This later surface is considerably lower, but its proximal end merges into the steep face of the cut-off higher terrace. The plain formed by the lower surface continues for several miles to the vicinity of Plaza Media where its distal border is also marked by a steep terrace. At this point a still lower plain abuts against the terrace and can be traced for several miles. Other erosion surfaces can be observed at progressively lower levels, each one cutting into the deposits of the higher one, and each leaving a remnant of the surface and a steep terraced scarp. The erosion of much of the type area of the Santa Fe Group seems to have been a result of a similar series of erosion surfaces, but, instead of being of small area as are those of El Rito Creek, the surfaces elsewhere may be much larger. In many respects erosion surfaces are similar to abandoned river terraces, and, in fact, many of the surfaces along El Rito Creek may be properly classed as such. Some of the characteristics of rejuvenated streams flowing across alluvial fans can be detected. Furthermore, some of the surfaces seem definitely to be the result of the lateral corrasion of streams.

The town of Espanola stands partly on the flood plain of the Rio Grande and partly on a well-marked terrace 60 to 80 feet high. The slope of the terrace ranges from an abrupt escarpment on the upstream side to a gentle slope downstream. This surface is about half a mile wide and abuts against another higher terrace remnant or erosion surface. This higher surface has been given a rolling appearance by the washes crossing it, and by the accumulation of alluvium that was spread out along the terrace face somewhat like the alluvial cones of a bajada. A remnant of a still higher and much more dissected terrace is preserved along the base of the very prominent Puyé Gravel terrace escarpment.

All the erosion surfaces in the type locality of the Santa Fe Group were cut after the post-Santa Fe Group deformation, and many of them, no doubt, record important Pleistocene events. Some of the erosion surfaces must have lasted for long periods of time to enable the lateral corrasion of streams to cut broad sloping plains. At what points, and in what manner, temporary base-levels were established on the master and on tributary streams can only be conjectured. The evidence shows only that a series of such temporary base-levels were established, and that for each base-level an erosion surface was cut. Erosion surfaces also show differences in size, elevation, and other characteristics depending on whether they were cut by the master stream system or by the tributary system.

## DRAINAGE

The Rio Grande rises in the San Juan Mountains of southern Colorado and flows southward for more than 400 miles across New Mexico. Near the southern boundary of New Mexico the river turns southeastward and, after leaving the state, forms the boundary between Texas and Mexico for nearly 1250 miles to its mouth on the Gulf of Mexico. The Upper Rio Grande Basin includes parts of Colorado, New Mexico, and west Texas. The part of the Upper Rio Grande Basin in which the deposits of the type area of the Santa Fe Group are exposed is known as the Espanola Valley, which, in turn, is part of the larger Middle Rio Grande Valley. The Middle Rio Grande Valley is about 200 miles long and extends from a point near Velarde to San Marcial, near the head of the Elephant Butte Reservoir. The Espanola Valley is about 25 miles long and extends from the point where the Rio Grande leaves the Rio Grande Canyon near Velarde to White Rock Canyon near the San Ildefonso Indian Pueblo.

The present flood plain of the Rio Grande is 1 to 3 miles wide for most of its length through the Espanola Valley. The river bottom lands are almost all under irrigation and are surprisingly fertile, although some of the land has been under continuous cultivation for hundreds of years. The first white settlement within the boundaries of the United States was established in 1598 on the west side of the Rio Grande just above the mouth of the Chama River, near what is now the San Juan Pueblo. The colonists were led by Don Juan de Oñate who called the settlement San Gabriel de los Espanolas. Before the coming of the Spaniards, the Indians of the Tewa tribes long had farmed the lands, and before them the vanished tribes of the Pajarito Plateau had built their pueblos near the river and irrigated parts of the bottom lands. Some of the present irrigation canals are said to follow some of the prehistoric canals.

Near the head of the Espanola Valley the Rio Truchas enters the Rio Grande from the east. All its perennial waters are utilized to irrigate between 1250 and 1500 acres of land in the mountain valleys and on the erosion surfaces along the foot of the mountains.

The Chama River, a perennial stream draining an area of about 3200 square miles, empties into the Rio Grande from the west just below the San Juan Pueblo. The annual runoff of the Chama River has ranged from 977,200 acre-feet in 1916 to 179,700 acre-feet in the drought year of 1934. The Chama, with its tributaries, the Ojo Caliente River, El Rito Creek, Abiquiu Creek, and Rio del Oso, drains the part of the type area of the Santa Fe Group that has been called the Abiquiu re-entrant (Cabot, 1938, p. 89).

The Santa Cruz River enters the Rio Grande from the east at Riverside. Most of its waters are diverted for irrigation. Santa Clara Creek joins the Rio Grande from the west just below Espanola. Most of its water is diverted for use as the community water supply of the Santa Clara Indian Pueblo; the rest is used for irrigation by the Pueblo.

Pojoaque Creek and its tributaries, Nambé Creek and Tesuque Creek, supply little water to the Rio Grande, for nearly all its perennial flow is used by the residents of the valley, particularly by the Nambé, Tesuque, and San Ildefonso Indian Pueblos.

The Chama River and Embudo Creek are the only perennial tributaries of the Rio Grande in the type area of the Santa Fe Group. Very numerous washes, arroyos, and canyadas are tributary to the Rio Grande, but these may run for only a few hours on a few days during the year when heavy thunderstorms move down from the mountains and send torrents raging down the dry channels. Vast quantities of silt and sand are swept into the Rio Grande by the flash floods of the sudden summer storms.

## DEPOSITION OF ALLUVIAL PLAINS IN DRAINAGE VALLEYS

The present channel of the Rio Grande in White Rock Canyon below the site of the old Buckman Bridge is known to have cut down at least 55 feet below the present bed of the river. In a reconnaissance of the east bank of White Rock Canyon in 1941 we were privileged to examine a drill core taken from the bed of the river by an exploration party for the United States Reclamation Service which was testing the locality as a possible dam site. The drill core showed 55 feet of heterogeneous gravel, basalt, sand, and other sediments, and did not contain any sediments of the Santa Fe Group. It is probable that the river-channel deposits in the river bed extend to a greater depth than the 55 feet shown by the core. It seems unlikely that the normal processes of scour and fill in the river channel would result in river-laid sediments as deep or deeper than 55 feet; therefore, a special set of hypotheses is required to explain such an occurrence. The fall of the Rio Grande through White Rock Canyon is about 10 feet per mile (Herron, 1916).

The interpretation here presented is that the Rio Grande at one time cut down much below its present level. The temporary base-level endured for a sufficiently long period to permit several of the tributary streams to entrench themselves and become partly graded to the lower (temporary) base-level. At this stage the Rio Grande apparently was impounded, possibly by a lava flow, the temporary base-level was raised abruptly, and a cycle of deposition started in which the alluvial plains which now extend far up the tributaries were formed. After these alluvial plains had attained approximately their present contour, the Rio Grande began cutting down again. The constructional deposits were trenched by the tributaries as the temporary base-level of the master stream began moving down. The degradation of these constructional plains is going on at the present time, and the steep-walled arroyos that incise the plains are regarded as an integral part of the adjustment to the lowering of the base-level.

## SUPERIMPOSED STREAMS

Superimposed streams are numerous in the region. Cabot (1938, p. 96) recognized the superimposed nature of Embudo Creek and its tributaries, and also of the Santa Cruz River.

Ojo Sarco Creek, a tributary of Embudo Creek, flows alternately across crystalline and sedimentary rocks at least six times. Each time that the creek crosses the Dixon granite (Just, 1937, p. 24), it could have cut its course in the soft sediments of the Santa Fe by a detour of only a few yards. The Santa Fe beds are banked against the Dixon granite in this locality and have been stripped from the contact along many of the granite hills and spurs.

The Rio Pueblo is clearly superimposed. It rises high in the Sangre de Cristo Range, principally in areas underlain by beds of the Magdalena Group, crosses a small area of Precambrian crystalline rocks, and then flows again across limestone of the Magdalena Group. Near Vadito the creek flows across several miles of Picuris Tuff before passing through a notch in a low granite ridge near the Picuris Pueblo. Below the town of Rio Lucio the Rio Pueblo flows through a scenic gorge that has been cut in the Dixon granite to a depth of several hundred feet and finally emerges from the gorge a short distance above the mouth of Ojo Sarco Creek to cross beds of the Santa Fe Group. Below the junction of the Rio Pueblo with Ojo Sarco Creek, the stream becomes known as Embudo Creek, which then crosses one more narrow belt of Precambrian rocks about a mile below the town of Dixon before entering the Rio Grande across a strip of Santa Fe beds.

Nambé Creek rises in a lake high in the Sangre de Cristo Range, leaves the crystalline rocks a few miles southeast of the Nambé Pueblo, whereupon it flows for less than a mile across a belt of sedimentary rocks of the Picuris Tuff, and the Nambé Member of the Tesuque Formation. At the Nambé Falls the creek plunges over a small inlier of crystalline rocks on which more than 150 feet of Magdalena beds have been preserved. The Magdalena rocks, although areally very small in this particular block, bulk as a rather high hill at the falls. The attitude is N. 10° W., 42° W. The basal portion of the exposed Magdalena is composed of 80 to 100 feet of alternating sandstones, mudstones, and impure limestones in which cherty nodules are abundant. The upper portion is a series of alternating shales, sandstones, and some highly fossiliferous and crinoidal limestones. Nambé Creek, after leaving the small block of Magdalena rocks, flows for several miles across beds of the Santa Fe Group. Finally it joins Tesuque Creek just below Pojoaque, New Mexico, and there becomes known as Pojoaque Creek.

The streams of the type area showing superposition are the Rio Pueblo, Ojo Sarco Creek, Embudo Creek, Santa Cruz River, Rio Quemado, Rio Chiquito, Medio (Frijoles) Creek, Nambé Creek, and even the Rio Grande. The Rio Grande has been let down through the Hinsdale basalt underlying the Taos Plateau (Upson, 1941), and has cut more than a thousand feet below the surface of the lava plains. Between Pilar and Rinconada, the Rio Grande flows along the contact between the Santa Fe and Precambrian rocks. For most of the distance it flows on the Santa Fe beds, but at a few places it has cut through small spurs of the Rinconada schist phase of the Ortega quartzite (Just, 1937, see map). The Rio Grande has followed the pattern of some of its tributaries and has cut through rather than around crystalline rocks. At some places a diversion of only a few feet would have carried the river entirely on sedimentary rocks.

The superimposed streams have been let down through a thick cover of Santa Fe Group deposits. Erosion surfaces, rather than the differential hardness of the rocks, have controlled the position of most of the streams.

# STRUCTURE

Structural relations of parts of the Rio Grande depression have been described by Renick (1931, p. 74), Bryan and McCann (1937, p. 818), Bryan (1938, p. 199), Cabot (1938, p. 97), Harold T. U. Smith (1938, p. 959), Denny (1940a, p. 99; 1940b, p. 683), Stearns (1943, p. 317), Wright (1946, p. 414), Kelley (1952, p. 93; 1956, p. 109), Ross, Smith, and Bailey (1961, p. 142), and Spiegel and Baldwin (1963, p. 68). Some of the features described by these writers, and by others not listed above, were noted as structural relations of the Santa Fe Formation, and indeed many of them are identical. No clear distinctions have been attempted, with one or two exceptions—namely, Wright (1946) and Stearns (1953b)—to interpret the sequence of events from the inception of the initial basins through the deposition of the various formations filling them, eventually culminating in the post-Santa Fe Group deformation and subsequent erosional history.

Bryan and McCann (1937, p. 818) first used the term Rio Grande depression for the series of structural basins or troughs in the Rio Grande Valley in New Mexico, and the term appears several times in their report on the stratigraphy and structure of the Ceja del Rio Puerco. Later Bryan (1938, pp. 197, 199) further expanded the concept of structural basins by describing several of them and relating them to the broader features of the Rio Grande Valley. In this respect, understandably, he followed Lee (1907, p. 12) in emphasizing the erosional character of most of the inner valleys. That the term Rio Grande depression was in use, if not in print, prior to 1937 is implied by the use of the term by Bryan's students or associates [Cabot (1938, p. 88), Harold T. U. Smith (1938, p, 933), and Denny (1940a, p. 73; 1940b, p. 680)], whose field work in New Mexico antedated their published reports by several years.

Tectonic studies of the Rio Grande depression were published by Kelley (1952, 1954, 1956), whose work greatly expanded knowledge concerning the structural troughs comprising the depression. His description of embayments, salients, constrictions, and uplifts, in addition to those described by Bryan (1938, p. 198) and Lee (1907, p. 12), should greatly facilitate future work on the tectonics of the region. Kelley (1952, p. 93) emphasized the necessity of including the borders or rims in the consideration of the depression and stated, "In consequence, the width of the total structure, including the bordering uplifts, is often twice that of the intervening depression." In 1956 (p. 109) he further stated, "The deformations throughout the length of the intermontane depressions do not appear to have been synchronous." With the last statement we are in general accord, although the post-Santa Fe deformation that outlines the Rio Grande depression in the Espanola basin and the Albuquerque-Belen basin appears to be synchronous throughout both basins.

The discussion of structure herein is confined mostly to the Espanola basin and to the parts of the Albuquerque-Belen basin in which Santa Fe Group beds, as restricted in this report, are exposed.

The western border of the Sangre de Cristo Range north of Santa Fe commonly has been regarded as a post-Santa Fe fault-line scarp. We present evidence to show that the fault border is pre-Santa Fe Group in age (figs. 11, 38; see also p. 104). Moreover, we show that the Santa Fe beds are in sedimentary contact with the crystalline rocks of the range (p. 45). A few small post-Santa Fe faults are at the contact locally between Nambé Member beds and the crystalline rocks, but they pass into, and die out in, the Nambé Member (fig. 38). The post-Santa Fe faults do not follow the contact and cannot be considered as marking a fault border of the Sangre de Cristo Range.

Postulated gradual subsidence associated with downfaulting or downwarp during the deposition of the Santa Fe beds lacks field evidence. Indeed, no simple hypothesis will suffice to explain the accumulation of the thick Santa Fe Group deposits. It is not enough to interpret the original extent of the Santa Fe Basin, in which the beds of the type area were deposited, by the outlines of the post-Santa Fe Group deformation, which is now considered to mark the Rio Grande depression. An attempt must be made to separate the concepts of pre-Santa Fe and post-Santa Fe deformations; this is incorporated in the succeeding pages.

The faults of the type area of the Santa Fe Group must be sharply discriminated as to their age relations. An Oligocene period of deformation can be regarded as the pre-Santa Fe Group deformation (this paper, p. 104). The post-Santa Fe Group deformation is the primary factor in outlining the recent Rio Grande depression. This post-Santa Fe deformation probably started in the late Pliocene and may have continued into early Pleistocene time. The recognized late Pleistocene formations are not involved in the major post-Santa Fe deformations.

Beds of the Santa Fe Group, as restricted to the type area, dip westerly, and, although the dip is not so great near the Rio Grande as farther east, we have failed to confirm reports of low easterly dips which have been interpreted as part of a broad synclinal structure across the basin (Kelley, 1956, p. 111). Such dips may be typical of beds in the Santo Domingo Basin farther south along the Jemez uplift that are not included in the Santa Fe Group of the type area but are lithologically and temporally compatible with the Upper Buff of Bryan, which, as indicated elsewhere in this report, should be rock-stratigraphically and biostratigraphically separated from the Santa Fe Group. Spiegel (1961, p. 133) suggested that two unnamed formations are exposed in the Lower Jemez River area and that these also appear to represent facies of the Upper Buff. Moreover, apparently they are part of the beds in which Kelley (1956, p. 111) detected "an abundance of rock fragments of Jemez provenance, and little material from the Sangre de Cristo and northern areas." We emphasize and reiterate our opinion that the beds formerly included in Bryan's Upper Buff, Spiegel's two unnamed formations, various axial river gravels, and other late gravel and associated deposits, as well as late volcanic deposits, should be excluded from the Santa Fe Group.

Ross, Smith, and Bailey (1961, p. 140), on a generalized geologic map, show a small wedge of Tertiary rocks along the southern end of the Pajarito fault zone.[1] These Tertiary rocks include a surprisingly diverse lithologic sequence in which rocks suggestive of the Galisteo Formation, El Rito Formation, Espinaso Volcanics, and the Pojoaque Member of the Tesuque Formation are exposed. Fragments of *Ramoceros* horns and mastodont tooth fragments were collected in the Santa Fe beds in this fault block. These beds lie outside the map area covered in the present report, but they are extremely important because they form the only tangible link between the beds of the type area and the beds of Jemez Creek and Ceja del Rio Puerco. On these rests the evidence for continuity of the Pojoaque Member of the Tesuque Formation to the Albuquerque-Belen basin, and not on the beds cited by Bryan (1937, p. 810) in the Santo Domingo Valley and in the vicinity of Bernalillo (see discussion, this paper, p. 39).

[1]The Pajarito fault zone was mapped and named by Griggs (1964, p. 73). Unfortunately the critical area containing the Tertiary rocks occurs in the part of the map occupied by the map legend.

## FAULT SYSTEM

The fault system in the type area of the Santa Fe Group is a series of high-angle, normal, strike faults, with their strikes about parallel to the trend of the Rio Grande Valley. In the Espanola Valley the strike of many of the faults is nearly true north, varying at most only a few degrees (figs. 12, 20, 25, 38). A few faults in the type area strike northeasterly, but these are exposed principally along the northwestern edge of the area in the Abiquiu re-entrant north of Black Mesa. The fault traces may show a marked local sinuosity (fig. 38), but normally they are straight or gently curving. The direction of dip of the fault planes may be either easterly or westerly, resulting in closely spaced fault blocks with downthrown blocks on the east or west. The faults with east side down are more numerous, but those with west side down are usually larger. Faults within the type locality of the Santa Fe Group commonly have net dip-slips of less than 300 feet, but the greater number of them have dip-slips of only a few feet, yet the sum of the displacements of the small faults is large. The average angle of dip of the faults throughout the Santa Fe Group is about 70 degrees. Fault dips of less than 45 degrees are rare and, where observed, are commonly in short branch faults bounding small, wedge-shaped blocks.

The geologic map (fig. 38) showing the faults of the type area of the Santa Fe Group emphasizes the point that the faults seem to be arranged in clusters. Such apparent clustering results from our having mapped observed fault traces, for rarely were inferred faults plotted. The clusters, therefore, are controlled primarily by the arrangement of the outcrops of Santa Fe Group beds, which afforded us an opportunity to observe the faults, rather than by any lack of faults in the intervening areas. These intervening areas are commonly effectively masked by late deposits lying on erosion surfaces that occupy parts of local drainage basins between the areas of outcrops.

Small branch faults locally complicate the general fault pattern by forming acute-angled splinter blocks. Branching, however, is not characteristic of the fault pattern in the Espanola Valley, but several fine examples occur in the eastern part of White Operation Wash, in the North Pojoaque Bluffs, and west of Black Mesa between Ojo Caliente River and El Rito Creek. In White Operation Wash some faults, especially those with the downthrown block on the west, have been observed to split, hinge-out, or to dovetail with east-side-down faults. The east-side-down faults commonly intersect at a slight angle, resulting in minor warping and torsion. A small degree of differential rotation, particularly of the acute-angled blocks, has locally complicated the interpretation of the stratigraphy.

The fault pattern and the attitude of the strata of the Santa Fe Group are closely related and, therefore, can be discussed together conveniently and advantageously. The prevailing dip of the beds in the Espanola Valley is westward. The angle of dip of the individual fault blocks is low, normally about 9 degrees, but dips as high as 30 degrees are present locally, notably in the North Pojoaque Bluffs. At various localities elsewhere in the region the beds may dip in various directions; for instance, immediately west of the Ojo Caliente River the prevailing dip is northeast or east. Beds around the periphery of the type area of the Santa Fe Group may dip in any direction, but commonly the dip is to the west.

In the Espanola Valley, as stated above, the prevailing dip of the beds is to the west. When these westward-dipping beds are deformed by faults, with fault dips to the east, the result is that the same beds may be repeated in a series of fault blocks. Wherever the pattern is interrupted by westward-dipping faults, the continuity is broken, and the westward dip of the beds combined with the westward dip of the fault results in omission rather than repetition of the beds. The mere mention of the combination of dip of beds with fault dips makes the problem of correlation within the Santa Fe Group sound deceptively simple. It is, in reality, only one of a series of necessary observations required to make a stratigraphic correlation of each fault block.

Fault traces throughout the Santa Fe Group vary greatly along the strike. Sandstone and conglomeratic sandstone dikes often occur in the fault traces and range from a fraction of an inch to more than 10 feet in thickness. Thin crystalline calcitic dikes were observed in the fault planes at many places, and, rarely, as at the base of the North Pojoaque Bluffs, calcite pseudomorphs after aragonite occur. One fault observed in the eastern part of White Operation Wash, and also in its probable extension to the south on the Nambé Grant, has brecciated material along the trace and also crystalline calcite, and both of these have been encrusted by botryoidal chalcedony. These, and somewhat similar occurrences in which hyaline opal is the encrusting material, will commonly fluoresce and, in addition, are weakly radioactive.

Fault traces in the more consolidated sediments of the Santa Fe Group are usually well defined, although the fault traces may narrow markedly where the two fault walls are tightly appressed. Faults with a vertical displacement of more than 100 feet have at many places a fault trace that is less than 1 inch wide. Slight bends or undulations in the fault planes apparently caused open spaces that were later filled with sediments, which upon consolidation formed dikes. Just how these spaces were filled is not known, but it may have been by injection of mixtures of sand and water, or sand, water, and conglomerate under pressure coincident with movement of the fault blocks. Rarely, if ever, were planes of stratification noted in these dikes.

Several of the faults that deformed the eolian sand that comprises the bulk of the Ojo Caliente Sandstone instead of shearing cleanly, crushed and crumpled the soft sandstone and formed a great series of interlocking cracks that produced a wide fault zone. These cracks formed a distinctive dike system where percolating waters have formed concretions or have caused cementation. The dikes are composed mostly of calcareous sandstone; a few have siliceous cement; a few are composed of sandstone concretions, which probably are epigenetic; and the smaller cracks commonly contain thin, soft, white, powdery calcareous material. A large fault zone with a complex dike system forms high, resistant cliffs or pinnacles in the apex of the triangle (fig. 38) bounded by the Chama River and the Ojo Caliente River, which is a tributary of the Chama. On the high pinnacles the cementation was observed to become less downward except in the fault plane itself. Cross-bedding of some of the cemented sandstones is brought into sharp relief by wind erosion, which has sandblasted the surface; some of the laminae were softer than others and were filed down, leaving the hard laminae to stand out as ribs. Inexplicably, and unfortunately, this particular set of cemented zones, and two others southeast of Medanales, were mapped on the geologic map of New Mexico (Dane and Bachman, 1965) as intrusive rocks, apparently in the mistaken belief that they were of igneous origin.

Cemented zones occur at several points in a large fault near the town of Abiquiu; one of these was known to the early Spanish settlers as El Cuchillo (Spanish: The Knife). This same cemented zone was called "Battleship Rock" by Harold T. U. Smith (1938, p. 960) and is mapped on the United States Geological Survey Abiquiu Quadrangle (1953) as Cerrito Blanco. This large fault brings the Santa Fe beds down into contact with the Abiquiu Tuff.

A small cemented zone lies between Black Mesa and the east bank of the Ojo Caliente River about 2 miles above its mouth. Cemented zones also occur as dikes in several faults in the Rio del Oso-Abiquiu locality (figs. 2, 38), and in these, as in most other places in the general area, the cemented zones commonly occur in the downthrown blocks along the fault planes.

A swarm of basaltic dikes in the Rio del Oso-Abiquiu locality (see geologic map, fig. 38) have been injected into fault planes, and these igneous intrusions have been described briefly in the section on Rio del Oso dikes (above, p. 90). A major fault with east-side-down brings the Ojo Caliente Sandstone down into contact with the fossiliferous beds of the Chama-el rito Member of the Tesuque Formation in the western part of the Rio del Oso-Abiquiu locality (fig. 38). The dip-slip of this fault is estimated as about 600 feet. The Ojo Caliente Sandstone also crops out west of this fault along the high Lobato lava flow escarpment. Another fault with a comparable slip crosses the Chama River near the Kunya (Tewa Indian: turquoise) Indian ruins about 2 miles below Abiquiu and curves toward the east and passes along the south end of Cerro de las Minas. The Santa Fe beds are thrown down against the Abiquiu Tuff by this fault in the vicinity of Cerro de las Minas. The Abiquiu Tuff is also broken by several other faults in the general Abiquiu area.

The fault pattern that is observable in the type locality of the Santa Fe Group is clearly that of the post-Santa Fe deformation. Cross sections (fig. 38) across the Espanola Valley show the general fault relations. The cross section of the Skull Ridge Member of the Tesuque Formation displays some of the structural details, and many of the areal maps and cross sections covering the outcrops of volcanic ash beds of particularly significant localities, such as Skull Ridge, Pojoaque Bluffs, East Cuyamunque, and West Cuyamunque, illustrate the close relation between outcrop patterns of the ash beds and of the fault pattern. Obviously it is unrealistic to attempt extremely detailed mapping of the entire Santa Fe Group, but we believe the examples given will present a framework for better understanding of the stratigraphy and structure of the type area of the Santa Fe Group.

The post-Santa Fe faults of the Espanola Valley are interpreted as the result of tension of the beds. The observed facts that support this view are: (1) all the Santa Fe group beds dip to the west, even in closely spaced fault blocks, (2) the faults are normal faults and dip at high angles either to the east or west, (3) reverse faults are absent, and (4) the contact with the crystalline rocks of the Sangre de Cristo Range is an unconformable sedimentary contact and not a fault contact.

Uplift of the Sangre de Cristo Range probably provided the tensional forces needed to account for the lengthening of the beds, as shown by the cross sections (fig. 38). If the fault system had been controlled primarily by compression or even downwarping of the Santa Fe beds against the pre-Tertiary rocks, the effect should have been shortening of the beds instead of lengthening. The horizontal compression resulting from such a downwarp should have caused buckling of some of the fault blocks, probably large numbers of reverse faults, and other complications that do not exist. The large number of normal faults in the Espanola Valley, although of the high-angle variety, actually represent a significant extension of the beds when estimates are made of the horizontal separation. Only a few of the total number of faults can be measured accurately, and a tabulation of these would, at best, produce an inadequate picture of the total horizontal separation. It should suffice merely to point out that the faults all show horizontal separation. The hundreds of small fractures that are unmeasured or are unmeasurable in the fault blocks, that is, faults with 2 or 3 inches up to 6, 8, or 10 feet, or even more, of vertical slip, all show some horizontal separation the sum of which would be substantial.

Faults that involve beds of the Santa Fe Group along the western border of the Sangre de Cristo Range are few in number and small in size (either in length of trace or amount of displacement), and all die out in the Santa Fe beds without causing major dislocations. In our opinion the faults mapped by Cabot (1938, p. 92) and Spiegel and Baldwin (1963) along the mountain front from the vicinity of Bishop's Lodge south to Santa Fe and beyond are pre-Santa Fe Group in age because they cut older rocks and do not involve Santa Fe beds directly.

## AGE OF THE PRE-SANTA FE GROUP DEFORMATION

The age of the pre-Santa Fe Group deformation must be inferred from the results of observations of widely separated exposures.

Beds along the Chama River had been deformed by the subsidence of the original depression in which Tertiary beds were deposited. This can be seen by the manner in which the edge of the Mesozoic platform has been successively faulted down on the south and east in the vicinity of Cerro Pedernal, the Abiquiu Dam, and Abiquiu, New Mexico. The first formation laid down along the edge of the depression at this point was the El Rito Formation (Harold T. U. Smith, 1938, p. 940). Stearns (1943, p. 315) discussed the pre-Galisteo unconformity in the Galisteo-Tonque area. He also pointed out (p. 301): "... the igneous rocks of the Ortiz Mountains and the Cerrillos Hills intrude the Galisteo formation and the Espinaso volcanics. These formations were deformed and eroded before deposition of the late Tertiary Santa Fe formation. The Rio Grande depression was not outlined until late Tertiary time." He also concluded that warping had occurred during the deposition of the Galisteo beds in Duchesnean time.

Beds at the south end of the Sierra Nacimiento, and in Canyada Piedra Parada, which is a tributary of Jemez Creek, were assigned by Renick (1931, pp. 57–58) to the lower Wasatch; by Bryan and McCann (1937, p. 808) to Cretaceous or older beds; and by the senior author (Galusha, 1966, p. 4) to the Galisteo Formation. The field evidence indicates that the age of the pre-Santa Fe Group deformation at this point was post-Galisteo. The Galisteo Formation was the last formation laid down preceding deformation by the Sierrita fault, and the Zia Sand Formation (Galusha, 1966) was the first to be deposited across its trace. The age of the Sierrita fault, which Renick (1931, p. 74) considered part of the Nacimiento overthrust, thus can be assigned to some part of the Oligocene. At this stage of the investigation it is not possible to allocate the deformation to Chadronian, Orellan, or Whitneyan time (Wood et al., 1941) with precision.

## AGE OF THE POST-SANTA FE GROUP DEFORMATION

The age of the post-Santa Fe Group deformation never has been established accurately. Renick (1931, p. 77) noted that the beds of the Santa Fe Formation were involved in the deformation of the Sierra Nacimiento and San Pedro Mountain. He did not, however, recognize that numerous faults deform the basalt mesas north of Jemez Creek. Chamisa Mesa is a remnant of a downthrown fault block west of the Ojo Chamisa fault. Borrego Mesa is broken by several faults, and Santa Ana Mesa is also faulted. All these lava flows are later than the (?)Gila Conglomerate equivalent (the Upper Buff Member of Bryan and McCann) and hence are of early Pleistocene age.

Bryan and McCann (1937, p. 827) described three distinct fault systems in the Ceja del Rio Puerco area. They stated that "the Ceja faults are post-Santa Fe and thus not earlier than late Pliocene or perhaps the beginning of the Pleistocene." Denny (1940a, p. 101) postulated several periods of Tertiary deformation in the San Acacia area. He mentioned three pre-Santa Fe deformations: one during the Santa Fe, and two post-Santa Fe deformations. Denny considered the "Santa Fe" beds in the San Acacia area to be upper Pliocene in age, although the fossils he listed are probably more characteristic of the early Pleistocene. The difference in fundamental interpretation of the age of fossils profoundly affects the dating of the post-Santa Fe Group deformation.

Harold T. U. Smith (1938, p. 964) stated, "... it seems probable that the deformation must have taken place well before the close of the Pliocene period." Denny (1940b, p. 684) described faults in the Espanola Valley but did not speculate concerning their age. In his conclusions Denny (p. 691) stated, however, "Since the Pliocene the formation has been tilted westward and broken along many normal faults."

Wright (1946, p. 415), in speaking of the Albuquerque-Belen basin, postulated that the "subsidence of the depression continued apace with deposition during the late Tertiary." He also stated, "In the late Tertiary downwarping and downfaulting formed the Albuquerque-Belen basin, in which the Santa Fe formation was deposited." Wright regarded the post-Santa Fe deformation as a period of accelerated subsidence of the depression.

The age of the post-Santa Fe deformation is inalienably involved in the problem of the so-called "Upper Buff Member of the Santa Fe Formation" (see Bryan and McCann, 1937, p. 815). The post-Santa Fe faults cut and displaced the "Upper Buff." Fossils collected from this member (?Gila Conglomerate equivalent) will ultimately provide the solution as to whether the deformation was Pliocene, ended in the Pliocene, or was of early Pleistocene age. We collected fragments of horse bones of appropriate size for *Equus* at several points in the "Upper Buff" along the Ceja del Rio Puerco. A section of a mastodont tusk was observed in the member in the Sand Hill fault-zone locality (Wright, 1946, pl. 8). A small collection of fossils was obtained from the "Upper Buff" along the Ceja del Rio Puerco at the north end of the Isleta Indian Pueblo Grant. A larger and more complete fauna is needed before the age of the member (?Gila Conglomerate equivalent of the writers) can be definitely established, but if, as we believe, the "Upper Buff" of Bryan and McCann is an equivalent of the fine-grained phase of the Gila Conglomerate the age of the deformation is considerably later than previously supposed.

The Ortiz erosion surface was cut following the post-Santa Fe deformation, and the deposits lying on the Ortiz surface have not been deformed by the post-Santa Fe faults. Pleistocene fossils collected from deposits on later erosion surfaces and from the Espanola Formation (above, p. 80) suggest an early Pleistocene age for the Ortiz surface. The post-Santa Fe deformation is interpreted on the basis of the foregoing evidence to have taken place not at the very start of Pleistocene time, but somewhat later in early Pleistocene time.

# AGE OF THE SANTA FE GROUP

Deposits north of Santa Fe, New Mexico, that have been described by various writers during the past 100 years, first as the Santa Fe Marl, then as the Santa Fe Formation, and in recent years as the Santa Fe Group, in this report have been redescribed, subdivided, and restricted to the type area. These rocks provide an essential lithogenetic unity in the geologic history of this part of New Mexico. Beds in other parts of New Mexico that are not represented in the type area are excluded from the Santa Fe Group.

A recognizable rock sequence in the type area that can be given reasonably accurate age assignments should enable both paleontologists and geologists to provide a basis for separating lithogenetically distinct beds in other parts of the Rio Grande depression in New Mexico. Fossils that were collected in the various units have provided controls for the age assignments, but even these fossils are subject to different interpretations by paleontologists.

Over the years the concepts of the age of the Santa Fe beds have gradually evolved from Miocene to the more inclusive Mio-Pliocene; finally to (?)middle Miocene to (?)Pleistocene (Keroher et al., 1966, p. 3463). A review of the literature on the Santa Fe Formation (see Historical Sketch, p. 16) shows general uncertainty among paleontologists and geologists regarding the time-stratigraphic boundaries to be used in the area. Attempts to apply the usual geologic-time (geochronologic) units and North American Land-Mammal ages to the beds can be, and have been, criticized, but the application of these terms at least serves as a point of reference for the particular beds.

Radiometric (absolute) dating ultimately may provide a precise scale for measuring the range zone of any particular taxon, or, better still, the concurrent-range zones of specified taxa. Until these refinements are available, however, and regardless of eventual changes in usage of the time-concepts here discussed, we present the information in this report in a manner that we hope will be intelligible and useful to future investigators.

Reasons for restricting the term Santa Fe Group to the beds in the type locality are given in the Introduction (p. 9), in the general statement on the Santa Fe Group (p. 40), and in the discussion of the Tesuque Formation (p. 44). The restricted Santa Fe Group comprises two formations: (1) the Tesuque Formation, with five members, namely, the Nambé Member, the Skull Ridge Member, the Pojoaque Member, the Chama-el rito Member, and the Ojo Caliente Sandstone; and (2) the Chamita Formation. We believe that these subdivisions are a practical solution to the stratigraphy of the Santa Fe Group, for they present a rock framework established primarily on a lithologic sequence, on which the biostratigraphy can be superposed and interpreted. When the local biostratigraphic ranges are known in a controlled area, such as the restricted type area, then the data thus obtained can be confidently applied to the solution of other problems. Any meaningful discussion of the age of the Santa Fe Group must necessarily deal with fossils; consequently in this section we comment briefly on our general interpretations of the ages of the fossils that we have collected in the group.

Much of the confusion and uncertainty concerning the age of the Santa Fe can be traced to imprecise stratigraphic allocation of the original fossil collections from the Santa Fe area. Klett collected fossils north of San Ildefonso in 1873; Cope and Shedd in 1874 worked in the same locality and also obtained some material north of Pojoaque and some south of Nambé. The two latter localities introduced a few late Miocene forms into Cope's predominantly early Pliocene fauna and resulted in a mixed faunal list, which for nearly 100 years has formed the basis for discussion of the age of the Santa Fe Formation.

By 1909 Osborn and Matthew (1909, p. 79) listed "the Santa Fe marls of Cope, New Mexico," as Upper Miocene and correlated them with the Ogalalla [*sic*] Formation in part. In a faunal list in the same paper, Matthew (p. 115) listed the fossils then known from the Santa Fe and placed them under Upper Miocene and (?) Lower Pliocene headings without further comment. Frick (1933, pp. 549, 571) reported the existence of mid-Miocene to Pleistocene deposits in the type area and discussed possible time equivalents of the beds in terms of the mastodonts and horses that he had collected. The Pleistocene deposits he mentioned are herein described as the Espanola Formation. The

Uppermost Pliocene that he mentioned (p. 549) proved to represent a part of the Hemphillian. Latest Hemphillian and Blancan faunas so far have not been recognized in the type area, although Morris Skinner (personal communication) detects horses in the collections from Lyden Quarry and the San Juan locality that he regards as late Hemphillian forms. Osborn (1936, p. 320), in his monograph on the Proboscidea, called the Santa Fe beds "the Mio-Pliocene Santa Fe Marls." All subsequent workers, with one notable exception,[1] either directly or indirectly have quoted Cope, Matthew, Osborn, and Frick as authorities for age determinations.

Parts of the very large collection of mammalian fossils from the beds of the Santa Fe Group in the Frick Collection of the American Museum of Natural History are being studied, but much time may elapse before an evaluation can be made of the complete fauna. Preliminary analyses by our colleagues of portions of the collection of carnivores, horses, mastodonts, camels, merycodonts, oreodonts, rhinoceroses, rodents, lagomorphs, and insectivores from these deposits show that the fossils are broadly equivalent to those ranging from late Hemingfordian (late medial Miocene) to Hemphillian (medial Pliocene) in age as compared with assemblages from the Great Plains sequence. The oldest fossils collected from the type area (Nambé Member) compare closely with those obtained in the Sheep Creek quarries of western Nebraska and their equivalents.

Deposits containing early Miocene (Galusha, 1966) and very late Pliocene or Pleistocene fossils (Needham, 1936) have been assigned to the Santa Fe Formation in the past, but these deposits crop out in sedimentary basins in localities outside the type area, in some areas even 100 or 200 miles or more away, and more properly should have been named as distinct formations. They are not genetically, lithologically, or faunally like beds of the Santa Fe type locality.

An effort has been made to correlate the field and laboratory evidence of the Santa Fe Group with the provincial time scale proposed by the Committee on Nomenclature and Correlation of the North American Tertiary (Wood et al., 1941). The conclusion that has been reached is that the provincial terms can be applied in a general way to the beds of the Santa Fe Group, but the use of the terms implies an arbitrary division of the faunas of the Santa Fe Group at a point supposed to mark the boundary between the Barstovian and the Clarendonian. These provincial time terms were erected by the committee avowedly to circumvent the question of the Miocene-Pliocene boundary, yet a comparable problem is created in deciding where the Barstovian ends and the Clarendonian begins. The difficulties encountered in making a decision involving these particular time terms can be better understood when it is pointed out that *Hemicyon*, one of the five index fossils for the Barstovian as determined by the committee, is more characteristic of later beds and more often found in association with Valentinian (p. 12) and Clarendonian fossils than with those listed for the Barstovian.

Two species of *Hemicyon* from the Barstow area, California (*Hemicyon barstowensis* Frick and *Hemicyon californicus* Frick) are from the Hemicyon stratum, a bed in the uppermost ?pre-Valentinian (p. 12) portion of the Barstow section. *Hemicyon* (*Canis*) *ursinus* (Cope) Frick was collected from Clarendonian (early Pliocene) beds of the Pojoaque Member of the Tesuque Formation of the Santa Fe Group. *Hemicyon barbouri* Colbert from the Ainsworth area, Nebraska, is also from beds in the Pliocene section.[2] An undescribed *Hemicyon* specimen in the Frick Collection from the Skull Ridge Member of the Tesuque Formation, one from Steep Side Quarry, and one from Turbin Quarry of the Barstow area are the only *Hemicyon* specimens known to us that are unreservedly referable to the Barstovian.

[1]Schultz and Falkenbach (1940, p. 254; 1941, pp. 15, 33, 34, 43, 44, 48; 1947, p. 245; 1949, pp. 80–82; 1968, pp. 367, 368, 379) recognized *Brachycrus* and *Merychyus* (*Metoreodon*) as indicating a Miocene age for a portion of the sediments. They listed four species of *Ustatachoerus* from the area and designated the beds that contained them simply as "the Pliocene deposits north of Santa Fe, New Mexico." Their conclusions were based on their studies of the oreodonts.

[2]Morris F. Skinner (personal communication) was present when the type specimen was collected and says that it came from a site 70 feet above the base of the Cap Rock Member of the Ash Hollow Formation. (The stratigraphic section of the site is shown in Skinner's section book, vol. 1, p. 145, now in the Frick Collection, Department of Vertebrate Paleontology, the American Museum of Natural History).

TABLE 3

Faunal List and Stratigraphic Position of the Published Types of Specimens Collected in the Type Locality of the Santa Fe Group as Restricted in this Report[a]

| Faunal List of the Santa Fe Group | | Tesuque Formation | | | | | |
|---|---|---|---|---|---|---|---|
| Original Identification of Types and Referred Specimens by Cope | Current Identification of Types and Referred Specimens | Nambé Member | Skull Ridge Member | Pojoaque Member | Chama-el Rito Member | Ojo Caliente Sandstone | Chamita Formation |
| *Testudo undata* Cope, 1875a | Testudininae, Williams, 1950[b] | — | — | x | — | — | — |
| *Testudo klettiana* Cope, 1875a | Testudininae, Williams, 1950 | — | (?) | x | — | — | — |
| *Cathartes umbrosus* Cope, 1874a | *Palaeoborus umbrosus* (Cope), Brodkorb, 1964 | — | x | — | — | — | — |
| *Panolax sanctaefidei* Cope, 1874a | *Panolax sanctaefidei* Cope, Dawson, 1958 | — | — | x | — | — | — |
| *Steneofiber pansus* Cope, 1874a | *Monosaulax pansus* (Cope), Stirton, 1935 | — | — | x | — | — | — |
| *Hesperomys loxodon* Cope, 1874a | *Copemys loxodon* (Cope), Albert E. Wood, 1936 | — | — | x | — | — | — |
| *Canis wheelerianus* Cope, 1877 | *Aelurodon wheelerianus* (Cope), Matthew *in* Osborn and Matthew, 1909 | — | — | x | — | — | — |
| *Canis ursinus* Cope, 1875a | *Hemicyon ursinus* (Cope), Frick, 1926a | — | — | x | — | — | — |
| *Martes nambianus* Cope, 1874a | *Martinogale nambiana* (Cope), Hall, 1930 | — | — | x | — | — | — |
| *Mastodon productus* Cope, 1874a | *Serridentinus productus* (Cope), Osborn, 1936 | — | — | x | — | — | — |
| | *Trilophodon pojoaquensis* Osborn, 1936 | — | — | x | — | — | (?) |
| | *Megabelodon cruziensis* (Frick), Osborn, 1936 | — | — | x | x | — | — |
| | *Ocalientinus ojocaliensis* Frick, 1933 | — | — | x | x | — | — |
| | *Trobelodon taoensis* Frick, 1933 | — | — | x | — | — | — |
| | *Trilophodon (Tatabelodon) riograndensis* (Frick), Osborn, 1936 | — | — | — | — | — | x |
| | *Megabelodon joraki* (Frick), Osborn, 1936[c] | — | — | x | — | — | — |
| Cf. *Aphelops meridianus* Leidy, Cope, 1875a | Cf. *Aphelops meridianus* Leidy, Cope, 1875a | — | (?) | (?) | — | — | — |
| *Aphelops jemezanus* Cope, 1875b | *Aphelops jemezanus* Cope, Matthew, 1932 | — | — | x | — | — | (?) |
| *Hippotherium calamarium* Cope, 1875b | *Merychippus calamarius* (Cope), Osborn, 1918 | — | — | x | — | — | — |
| *Hippotherium speciosum* (Leidy), figured and referred by Cope, 1877 | *Hipparion sanfondensis* Frick, 1933[d] | — | — | — | — | — | x |
| Cf. *Procamelus occidentalis* Leidy, Cope, 1875b | Cf. *Procamelus occidentalis* Leidy, Cope, 1875b | — | (?) | (?) | — | — | — |
| *Pliauchenia humphresiana* Cope, 1875b | *Pliauchenia humphresiana* Cope, Matthew *in* Osborn and Matthew, 1909 | — | x | — | — | — | — |
| *Pliauchenia vulcanorum* Cope, 1875b | *Pliauchenia vulcanorum* Cope, 1875b | — | — | x | — | — | — |
| *Cosoryx ramosus* Cope, 1874a | *Ramoceros ramosus* (Cope), Frick, 1937 | — | — | x | — | — | — |
| *Dicrocerus necatus*, Cope, 1875b | *Meryceros (Submeryceros) crucianus* Frick, 1937 | — | — | x | — | — | — |
| *Cosoryx teres* Cope, 1874a | *Cranioceras teres* (Cope), Frick, 1937 | — | — | x | — | — | — |
| *Dicrocerus trilateralis* Cope, 1877 | Camelidae, indet. Frick, 1937[e] | — | — | (?) | — | — | — |
| *Dicrocerus tehuanus* Cope, 1877[f] | ? | — | — | (?) | — | — | — |

TABLE 3—(*Continued*)

| Faunal List of the Santa Fe Group | | Tesuque Formation | | | | | |
|---|---|---|---|---|---|---|---|
| Original Identification of Types and Referred Specimens by Cope | Current Identification of Types and Referred Specimens | Nambé Member | Skull Ridge Member | Pojoaque Member | Chama-el Rito Member | Ojo Caliente Sandstone | Chamita Formation |
| *Dicrocerus gemmifer* Cope, 1874b | (?) *Longirostromeryx blicki* Frick, 1937 | — | — | x | — | — | — |
| | *Longirostromeryx novomexicanus* Frick, 1937 | — | — | x | — | — | — |
| | *Blastomeryx francesca* Frick, 1937 | — | — | (?) | — | — | — |
| | *Blastomeryx francescita* Frick, 1937 | — | — | x | — | — | — |
| | *Ramoceros ramosus quadratus* Frick, 1937 | — | — | x | x | — | — |
| | *Ramoceros* (*Paramoceros*) *marthae* Frick, 1937 | — | — | x | — | — | — |
| | *Ramoceros* (*Paramoceros*) *palmatus* Frick, 1937 | — | — | x | — | — | — |
| | *Cosoryx* (*Subcosoryx*) *cerroensis* Frick, 1937 | — | — | — | — | — | x |
| | *Cosoryx ilfonsensis* Frick, 1937 | — | — | x | — | — | (?) |
| | *Meryceros major* Frick, 1937 | — | — | x | — | — | — |
| | *Meryceros crucensis* Frick, 1937 | — | — | x | — | — | — |
| | *Osbornoceros osborni* Frick, 1937 | — | — | — | — | — | x |
| | *Plioceros blicki* Frick, 1937 | — | — | x | — | — | — |
| | *Pseudoceras klausi* Frick, 1937 | — | — | — | — | — | x |
| | *Rakomylus raki* Frick, 1937 | — | x | — | — | — | — |
| | *Ustatochoerus skinneri santacruzensis* Schultz and Falkenbach, 1941 | — | — | x | — | — | — |
| | *Brachycrus rusticus riograndensis* Schultz and Falkenbach, 1968 | — | x | — | — | — | — |
| | *Brachycrus vaughni rioosoensis* Schultz and Falkenbach, 1968 | — | — | — | x | — | — |
| | *Ustatochoerus californicus raki* Schultz and Falkenbach, 1941 | — | — | x | — | — | — |
| | *Ustatochoerus medius novomexicanus* (Frick), Schultz and Falkenbach, 1941 | — | — | x | — | — | — |
| | *Ustatochoerus profectus espanolensis* Schultz and Falkenbach, 1941 | — | — | x | — | — | — |

[a]Authority for current identification is given in each example, but it may not represent the latest consensus. The purpose of this table is to direct attention to the various taxa described from the type locality of the Santa Fe Group; it is not within the scope of this paper to pass on the validity of any of the taxa cited. The stratigraphic positions of Cope's specimens are shown as interpreted from a personal knowledge of the stratigraphy of the beds in which Cope was collecting, as recorded in the daily entry in his 1874 field notebook, further supported by the matching of many of the Cope specimens in the stratigraphically controlled Frick collection.

[b]Williams (1950, p. 30) listed both *Testudo undata* and *Testudo klettiana* with an asterisk in his check list of New World testudines and supposed testudines to indicate that the material was so fragmentary as probably to be indeterminable.

[c]Osborn (1936, p. 738).

[d]Frick (1933, p. 549) cited the maxilla figured and described by Cope (1877, pl. 75) as the type of *Hipparion sanfondensis*.

[e]Frick (1937, p. 315), "*Dicrocerus trilateralis* Cope, in the camel fragment at least, is probably of the Camelidae."

[f]Frick (1937, p. 315), "The actual affinity is yet to be determined in: *M. tehuanus* (Cope), 1877, from New Mexico, type representing an immature individual [*Dicrocerus tehuanus* Cope, 1877; ??*Merycodus tehuanus* (Cope) Matthew, 1909]."

Provincial time terms of the Wood Committee, or Land-Mammal Age terms of Savage (1962), that are generally applicable to the restricted beds of the Santa Fe Group are: (1) Hemingfordian for the Nambé Member of the Tesuque Formation; (2) Barstovian for the Skull Ridge Member of the Tesuque Formation; (3) unrecognized Valentinian (this paper, p. 12) and Clarendonian for the Pojoaque Member, Chama-el rito Member, and Ojo Caliente Sandstone of the Tesuque Formation; and (4) Hemphillian for the Chamita Formation. These terms can be used only in the most general sense.

Deposits that temporally are transitional between the Sheep Creek and the Lower Snake Creek of the Great Plains sequence have been recognized in the Nambé Member of the Tesuque Formation. This allocation is based on a careful unpublished comparison of the contained faunas with those from the Sheep Creek and the Lower Snake Creek quarries of western Nebraska. An adequate presentation of the paleontological evidence to support some of the age allocations made herein is beyond the scope of this paper. Indeed, such a presentation of the fauna of the Santa Fe Group would be of monograph proportions and must await the toil of future investigators, inasmuch as several thousand individual specimens are involved. General statements of the results of comparisons of faunal sequences in New Mexico with those of the central Great Plains may aid in the orientation of the biostratigraphic position of the members of the Santa Fe Group.

The taxa of the Skull Ridge Member of the Tesuque Formation are most closely matched by those of the Lower Snake Creek quarries of western Nebraska. Beryl Taylor (personal communication) states that many of the same genera of camels, merycodonts, and carnivores occur in the Skull Ridge beds of New Mexico, in the Lower Snake Creek quarries of Nebraska, and in the Trinity River Pit No. 1 in the upper part of the Fleming Formation in Texas. He also says that it is difficult in many cases to make specific separations among the three faunas.

The beds of the Santa Fe Group cross the generally accepted Miocene-Pliocene and the Barstovian-Clarendonian time boundaries regardless of the point or points at which these boundaries ultimately may be drawn. In this report the contact of the Skull Ridge Member and the Pojoaque Member of the Tesuque Formation has been selected arbitrarily as the reference point nearest to fulfilling the requirements of a boundary between the concept of North American Miocene and the North American Pliocene. This contact of the members is even less satisfactory as a boundary for the Barstovian and the Clarendonian, because additional beds and additional taxa appear to be present that are not commonly recognized in the Barstovian-Clarendonian sequence.

The Pojoaque Member, the Chama-el rito Member, and the Ojo Caliente Sandstone all have produced Valentinian-Clarendonian taxa. Moreover, the faunal list is so rich in new taxa that it is inadvisable to present even a tentatively complete faunal list in a report such as this, which is primarily oriented toward establishing an outline of the physical stratigraphy.

An evaluation of Cope's (1877) faunal lists may be included here (table 3), as well as some remarks concerning the stratigraphic position of some of Frick's (1926a, 1926b, 1933, 1937) published specimens. Cope's collection was almost wholly from the Valentinian-Clarendonian (early Pliocene); it was predominantly from beds that are assigned to the Pojoaque Member of the Tesuque Formation in the present report. Cope's diary showed that most of his collecting was done in the general areas shown in figure 2 as (7) Central Pojoaque Bluffs and (8) Lower Pojoaque Bluffs collecting localities. No Barstovian (late Miocene) beds are exposed in these two areas. Table 3 shows the published fauna of the Santa Fe type locality. The only species that can be assigned unequivocably to the Skull Ridge Member is *Pliauchenia humphresiana* Cope, for it has been matched by many specimens from that member. *Procamelus occidentalis* Leidy, Cope ranges throughout the section and could be either Miocene or Pliocene in age. *Pliauchenia vulcanorum* Cope is matched only in the collections from the Pojoaque Member, which is Valentinian-Clarendonian (early Pliocene) as currently understood. The listing of the types of the various species that have been described from the Santa Fe do not reflect necessarily the latest consensus regarding the present status of the genera involved, but attempts to show how a recognized authority dealt with each type species. Each of these authorities is cited with the date of the appropriate publication. Many of these taxa currently are being studied, and many changes will be made in the classification of them. Until these are published they have no standing under the Code of International Zoologic Nomenclature. Table 3, therefore, does not imply that we agree with the generic allocation of each type species. It is designed to show the stratigraphic position of each type specimen, regardless of what it may be called ultimately.

Cope (1884b, p. 58) correlated the beds of the Upper Gila River, and those of the Rio Grande Valley near Hatch, New Mexico, with the Santa Fe marls, and, strangely, this reference seems not to have been questioned until the present time. The beds of the Upper Gila contain a fairly rich fauna characterized by remains of *Plesippus* or *Equus* (depending on the interpretation of the status of the genus *Plesippus*). Knechtel (1938, p. 197) correlated the Upper Gila beds near Safford, Arizona, as a fine-grained phase of the Gila Conglomerate. Beds in the Rio Grande Valley in the southern half of New Mexico contain fossils that are more similar to those from the Gila Conglomerate fine-grained phase than they are to those collected from beds in the type locality of the Santa Fe Group. Moreover, these beds are lithologically more like those of the Gila Conglomerate than they are like those of the Santa Fe Group, and therefore should be correlated with the Gila Conglomerate.

Elston et al. (1968, p. 264) pointed out that "the clastic rocks are loosely named Gila Conglomerate in the Pacific drainage and Santa Fe Group in the Atlantic drainage (Dane and Bachman, 1965), although some specialists have suggested restricting these terms to the upper parts of the deposits (for example, Morrison, 1965)." Just which terms, whether Santa Fe Group or Gila Conglomerate, should be applied to the upper parts of the deposits was not clear, but, as repeatedly reiterated in our discussions of the reasons for restricting the term Santa Fe Group, we believe that these later beds of southern New Mexico should be removed from the Santa Fe Group, and, if not correlated with the Gila Conglomerate, a new formation or group should then be proposed to receive them.

Fossils from beds in the Rio Grande Valley near Socorro, New Mexico, have been reported by Needham (1936, p. 537) and referred to the Santa Fe Formation. Denny (1940a, p. 93) cited the presence of *Equus* and *Stegomastodon mirificus* in Santa Fe beds near San Acacia, New Mexico, and suggested a "Middle to Upper Pliocene age" for the Santa Fe Formation in that area. The fossils cited by Needham and Denny would necessarily indicate at least Blancan and, more probably, early Pleistocene age for the deposits of that locality.

# SUMMARY OF THE GEOLOGIC HISTORY OF THE SANTA FE BASIN

THE GEOLOGIC HISTORY of the Santa Fe Basin is a record of a complex series of lithic and faunal events. The Santa Fe area may be one of the few places where sedimentation was continuous during the transition from Miocene to Pliocene time, as North American Miocene and Pliocene are currently understood.[1] A sharp faunal break is difficult to recognize at any horizon, although the study of certain groups of animals, notably horses and merycodonts, suggests that such faunal breaks may actually exist at one or more points in the section. The base of the Pojoaque Member of the Tesuque Formation can be stated to be the horizon below which the fossils are mostly Miocene in aspect and are essentially equivalent to, or older than, those of the Lower Snake Creek quarries of western Nebraska, those of the Barstow, California, Green Hills and Second Division, and above which the fossils are mostly Pliocene in the sense of being equivalent to fossils from the Valentine and Ash Hollow formations of the Great Plains.

Lee (1907) and, later, Bryan (1938, p. 197) described a series of structural basins extending along the Rio Grande from the point where it enters the San Luis Valley near Monte Vista, Colorado, to Fort Quitman, Texas. To this group of basins Bryan applied the excellent descriptive term Rio Grande depression. Not all structural basins of the Rio Grande depression afford good opportunities for study of the sediments filling them—many of them because they are covered mostly with later detrital sediments, and others because they have not been subjected to extensive and rapid erosion. Fortunately, the best-exposed and thickest section of the Santa Fe Group crops out in the type area north of Santa Fe, New Mexico. The magnificent badlands of that area have resulted from an interaction of many geologic agencies over a long period of time, but probably the most significant events that shaped the pattern of the present topography were the post-Santa Fe deformation and the successive damming of the Rio Grande by the Otowi and Cerros del Rio lava flows in Quaternary time.

[1]On page 9 of this report, and in figure 10, an attempt is made to clarify our use of various time terms. Our intent is to use terms that are amenable to adjustments regardless of future shifts in concepts of age boundaries.

Several temporary base-levels were established for the ancestral Rio Grande by lava flows, and extensive erosion surfaces were cut in the area, but were it not for the intricate post-Santa Fe deformation the exposures in the type area would be inadequate to give an integrated concept of the stratigraphy.

The study of the geologic history of the Santa Fe Basin must be approached from several angles. Of primary importance is the necessity of determining, as nearly as possible, the series of events that resulted in the forming of the original Santa Fe Basin. A distinction should be drawn between the Rio Grande depression and the original Santa Fe Basin. The concept of the Rio Grande depression is currently that of a structural basin outlined by features mostly associated with the post-Santa Fe deformation. Actually the major features of the Rio Grande depression were outlined in at least two periods of deformation, and the post-Santa Fe deformation merely followed closely that of the initial faulted basin. Depositional limits of the original Santa Fe Basin were much broader, however, than the more recently deformed and down-faulted Rio Grande structural depression.

Kelley (1956, p. 110) has subdivided and redefined a part of the Rio Grande depression, and his designation of the salient features of the type and adjacent areas should be helpful for future research. The wider lateral extent of the deposits of the Santa Fe group is indicated by several hundred feet of Santa Fe sediments that are preserved in the downthrown blocks that form the footwalls of some of the faults bounding the Rio Grande depression. Erosion has stripped the Santa Fe beds from the upthrown blocks. In the Abiquiu area Santa Fe beds are preserved in footwall blocks, and along the Lobato flows in the Rio del Oso-Abiquiu locality (fig. 2) deposits of the Santa Fe Group have been preserved from erosion by high-altitude basalt flows. South of Los Alamos, part of the Pojoaque Member is exposed west of the Pajarito fault, which drops the Bandelier Tuff down along the east base of the Jemez Mountains. The clearest examples of these relations can be seen along the Canyada de las Milpas fault at the south end of the Sierra Nacimiento, and along the faults forming the western border of the Albuquerque-Belen basin, which is a part of the depression. Projection of the surfaces of the great alluvial fans that once filled the Espanola Valley would extend far to the east of any known exposures of the deposits of the Santa Fe Group.

Rocks of Precambrian age crop out in the core of the Sangre de Cristo Range, and along the east periphery of the type area of the Santa Fe Group. Just (1937) described several Precambrian formations in the Picuris, Ojo Caliente, and Petaca mining districts. Montgomery (1953), in his report on the Precambrian geology of the Picuris Range, expanded some of Just's formations and redefined others. These rocks underlie the Picuris and Ortega Mountains, and fragments derived from them can be recognized readily in deposits of the Santa Fe Group, which commonly contain a high proportion of Precambrian quartzite. The Sangre de Cristo Range has supplied most of the sediments making up the Santa Fe Group south of Black Mesa to Santa Fe Creek. Granitic rocks at the south end of the Sangre de Cristo Range near Santa Fe contain much red feldspar in contrast to the light, flesh-colored feldspar of the rocks farther north in the range. Lenses of gravel composed primarily of red granite that have been observed in the Pojoaque Member in the West Cuyamunque and Tesuque collecting localities indicate that parts of the sediments in those localities were derived from fans built along the south end of the range. Interfan areas can be recognized, and intensive sedimentation studies might explain some of the anomalies of lithology that have led previous investigators to state that Santa Fe beds are discontinuous and that key strata do not exist in the area.

The early Tertiary geologic history of the Rio Grande depression is based on fragmentary records. No Paleocene formations have been recognized definitely in the depression, with the possible exception of the upper part of the McRae Formation (Kelley and Silver, 1952, p. 119), despite the fact that beds of that epoch were extensively deposited in the San Juan Basin in northwestern New Mexico. No deposits of early Eocene (Wasatchian or Bridgerian) age have been described in the Rio Grande depression, although Gardner collected a mammal tooth that Gidley identified as *Palaeosyops* from the Baca Formation (Wilpolt et al., 1946). The Baca Formation has not been identified outside the Socorro region, and Wilpolt et al. (1946) noted the lithologic similarity of the Baca to the Galisteo Formation and suggested that the two formations may be correlative. If the identification of the brontothere tooth is correct, the Baca Formation conceivably may contain a medial Eocene fauna.

Renick (1931, p. 57) referred beds at the south end of the Sierra Nacimiento to the lower Wasatch, but Frick Laboratory field parties recovered Duchesnean fossils from the supposed lower Wasatch beds, and therefore the deposits are now correlated with the Galisteo Formation. At the south end of the Sierra Nacimiento the Galisteo rocks are exposed only between the Jemez fault on the east and the Sierrita fault a mile or two to the west. They lie unconformably on rocks referred by Renich (1931, p. 53) to the Puerco-Torrejon (=Nacimiento) formations.[1] The Sierrita fault, according to Renick (p. 74), is a part of the Sierra Nacimiento overthrust zone. The age relations of the formations involved at the south end of the Sierrita fault may prove to be important in dating the Sierra Nacimiento overthrust. The drab "Puerco-Torrejon" beds were deformed by the Sierrita fault, and the Galisteo equivalent was apparently the last formation deposited in the locality preceding the deformation, tending to date the movement as occurring in some part of the Oligocene. Deposits in this locality at the top of the Galisteo Formation equivalent consisting of greenish clay, sand, silt, and some bentonite may conceivably represent the so-far unrecognized New Mexico equivalent of the Oligocene formations of the Great Plains. The Zia Sand Formation (Galusha, 1966), with its faunal equivalent of the Harrison Formation of late Arikareean to late Hemingfordian age, lies unconformably on the deposits at the top of the Galisteo equivalent and extends without interruption across the trace of Sierrita fault as far west as the Canyada de las Milpas fault.

The Canyada de las Milpas fault was a part not of the Nacimiento overthrust, but of the post-Santa Fe deformation. Beds of the "Puerco-Torrejon" were deformed by the Canyada de las Milpas fault, but a Galisteo Formation

[1]Additional work in these sediments has produced hadrosaurian ossified tendons that suggest Cretaceous age for part or perhaps all of these deposits.

equivalent does not crop out along the fault, and hence probably was absent from the vicinity. In the downthrown block along the east side of the fault about 1000 feet of sediments are preserved that are referable to the following three formations: (1) a part of the Zia Sand Formation, (2) an equivalent of part of the Pojoaque Member of the Tesuque Formation, and (3) a thin wedge of the Upper Buff of Bryan and McCann. None of these formations crops out west of the Canyada de las Milpas fault, yet it is obvious that the original thickness of the Zia Sand and beds of the Santa Fe Group that extended west of the fault must have exceeded 1000 feet. The approximate thickness and extent, however, can only be inferred. Mesa Prieta, 15 miles to the west, is capped by Quaternary basalt that lies directly on Cretaceous rocks, and, if the Santa Fe Group ever extended so far west, no evidence can be adduced to prove it.

The Zia Sand Formation comprises about 1000 feet of predominantly quartz sand. The formation accumulated along the southeast end of the Sierra Nacimiento; equivalent deposits have not been recognized elsewhere in the Santa Fe region or reported from New Mexico. The Zia Sand originated as dominantly eolian deposits, as shown by eolian cross-bedding, and by the frosted, rounded, sand grains comprising most of the deposits. A few thin, fresh-water, limestone layers occur in the section, and these crop out in discontinuous belts, commonly in conjunction with sand and silt strata showing few eolian characteristics. These features are interpreted as indicative of local leveling among low dunes. The low dune areas did not receive direct sedimentation from alluvial fans, as shown by the absence of channels containing gravels and by the absence of original structures commonly regarded as of alluvial-fan derivation. The limestone and other noneolian strata might well have accumulated in shallow interdune valleys similar to those in some areas of the Sand Hills of Nebraska. Worm borings, casts, and trails have been noted on many of these limestones. The sandy strata immediately underlying the limestones are commonly green in color. Toward the top of the Zia Sand are bands of yellowish sand and silt or reddish sand and silt which alternate with the pinkish gray eolian sand. Fossils from horizons high in the section indicate that the time period covered by the Zia Sand Formation extends from late Arikareean (Harrison Formation equivalent) to late Hemingfordian (Sheep Creek equivalent). Fossils from the Kiva Quarry, which occurs in an isolated, local, valley fill south of Jemez Creek, indicate that sediments equivalent to the Sheep Creek Formation may be present. South of Jemez Creek the Tesuque Formation unconformably overlies the Zia Sand Formation. Here it should be emphasized again that no beds in the type locality of the Santa Fe Group have produced fossils equivalent in age to those from the Zia Sand.

Analysis of the stratigraphy of the formations in the type area of the Santa Fe Group clearly points to the inadequacy of the known deposits to provide a basis for systematic interpretation of the earlier part of the geologic history of the Santa Fe Basin. For example, formations laid down during the later part of the late Cretaceous, the Paleocene, and early to medial Eocene times are inadequately known or have not been identified positively in the Rio Grande depression. In the San Juan Basin and other adjacent areas these formations may be thick and extensive.

Stearns (1943, p. 315) discussed the pre-Galisteo unconformity and the general geologic history of the Galisteo Formation. The deposition of the Galisteo Formation was terminated by regional volcanism. During the period of volcanism several formations were deposited; their relations are discussed at length below.

The accumulation of the Abiquiu Tuff, the Picuris Tuff, and the Espinaso Volcanics marked a time of widespread volcanic activity in the type area of the Santa Fe Group. Only three possibly earlier occurrences of Tertiary volcanic rocks have been reported from the Rio Grande depression. Stearns (1943, p. 307) cited a few localities in which thin beds of water-laid tuff crop out in the upper part of the Galisteo Formation. The other formations were reported from the Socorro area, which is about 150 miles south of the type area. Winchester (1920, p. 9) described the Datil Formation. Later, Wilpolt et al. (1946) restricted the Datil to the upper part of Winchester's section, named the lower part the Baca Formation, and suggested that the Baca Formation may be equivalent to the Galisteo. If so, then the Datil Formation may be correlative also with the Abiquiu Tuff, Picuris Tuff, and Espinaso Volcanics. We believe that the Abiquiu Tuff was derived from volcanic centers north or northeast of the type area, probably in the San Juan region of Colorado. The other formations are believed to be accumulations from local vents.

Denny (1940a, p. 77) described the Popotosa Formation in the San Acacia area, which lies at the north end of the larger, more inclusive, Socorro basin. The Popotosa, according to Denny, consists of debris eroded from volcanic rocks, and a small amount of tuff. He stated that the Popotosa Formations rests unconformably on volcanic rocks of Miocene(?) age, and further stated that locally the two formations are conformable. In view of the general uncertainty of the age of the Popotosa Formation, subsequent work might well investigate a hypothesis that the Popotosa may belong in the general Abiquiu Tuff-Picuris Tuff-Espinaso Volcanic period of volcanism. Denny (1940a, p. 81) tentatively ascribed a late Miocene age to the Popotosa. The formation is more likely to be correlative with Oligocene deposits than with the late Miocene, although it must be admitted that, as yet, no deposits have been found in New Mexico that contain a fauna that represents a time-unit equivalent to that assigned to the Gering and Monroe Creek formations (Arikareean) of the Great Plains section. The Popotosa is composed mainly of debris from volcanic rocks and is not likely to have been formed contemporaneously with the Zia Sand Formation or with the Nambé Member of the Tesuque Formation. A fossil collection is needed from the Popotosa and other formations of doubtful correlation in the Rio Grande depression. Absolute dating by radiometric methods should be made of these formations, and a careful petrographic, petrologic, stratigraphic, and paleontologic study of the Abiquiu Tuff-Picuris Tuff-Espinaso Volcanics, and the Popotosa Formation would be a highly desirable contribution to the geology of the general area.

Atwood and Mather (1932, p. 98) traced sand and gravel derived from andesite flows and breccia of the Conejos Formation, which is exposed principally in the San Juan Mountains of Colorado, southward to the type area of the Santa Fe Group [some of the beds correlated by them with the Conejos Formation were included by Harold T. U. Smith (1938, p. 958) in his Abiquiu Tuff]. They stated (1932, p. 19): "Streams descending the flanks of the Conejos volcanoes washed debris derived from their easily eroded slopes to distances far beyond that reached by the flows of lava or the unwashed ejecta ... The finer gravel and sand were washed scores of miles southward into the region adjoining Santa Fe and Espanola, where they form the lower part of the Santa Fe Formation." The beds that they cite as lower Santa Fe, however, belong to both the Chama-el rito Member of the Tesuque Formation and to the Abiquiu Tuff—two formations separated by a hiatus covering a period of several million years. The possibility is good that both the Conejos Formation and the Abiquiu Tuff will prove to be of Oligocene age. The lenses of volcanic pebbles in the Chama-el rito Member were obviously reworked from the Abiquiu Tuff or were derived or reworked from volcanic beds northeast and north of the area. Many of the volcanic pebble lenses are directly associated with early Pliocene fossils in the Ojo Caliente, Chama-el rito, and Rio del Oso-Abiquiu collecting localities (fig. 2), and consequently the implications are that the history of the sedimentation is much more complex than the mere identification of Conejos rocks in the Santa Fe Group would indicate.

The start of deposition of the formations that comprise the Santa Fe Group, as restricted in this report, marks a change in the record of the geologic history of the Rio Grande depression in the type area of the Santa Fe Group. Sedimentation was favorable for the fossilization of mammalian remains for the first time on a scale sufficient to permit extensive collections to be made. Also for the first time large areas of fossiliferous strata were preserved to be later exposed as the major collecting areas.

It is clear that many of the beds in the type area east of the Rio Grande were built by alluvial fans issuing from the Sangre de Cristo Range, but it is equally clear from faunal and lithologic studies of the beds west and north of the Rio Grande in the same area that volcanic rocks supplied much of the sediments. These relations are discussed at length in this report particularly in the section on the Chama-el rito Member of the Tesuque Formation.

Any correlations of the beds of the Santa Fe Group based on the presence of tuffaceous sediments, or beds of ash, or bentonite, or eruptive rocks, must take into consideration the fact that volcanism in the area was not confined to any one portion of the section, but occurred in all members and formations from late Eocene to and including part of the Pleistocene. The conclusion is inescapable that these correlations must be made cautiously and be fully supported by paleontologic evidence or by stratigraphic relationships to beds that have been dated by fossils, or by radiometric methods, or by both.

The stratigraphy of the Nambé Member of the Tesuque Formation is discussed in this paper, and the nature of the contacts of the Nambé Member with the crystalline rocks of the Sangre de Cristo Range, and with the Picuris Tuff, is described. For the most part, the conglomeratic sandstone and sand portion of the Nambé was deposited on piedmont alluvial fans on which the gradient was not unusually steep; in fact, much of the Nambé as exposed appears to have developed on lateral distributaries of alluvial fans and in interfan basins. Some of the crystalline hills north of Nambé Creek are high and continuous, and the sediments of the Nambé Member banked against them are best explained by the hypothesis of deposition from alluvial fans that swept around the ends of the crystalline hills on the north; or crossed them in valleys toward the south, and then sent distributaries laterally parallel to the range of hills into the basins between the fans, here called interfan basins.

The fossiliferous portion of the Nambé Member indicates a period of deposition on slopes of lower gradient than that of the conglomeratic sandstone and sand portion. The relatively fine sediments of the fossiliferous part of the section occur marginally along lenses of conglomeratic sandstone and conglomerate. Beds of bentonitic clay of considerable lateral extent show that a relatively smooth depositional surface had been built in the area southwest of Chimayo. The bentonite and ashy strata testify to volcanism during the period of accumulation of the Nambé, but no direct evidence of proximity of the eruptive center is available. A petrologic comparison of volcanic ashes of the Nambé Member with those preserved in the Sheep Creek Formation of the Great Plains would be of great value. The Nambé and Skull Ridge members of the Tesuque Formation may contain ash strata correlative with those of the Sheep Creek-Snake Creek beds of Nebraska.

Evidence of the presence and significance of a series of ash beds in the Tesuque Formation is presented in the discussion of the stratigraphy of the Skull Ridge Member. These ash beds afford an opportunity for correlations of the fault blocks both along and across the strike and therefore are admirably adapted to sedimentation studies. Field evidence suggests that, by the start of Skull Ridge time, the sediments had built up sufficiently so that they eventually buried the front range of crystalline hills.

The deposits of the Red Wall (fig. 15B), in the lower part of the Skull Ridge Member, are somewhat more homogeneous and finer-grained than is usual in the rest of the member; only a few gravel lenses crop out, and these are north of White Operation Wash. A distinct change in sedimentation takes place at the horizon of the No. 2 White Ash, which caps the Red Wall cliffs, and this change continues to the horizon about 40 feet above No. 3 White Ash stratum.

Several channel-like deposits occur in the Tesuque Formation, and several different hypotheses could be explored to explain them. These channel-like deposits appear to have had their origin as distributaries of alluvial fans; the abrupt changes in lithology at some horizons can be interpreted as the result of breaches in the natural levees on the larger alluvial fans. Braiding, filling, and damming of the main streams on the fan could cause diversion and start local trenching of the levees and parts of the main fan. The extraordinary supply of sediments thereby obtained would differ in texture from those deposited under more normal circumstances. These postulates permit an explanation of local unconformities of low relief that are observed at the base of some of the channel-like deposits. The intraformational breccia in some of the channels consists of angular blocks of fine-grained silt or silty sand that could not have been transported more than a few hundred yards at most before redeposition. Each of these channel-like beds is overlain by deposits that gradually attain sedimentation characteristics that are similar to those underlying the channel. Perhaps the best example of this type of deposit is the channel above Ash F in the Skull Ridge Member (fig. 17).

During Valentinian time the Pojoaque Member of the Tesuque Formation began to receive coarser sediments from the granitic rocks of the Sangre de Cristo Range, and a thick section of irregular lenses of gravel in coarse sand or conglomeratic sand was built up. These deposits are of alluvial fan origin and comprise: (1) a large part of the great Picuris re-entrant fan north of the Santa Cruz River; (2) a few hundred feet of the gravels that form the higher parts of the Pojoaque Bluffs; and (3) deposits west of West Cuyamunque Wash (United States Geological Survey: Arroyo Jacona), south of Pojoaque Creek, where another large area of gravel lenses in sand occurs (but these were formed mostly by fans with sources farther south in the range). The cause of the increase in competency of the streams on the alluvial fans is unknown, but that increase may have resulted from a marked increase in the rainfall of the time; it may have accompanied differential uplift of the source areas of the range; it may have resulted from downwarp of the basin area; or the alluvial fans may have simply built up their lower ends and then were able to carry larger particles farther basinward. The hypothesis of downwarp has been explored by several investigators, but conclusive evidence for downwarp during the deposition of the Santa Fe beds has never been presented. The hypothesis of increased rainfall has little support when consideration is given to the 450 feet of Ojo Caliente Sandstone that formed mainly by eolian action in the upper part of the Tesuque Formation. These eolian deposits apparently overrode and overwhelmed the alluvial fans issuing from the volcanic highlands to the north. The alluvial fans were diverted to other regions, for no outcrops of volcanic pebbles characteristic of the Chama-el rito Member have been observed in the type area of the Santa Fe Group in beds later than the lower part of the Ojo Caliente Sandstone, indicating that the Ojo Caliente represents a time of change in the major sources of the sediments deposited in the type area; the San Juan Mountain region was no longer a provenance.

The widespread and thick Ojo Caliente Sandstone probably was an isolated dune-sand area similar to that of the Great Sand Dune National Monument in the San Luis Valley of Colorado. We question the interpretation of Bryan (1938, p. 207), and of Harold T. U. Smith (1938, p. 959), that the eolian sand of the Santa Fe beds (Ojo Caliente Sandstone) were of flood-plain dune or river-side dune origin. It is difficult to reconcile their hypothesis with the fact that deposits of the Ojo Caliente Sandstone can be traced for many miles from the Three Sand Hills Wash (United States Geological Survey: Canon la Madera) in the Rio del Oso-Abiquiu collecting locality northeastward across the Ojo Caliente collecting localities (fig. 2) to and across the Rio Grande near Embudo into the Dixon sub-basin south of the westward end of the Picuris Prong. Samples of sand collected from the Ojo Caliente Sandstone in the above localities show very little variation in the size of the grains. It is difficult to correlate these observations with the explanation given by Bryan (1938, p. 207) that a large river was being approached and the wind-blown sand indicated the probable border of a river flat. Particularly are the facts out of adjustment with Bryan's postulate that a large Pliocene perennial river occupied the position of what is now Chicoma Peak (altitude 11,507 feet) and Cerro Pedernal (altitude 9867 feet).

The Ojo Caliente Sandstone was obviously deposited in response to special environmental conditions. Local aridity that continued for a long period of time, perhaps thousands or even hundreds of thousands of years, would seem to be a logical prerequisite for the accumulation of several hundred feet of essentially eolian sediments. Strong and special wind conditions, perhaps directly associated with the size and shape of adjacent mountain areas during a particular part of the Tertiary, must be another requirement. Still other unrecognized conditions must have existed to cause such a profound change in the sedimentary environment.

Coincident with volcanic disturbances of Hemphillian time, deposition was resumed in the center of the depression in the type area of the Santa Fe Group. The Chamita Formation was laid down, of which a maximum of about 750 feet of deposits have been preserved from later erosion. On the north side of Black Mesa (fig. 27C) the Chamita Formation overlies the Ojo Caliente Sandstone. Wherever it can be observed, the contact at the base of the Chamita Formation with the upper beds of the Ojo Caliente Sandstone is interpreted as the result of leveling among the dunes or sandy areas at the top of the Ojo Caliente, heralding the start of new and vigorous deposition that resulted ultimately in the accumulation of the Chamita Formation.

Eventually the deposition of the Chamita Formation ended, possibly as a result of the post-Santa Fe deformation. Basins that had been separated and probably filling independently with sediments were at last integrated by a through drainage system. The ancestral Rio

Grande thus formed had tremendous erosive power and removed several cubic miles of sediments in the Espanola Valley and adjacent areas. Remnants of erosion surfaces cut on rock platforms along the mountain fronts or preserved beneath high-altitude basalt flows (fig. 30), such as Black Mesa, Lobato flows, and Cerro de las Minas (United States Geological Survey: Sierra Negra), when projected attest to a probable thickness for the original deposits in the area. Even such a projection may not be a maximum approximation, because each of these erosion surfaces represents a temporary base-level of unknown duration during which sediments were being removed.

No deposits of perennial rivers have been observed either in the Tesuque Formation or in the Chamita Formation; therefore the ancestral Rio Grande is post-Santa Fe Group in age. Bryan (1938, p. 207) reported the occurrence of perennial river gravels interbedded in the Santa Fe Formation at the north end of White Rock Canyon. Denny (1940b, p. 682) figured an exposure west of the old Buckman Bridge site. These are regarded by us as associated with the erosion period immediately antedating the deposition of the Puyé Conglomerate and the Otowi lava flows.

The history of the Santa Fe region following the post-Santa Fe deformation is extremely difficult to decipher, and bits and pieces of information must be fitted together from many sources to attempt an explanation. The high-altitude basalts provide evidence that volcanism was an important factor in events that brought deposition to an end in the type area of the Santa Fe Group. The 15- to 30-foot-thick bed of cleanly washed, well-sorted, mainly ovoid-shaped pebbles and cobbles that underlies the basalt capping Black Mesa (fig. 38) shows that a large perennial river had been established at that point and that a probable lava tongue followed its course.

Ozima et al. (1967, pp. 2618, 2619) have dated by potassium-argon methods a series of successive lava flows exposed in the Rio Grande gorge near Taos, New Mexico. The dating was a part of their study of the paleomagnetism of the area; it showed that the base of the upper normal polarity sequence is about 3.7 million years old. The exact relation of this part of the lava sequence to the lava capping Black Mesa from Embudo to the vicinity of Chamita, New Mexico, remains to be determined, but Black Mesa appears to be a valley tongue belonging to the general Taos Plateau sequence. This would indicate at least a Blancan (Evernden et al., 1964, p. 164) age for the Taos lava and, by correlation, at least a Blancan age for the Black Mesa lava and the cobbles that underlie it.

Magnetic reversal studies coupled with potassium-argon dating of Black Mesa, and other high level basalts, such as the Lobato flows, Cerros de las Minas, and Cerro Pedernal, would provide a valuable contribution to the geologic and geomorphic history of the Santa Fe Basin. If such studies were extended to include the Cerros del Rio, Otowi lava flows, Mesa de los Ortizes, and Round Mountain (*Tunyo piñ*), even greater results could be expected.

The present Rio Grande has cut a gorge about 1000 feet deep (Lambert, 1966, p. 43) in the southern end of the Taos Plateau; the river leaves the Rio Grande Canyon near the town of Velarde, New Mexico, and flows along the southeastern flank of Black Mesa for a distance of about 10 miles. Here, also, more than 1000 feet of sediments have been eroded, and an extremely complex series of erosion surfaces and terraces have been cut in the type area of the Santa Fe Group and some constructional deposits preserved thereon (the effects on the geomorphology and the geology are discussed in this report under the heading Erosion Surfaces). All these erosion surfaces were cut following the post-Santa Fe deformation, and probably many of them can be correlated with important Pleistocene events.

A volcanic pile had been building in the general area of the present Jemez (Valles) Mountains since the post-Santa Fe deformation, but apparently this did not interfere greatly with the removal of a large volume of sediments of the Santa Fe Group from the Espanola Valley by the time the Puyé Conglomerate was deposited. Perennial gravels observed at the base of the Puyé at several sites between Santa Clara Canyon and Guaje Canyon indicate that a large river was involved in excavating the valley into which the Puyé was deposited.

Increased volcanic activity in the Jemez area caused impounding of the drainage system along the edge of the rapidly building alluvial fan of Puyé gravel, thus forming long narrow lakes into which some sediments from the adjacent Santa Fe beds were reworked. These and other reworked sediments from the Santa Fe Group easily can be mistaken for Santa Fe beds because they are similar in appearance. This similarity has led to a variety of interpretations of intertonguing and interfingering, by Griggs (1964, p. 27) of Santa Fe beds and Puyé Conglomerate, and by Spiegel and Baldwin (1963, pp. 47, 50, 53, 59) of the Tesuque Formation, Ancha Formation, basalt tuffs, and Puyé Conglomerate. Lava flows eventually blocked these lakes, and one unit of these flows was observed intercalated between Puyé Conglomerate and the thick overlying Bandelier Tuff.

The Bandelier Tuff represents a period of intense volcanic activity in the Jemez Mountains in which hot turbulent ash flows (Ross, Smith, and Bailey, 1961, p. 141) erupted along the crest of the Valles (Jemez) Range and spread as coalescing fans on surrounding slopes. These ash-flow tuffs occur as welded tuffs, nonwelded tuffs, and pumice units. Extrusion of great volumes of free-fall pumice and volcanic ash must have accompanied these ash-flow eruptions, which immediately preceded the collapse of the roof of the magma chamber to form the caldera known as Valle Grande. The deposition of the Bandelier Tuff appears to have been the culmination of volcanic activity in the Jemez Mountains, for younger volcanic rocks by comparison are small in area and in volume. Coincident with the collapse of the caldera, the Pajarito fault along the east shoulder of the Jemez Mountains dropped the east side down, displacing the Bandelier Tuff.

The history of the post-Bandelier Tuff of the Santa Fe Basin continued to be primarily one of degradation, in which successive erosion surfaces were cut. Some of these erosion surfaces are surmounted by remnants of constructional deposits that testify to intermittent periods of aggradation during the Pleistocene.

A surface of relief almost as intricate as that of today had been eroded in the Espanola Valley in late Pleistocene time, and on this was deposited the loess-like Espanola Formation. Evidence for deposition in the Santa Fe Basin since that time has been negligible, consisting mostly of terraces or alluvial plains along drainage basins that reflect relatively long stands at temporary base-levels.

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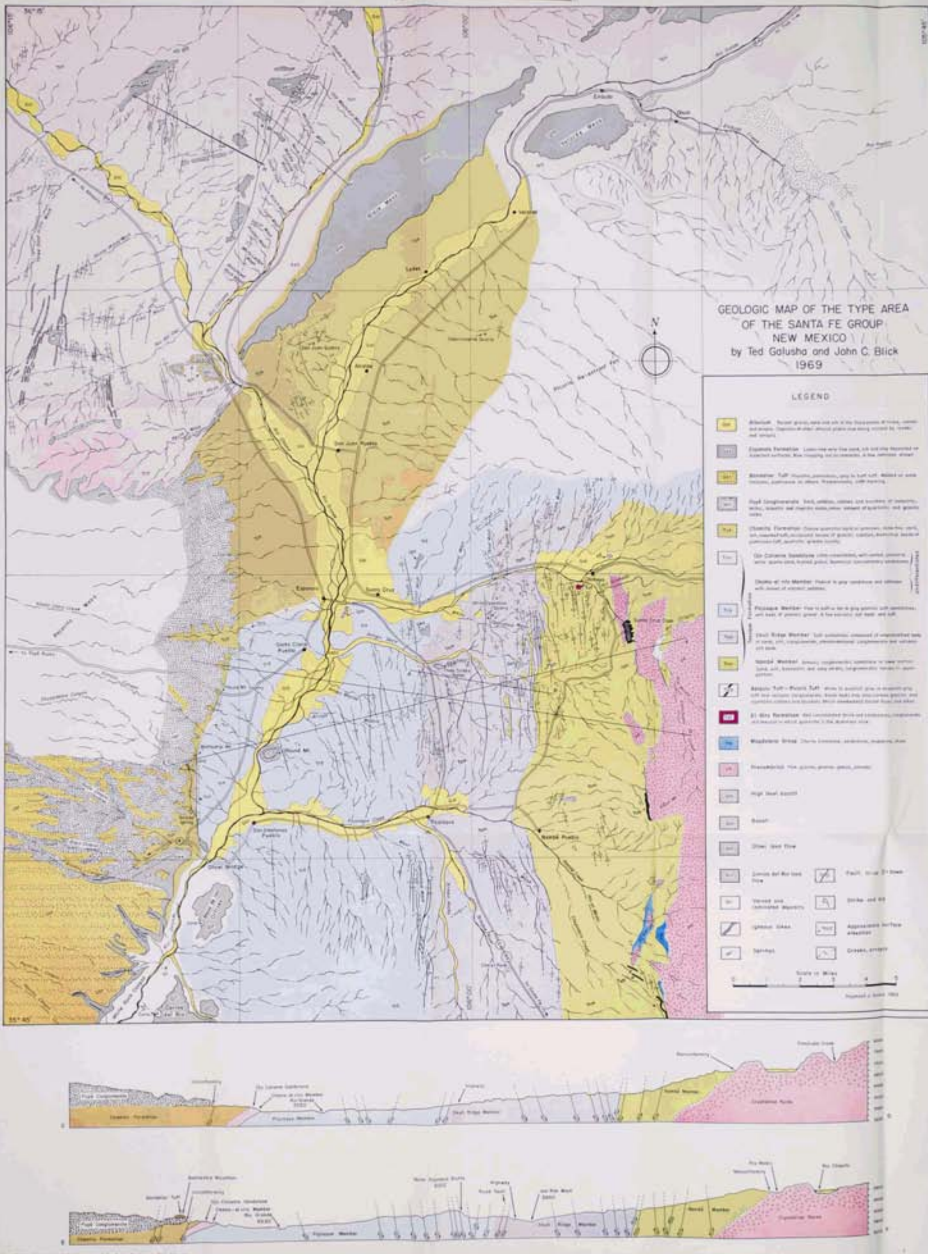

GEOLOGIC MAP OF THE TYPE AREA
OF THE SANTA FE GROUP
NEW MEXICO
by Ted Galusha and John C. Blick
1969
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