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SANTA FE FORMATION IN THE ESPAÑOLA VALLEY, NEW MEXICO

BY CHARLES S. DENNY

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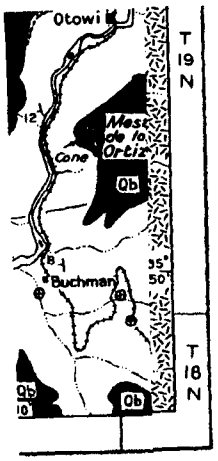

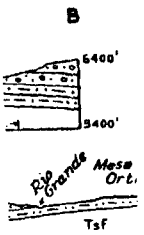

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1. Geologic map of southern half of Española Valley, New Mexico. 677
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ABSTRACT

The type area of the Santa Fe formation (late Tertiary) is the region north of Santa Fe, New Mexico, between the Sangre de Cristo and Jemez mountains. The formation includes gravel, sand, silt, volcanic ash, and a little clay. Intraformational breccias are abundant in certain zones. Most of these materials were laid down as coalescing alluvial fans in a basin which, at its maximum, extended to the east and probably far to the west of the present limits of the formation. This alluvium was deposited by streams which flowed westward from highlands that bordered the basin on the east. Throughout most of the period of deposition these highlands were relatively low. During late Santa Fe time the eastern highlands stood at a somewhat greater elevation relative to the basin floor, and river gravels indicate that the center of the basin was occupied by a through-flowing river. The events of post-Santa Fe time have either removed or concealed all trace of the deposits laid down in the western part of the basin. Post-Santa Fe deformation has given the beds a general westward dip at angles of 5 to 10 degrees or more. At many localities the beds are displaced by normal strike faults, many of which are filled with conglomerate or sand dikes. Similar faults displace the unconformity which separates the formation from the older rocks to the east. Along their west border the Santa Fe beds are covered by the younger sediments and volcanics of the Jemez Mountains.

INTRODUCTION

The unconsolidated alluvial deposits which partly fill the Rio Grande Depression near Santa Fe, New Mexico (Fig. 1), were first described by Hayden in 1869 and were called the "Santa Fe marl". Fossils found by Cope (1874, 1884) were assigned to the middle Miocene epoch. An Upper Miocene and Lower Pliocene age is recorded by later workers (Matthew, 1900, p. 19-75; Osborn, 1909, p. 65; 1918, p. 34; Simpson, 1925, p. 230; Frick, 1933, p. 505-652). In his latest paper Frick (1937, p. 6) lists all the fossil localities under the heading "Late Tertiary" or "Middle Miocene to Upper Pliocene". Although early workers interpreted the formation as a lacustrine deposit, recent studies support the fluviatile hypothesis originally proposed by Davis (1900) and elaborated by Johnson (1903). Throughout northern New Mexico most of the unconsolidated deposits of the Rio Grande Depression were originally considered to be one formation. For example, on the geologic map of New Mexico by Darton (U. S. Geol. Survey, 1928) these deposits are grouped together as one formation assigned to the Miocene and Pliocene. However, recent studies have shown that this unconsolidated alluvium is divisible into several formations, some of which lie above and some below the fossil-bearing beds of the type region. In the Abiquiu quadrangle Smith (1938) found two formations, the Abiquiu tuff and the El Rito formation, which are stratigraphically below the beds (Santa Fe formation) which he correlates with Hayden's "Santa Fe marl". Cabot (1938)

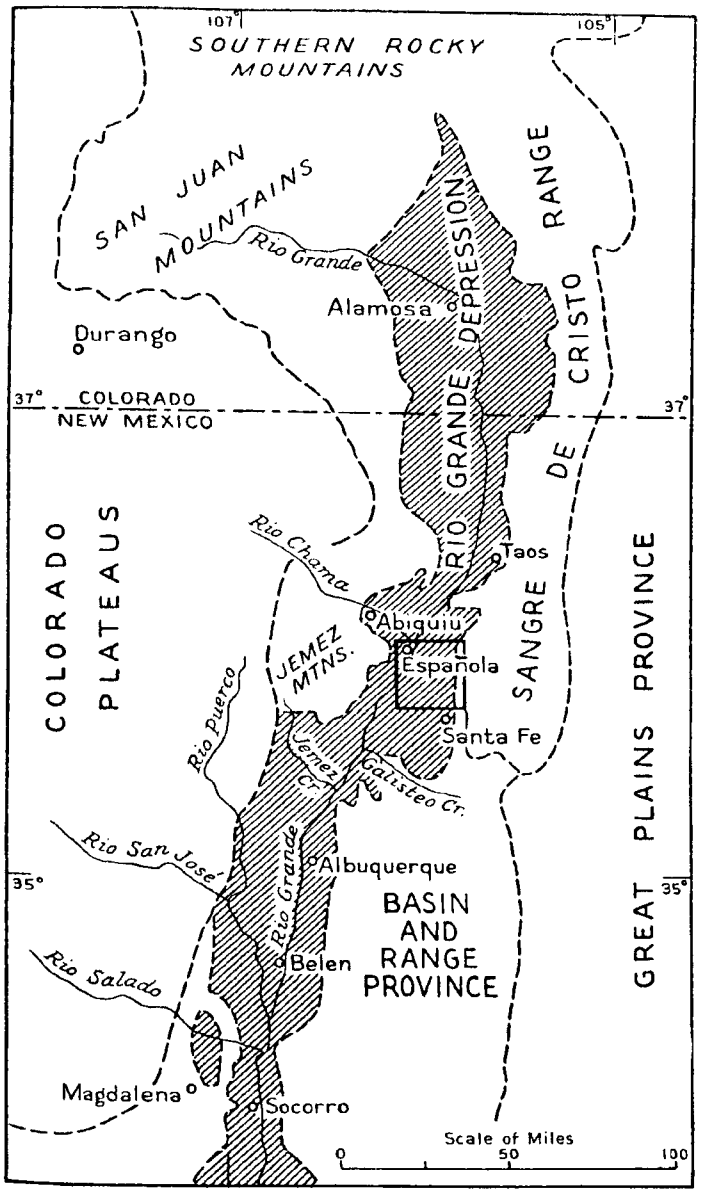

FIGURE 1.—*Index map*

Showing northern part of Rio Grande Depression and area discussed

found a tuffaceous deposit, the Picuris tuff, below the "Santa Fe ma in the Picuris re-entrant (Fig. 1. East side of Rio Grande, east Abiquiu).

The name, Santa Fe formation, is now used for those deformed a predominantly fluviatile deposits of the Santa Fe region that contain vertebrate fauna. Similar deposits which contain a few vertebr remains are found throughout most of the Rio Grande Depression in N Mexico and are correlated with the type region (Bryan, 1938, p. 20 These deposits are probably the equivalent of the Gila conglomerate southern Arizona (Gilbert, 1875; Knechtel, 1936).

Although extensive collections of fossils from the Santa Fe formati have been gathered in the region between Santa Fe and Taos, except f the study of the Abiquiu area by Smith (Smith, 1935, 1938) and th of the eastern contact of the formation by Cabot (1938), no detailed map of the formation in this area has been published. The writer devoted about six weeks to a study of the formation in the southern half of the Española Valley and compiled the geologic map (Pl. 1) from data recorded on aerial photographs and drainage maps of the U. S. Soil Conservation Service. The limited time available for field work, the variability of the formation, and the abundance of faults make it impossible to present a complete stratigraphic column for the Santa Fe formation in the type region or to give a precise figure for the total thickness of rocks exposed. The various subdivisions of the alluvial fan deposits cannot be mapped as distinct lithologic units and are given below for the convenience of description.

ACKNOWLEDGMENTS

This project was carried out under the direction of Professor Kirk Bryan of Harvard University. The writer was first introduced to the area by Mr. Edward C. Cabot. The aerial photographs and drainage maps were furnished through the kindness of Captain M. E. Musgrave and Messrs. Smith and Kippe of the Rio Grande District Office of the U. S. Soil Conservation Service at Albuquerque. Professor E. D. Elston of Dartmouth College has been kind enough to criticize the manuscript. The writer is indebted to A. M. D. for assistance in the field and in the preparation of the manuscript. Mr. Edward A. Schmitz prepared the figures.

LITHOLOGY

ALLUVIAL FAN DEPOSITS

Gravel and coarse-grained sand.—The gravel is irregularly stratified, and most outcrops show cross-bedding (Pl. 2, Fig. 1). Individual strata are from a few inches to 10 feet or more in thickness, and in most places

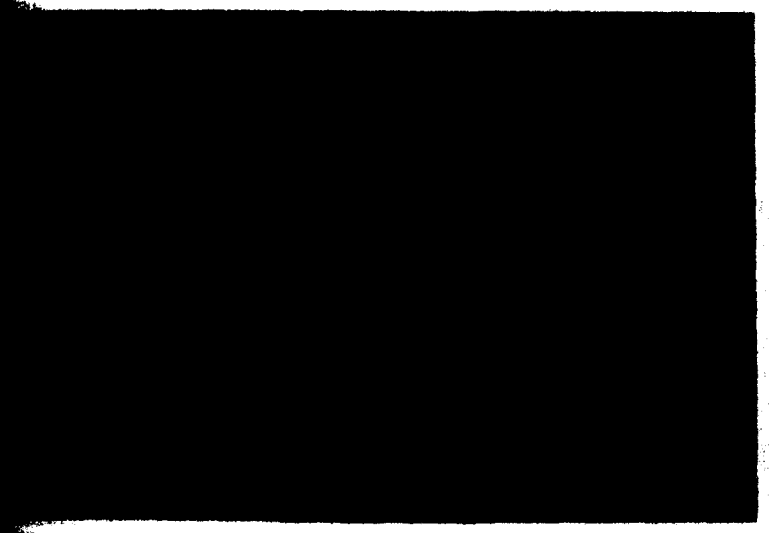

FIGURE 1. CROSS-BEDDED SAND AND GRAVEL
Exposure in arroyo bank about 2 miles northeast of Nambé.

FIGURE 2. IRREGULAR LENSES OF GRAVEL IN SAND
e of mesa about 2½ miles north of Chimayo. (Shadows at base of gravel lenses).

COARSE-GRAINED FAN DEPOSITS

FIGURE 2. INTRAFORMATIONAL BRECCIA
Angular and rounded fragments of clay in stratified sand.

FIGURE 1. SAND AND SILT WITH INTRAFORMATIONAL BRECCIA
South side of Arroyo Seco about 4 miles east of Rio Grande.
Breccia above hammer.

he coarse-grained members are the thickest. The constituent pebbles, cobbles, and boulders are angular and subangular. Colors vary from ight gray to reddish-brown. The stones in the gravel are predominantly ranitic. Limestone, sandstone, and volcanic rocks occur in relatively inor amounts. Most of the gravel is partly cemented by calcium arbonate.

Bouldery gravel occurs only near the eastern limits of the formation. n an arroyo about 1½ miles north of Nambé Falls (Pl. 1; T. 19 N., R. 0 E.) this gravel rests unconformably on pre-Tertiary rocks. The oulders are angular and more than one foot in diameter. Only a small mount of matrix is present. A faint stratification can be seen. This eposit is perhaps a true fanglomerate (Lawson, 1913).

Lens-shaped masses of gravel interbedded with coarse and fine-grained and are locally abundant. Exposures in cliffs show discontinuous beds f gravel which vary greatly in thickness and locally crosscut the stratifi- ation of the surrounding layers of sand (Pl. 2, Fig. 2).

The coarse-grained sand is unsorted. The individual grains are angular nd consist predominantly of quartz, feldspar, and rock fragments. ndividual strata range from one inch to several feet in thickness. Cross- edding is visible in many exposures. The texture changes rapidly from ed to bed or from place to place in any one bed (Pl. 2, Fig. 1). Pebbles nd fine sand are scattered through the coarse-grained sand.

Fine-grained sand and silt.—The fine-grained sand and silt form even yers which vary in thickness from a fraction of an inch to 10 feet. The dividual beds can be traced for considerable distances. Cross-bedding present. In some places the foreset beds are as much as 15 feet in ngth and dip at angles of only a few degrees. Perhaps such strata are lian deposits. Layers of grayish-white, clean, well-sorted sand form ick, massive beds which may also be of eolian origin. Fragments of rified bone are abundant on the outcrops of such beds.

Colors vary from white to gray to yellow to reddish-brown. Most of sand is poorly sorted, and some strata contain a few pebbles. stant sand concretions from an inch to one foot in diameter are found ayish-white sand.

assive beds of brownish, poorly-sorted sand are partially cemented lcium carbonate. Layers of brownish sand contain irregular masses lenses which are partly cemented by calcium carbonate. The inder of the layer is unconsolidated. Such strata resemble the beds aliche which mantle erosion surfaces in the vicinity (Bryan and ann, 1938, p. 5-6) and may be due to the evaporation of ground during deposition of the sand.

Fine-grained beds are well exposed in the south bank of Pojoaque C just east of the highway bridge at Pojoaque and in the vicinity o main highway from Pojoaque to Santa Cruz. Beds of tuff and i formational breccia are locally interstratified with these fine-gr rocks.

Clay.—Except at a very few localities clay is not found in th deposits. A gray, calcareous clay (?) interbedded with sand an was noted at a point about 2 miles north of Chimayo (T. 21 N., R. 1 Clay balls are found in fine-grained sand and silt at many localitie

Tuff.—Layers of white to gray tuff are intercalated with the grained fan deposits. The tuff beds range from a few inches to 6 in thickness and can be traced for a mile or two along the strike. E at a few localities the beds are disconformable on the underlying st Layers of unstratified tuff are probably the result of ash showers temporaneous with deposition of the alluvial fans. Stratification in tuff suggests reworking by streams. Tuff beds are abundant in the vici of the main highway from Pojoaque to Santa Cruz.

Intraformational breccia.—At several localities intraformational bre is found intercalated with fine-grained sediments. These breccias con of fragments of vari-colored clay and silt scattered throughout medi grained sand that shows definite stratification (Pl. 3, Fig. 2). The bre fragments are angular, oval, round, or slab-like, and range in len from one-half inch to 6 feet. Most fragments are less than one foot diameter. At one locality a cross-bedded sand contains balls of c as much as one foot in diameter, and irregular blocks from 2 to 3 f wide and 6 feet long. The breccias do not exceed 50 feet in length about 20 feet in width. They rest disconformably upon even-bed fine-grained sand or silt (Pl. 3, Fig. 1).

Many exposures show contemporaneous deformation of the st which surround a lens of breccia. Cross-bedding and channel filling fine sand and silt, similar to those figured by McKee (1939, Pl. 2) f the lower part of the delta of the Colorado River, are locally associa with the breccias. Intraformational breccias are exposed in the so bank of Pojoaque Creek just to the east of the highway bridge Pojoaque and also in a butte (Pl. 3, Figs. 1 and 2) on the south side Arroyo Seco about one mile east of the highway crossing.

RIVER DEPOSITS

Gravel and sand.—The river gravel in the Santa Fe formation cons of stones which are either round, oval or sub-angular (Bryan, 1 p. 207). A little brownish-gray poorly sorted sand makes up the ma

FIGURE 1. SANTA FE RIVER GRAVEL
North side of canyon 1½ miles west of Buchman. Largest boulders are one foot in diameter.

FIGURE 2. SAND DIKE ALONG FAULT PLANE
Prospect pit one mile east of Santa Cruz.

SANTA FE RIVER GRAVEL AND SAND DIKE

between the pebbles. Water-worn boulders of purplish and bluish-gray banded quartzite reach a maximum diameter of one foot; other stones reach a minimum of one-half inch. In some exposures the average diameter is from 6 to 8 inches (Pl. 4, Fig. 1); elsewhere it is 1 to 3 inches. Rock types include quartzite, quartz conglomerate, dark, fine-grained igneous rocks, a few pink "granites", fragments of tuff, and various volcanic porphyries largely of andesitic composition some of which are slightly water-worn. Individual strata range from 2 to 20 feet in thickness. A fine-grained sand is interbedded with the gravel. Cross-bedding was not observed. In some places the river gravel is interstratified with gravel of the alluvial fan type. In the area studied the only exposures of river gravel are in canyons on the west side of the Rio Grande (Pl. 4, Fig. 1) to west of Buchman (T. 19 N., R. 7 E.).

Silt and clay.—A greenish silty clay, which is associated with river gravel, was noted in one of the canyons to the west of Buchman. These outcrops were not studied.

VOLCANIC ROCKS

In this area volcanic rocks are almost lacking in the Santa Fe formation. Near Rio Nambé and Chupadero and to the west of Piñon Mountain (T. 18 and 19 N., R. 10 E.) there are outcrops of at least one basalt (?) flow, which ranges in thickness from 8 to 15 feet and is associated with tuffaceous gravel and sand. This sequence rests unconformably on pre-Tertiary rocks. These tuffaceous deposits lie conformably beneath typical arkosic Santa Fe sand and gravel, and perhaps represent a very early phase of Santa Fe deposition. They are described by Cabot (1938, p. 91) as a part of the Picuris formation.

On the west side of the Rio Grande near Buchman (T. 19 N., R. 7 E.) one or two flows of andesite-basalt are interbedded with river deposits. In the White Rock Canyon to the south of Buchman these flows increase greatly in number (Bryan, 1938, p. 207-208).

GEOLOGIC STRUCTURE

GENERAL STATEMENT

In northern New Mexico the Rio Grande Depression is a down-faulted basin (Fig. 2). That part of the depression which is known as the Española Valley (Bryan, 1938, p. 200) is bounded on the east and west by normal faults (Cabot, 1938; Smith, 1938). In this valley the Santa Fe formation dips westward, and the strata are broken by normal strike faults. Within the area studied (Pl. 1) the average strike of the beds is north and south, and the dip is westward at angles of from 2 to 10

degrees. North of the Santa Cruz River the strike is toward the nor east. Along the eastern contact of the formation most of the dips ran from 10 to 35 degrees. No folds were observed.

The normal faults have an average dip of about 72 degrees. Co glomerate or sand dikes are to be found along many of these fault pla (Pl. 4, Fig. 2). The formation is in contact with the older rocks to t

TABLE 1—*Data on fault planes*

Description	Number of examples	Average dip	Percentage of to number of faul
Angle of dip from 0°–90°	49	72°	100
Angle of dip more than 60°	43	75°	87
Angle of dip more than 70°	33	79°	67
Santa Fe in contact with pre-Tertiary rocks	6	70°	12
Conglomerate or sand dikes	17	.....	35

east along a faulted unconformity. Such a structure gives rise to a serie of westward-tilted fault blocks, bounded by normal faults (Structure sec tions C-D, E-F, and I-J; Pl. 1). To the west of the Rio Grande th formation disappears beneath the younger sedimentary and volcanic roc of the Jemez Mountains.

FAULTS

The geologic map (Pl. 1) shows many eastward and westward-dippin normal faults which are only a small percentage of the total numbe The abundance of faults in the structure sections and near the easter limit of the formation, in contrast to the rest of the region shown o Plate 1, is the result of more detailed field work in those special localiti rather than of any scarcity of faults elsewhere. The total displaceme along most of the inter-Santa Fe faults is probably small. A summar of data on the faults is presented in Table 1. Conglomerate or sand dike from one to 10 feet wide, are found along many fault planes. Thin band of silt with slickensided surfaces are locally associated with the san dikes. Many dikes are composite. In some places there are fault zon which range from a few to 100 feet in width. These zones contain min horsts and grabens, some of which are bounded by curved fault plan with dips along the individual plane varying from 40 to 90 degree Closely spaced parallel faults and small reverse faults are locally presen Mineralization is almost universally absent. A one-inch dike of calci was noted along a minor break which has a total displacement of abo 1½ feet.

RELATION TO SURROUNDING FORMATIONS

General statement.—In the southern part of the Española Valley the eastern contact between the Santa Fe formation and the pre-Tertiary rocks of the Sangre de Cristo Mountains is a faulted unconformity. The general nature of this contact from Santa Fe to Taos is described by Cabot (1938, Fig. 2). The average trend of the contact from Chupadero to Chimayo (Pl. 1) is north-south. The Santa Fe formation, which was laid down unconformably on the older rocks, has been tilted westward. The Tertiary beds are displaced along a series of normal faults which in some places parallel the unconformity and elsewhere cut across it at all angles. Later erosion of the Santa Fe beds has carved valleys which project into the foothills of the Sangre de Cristo Mountains to the east. The latter are underlain predominantly by granite and gneiss of pre-Tertiary age. North of Chimayo, outside of the area shown on Plate 1, the Santa Fe formation extends as a re-entrant into the pre-Tertiary rocks to the east ("Picuris re-entrant", Cabot, 1938, p. 98).

To the west of the Rio Grande the Santa Fe formation is overlain unconformably by a sequence of sedimentary and volcanic rocks of Quaternary age.

Nambé Falls-Chupadero section.—The Falls of the Rio Nambé (T. 19 N., R. 10 E.) are located in a small horst of pre-Tertiary rocks which is completely surrounded by the Santa Fe formation (Structure section I-J). To the east of the Falls there is an eastward-dipping (?) normal fault. To the west Tertiary gravel rests unconformably on the older rocks. The Santa Fe (Picuris tuff?) which is exposed to the east of the Falls can locally be seen resting unconformably on the pre-Tertiary rocks. At the southwest end of the horst, along the Rio en Medio, the Santa Fe rests unconformably on the older rocks. A few hundred feet to the west this unconformity is displaced along a westward-dipping normal fault (Structure section I-J).

A small outlier of pre-Tertiary rock is located about 1½ miles north of Nambé Falls. On the north and east sides of this outlier the Tertiary beds are down-faulted against it. On the west it is overlain unconformably by Tertiary gravel.

The eastern limit of the Santa Fe in the Nambé Falls-Chupadero section is an unconformity which is displaced along a normal fault at a point about a mile north of Rio Nambé and again about a mile southsoutheast of En Medio.

Piñon Mountain section.—To the west of Piñon Mountain the pre-Tertiary rocks are overlain unconformably by the Santa Fe formation. In some places there are faults in the younger rocks close to the contact.

These breaks are not traceable for any distance along the strike, are therefore not shown on the geologic map (Pl. 1). A finger-sh area of the Santa Fe formation extends northeastward from Piñon Mo tain for a distance of about 1½ miles. The eastern boundary of re-entrant in which the Tertiary strata are dipping westward nowhere seen, but it is interpreted as an unconformity locally br by faults. Piñon Mountain is bounded on the east by a normal (?) fa

Another projection of the Santa Fe formation into the older crystal rocks of the highlands is located about 2½ miles north of Piñon Mo tain. This re-entrant is bounded on the east by an unconformity and the southwest by a normal (?) fault (Structure section E-F). Near eastern border of this re-entrant there is an easterly-dipping normal fa with a maximum displacement of about 20 feet (Structure section E- The similarity of a minor structure such as this with the major structu of the re-entrant is typical of the eastern contact of the Santa Fe form tion throughout the area. About a mile to the east of this re-entra there is a down-faulted wedge of late Tertiary sediment which exten southward from the village of Cundiyo. Both to the north and sou of Cundiyo the Santa Fe formation can be seen resting unconformabl on the pre-Tertiary rocks to the east. To the west of Cundiyo t Tertiary strata are cut off along a normal (?) fault.

Santa Cruz reservoir section.—The valley of the Santa Cruz reservo (T. 20 N., R. 10 E.) is eroded in a down-faulted wedge of Santa F gravel. To the east Santa Fe beds rest unconformably on the pr Tertiary rocks. The contact is clearly exposed in the arroyo which ente the northeast corner of the reservoir. To the south of the reservoir th unconformity is displaced along a westward-dipping normal fault whic can be traced southward for a distance of about a mile where the conta is again an unconformity. To the west of the reservoir the Tertia gravel is down-faulted against the older rocks (Structure section C-D along the "Santa Cruz Reservoir Fault" (Cabot, 1938, Figs. 10 and 11 Uplift of the pre-Tertiary rocks along this fault has tilted westward th Santa Fe beds which rest unconformably on the older rocks to the ea of Sanctuario.

Buchman-Otowi section.—On the western side of the Española Valle to the west of Otowi and Buchman, the Santa Fe formation is overla unconformably by sedimentary and volcanic rocks of the Jemez Mou tains. These Quaternary rocks include the Puyé gravel, local basa flows, and the Bandelier rhyolite tuff (Smith, 1935; Bryan, 1938). The were not studied in any detail, and their distribution on the geolog map (Pl. 1) is based on a brief reconnaissance and a study of aeria photographs.

THICKNESS

The total thickness of the Santa Fe formation in the type region cannot be accurately estimated. The strata are cut by many faults along which the total displacement is unknown. The structural interpretation which is presented in the structure sections (Pl. 1) calls for a section of Santa Fe which is at least 2000 feet thick in the center of the basin, whereas 3000 to 4000 feet is probably a closer estimate on the assumption that the displacements along the inter-Santa Fe faults are relatively small.

ORIGIN

AN ALLUVIAL FAN DEPOSIT

The Santa Fe formation, excluding the river-laid beds, is interpreted as an alluvial fan deposit (Bryan, 1938, p. 205). The distinctive characteristics of the formation are in summary as follows: There is a lack of sorting of both the coarse and fine material. The pebbles, cobbles, and boulders are angular and subangular. Most of the individual particles, whether large or small, are relatively unweathered. Rapid changes in texture, both in a horizontal and vertical direction, are the rule. The stratification of many of the coarse-grained members is indistinct. Cross-bedding and cut and filled channels are visible in many exposures.

Intraformational breccia is abundant in the finer-grained members of the formation. The origin of these breccias may be explained in the following manner. Thin layers of fine-grained sand and silt are deposited where the lower end of an alluvial fan merges with the central part of the depositional basin, which in this case is a river flood-plain. The even-bedding and widespread distribution of the fine-grained material suggests deposition in flood-plain ponds, rather than in broad stream channels. As the flow of water from the fan decreases, silt and clay are deposited. With desiccation mud cracks develop. The next stream of water from the fan picks up these fragments of silt and clay and cuts a shallow channel. The fragments are carried a short distance and deposited in a muddy matrix. The mud balls are fragments of mud which were rolled along the bottom of the stream. They are found in present-day arroyos such as the Rio Salado, Socorro County, and the Rio Chaco, San Juan County (Gardner, 1908; Bell, 1940). Perhaps some of the blocks now in breccia originally fell from the undercut bank of a stream. The presence of foreign boulders, such as granitic rocks from the mountains, and of earthy material in the matrix indicate that the breccias are not mud flows (Blackwelder, 1928; Woodford, 1925). There is no evidence by which these breccias can be shown to be due to slumping on scarps developed along active faults.

The thick beds of grayish-white well-sorted sand that are found in association with the finer-grained members of the formation may be due to sand deposited near the lower end of an alluvial fan or on the edge of the flood-plain of a river (Smith, 1938, p. 956). Most of the gra

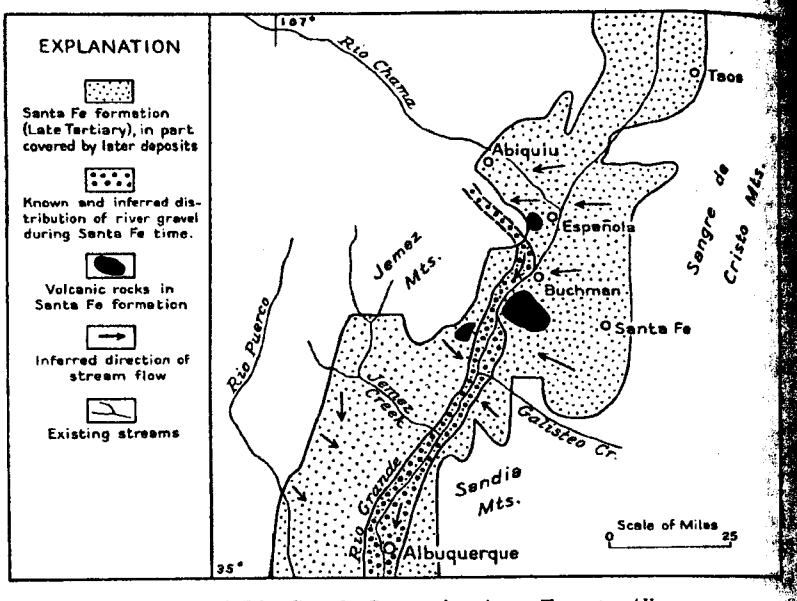

FIGURE 2.—*Map of Rio Grande Depression from Taos to Albuquerque*
Showing ancestral Rio Grande and inferred direction of stream flow during Santa Fe time. Modified from Bryan (1938), Fig. 46.

is partly cemented by calcium carbonate, and calcareous concretions are abundant in the finer-grained phases of the formation. These facts suggest deposition by streams rich in lime. The outcrops of limestone in the Sangre de Cristo Mountains to the east are the nearest available source.

The formation has many of the characteristics of the "Desert Environment", and the "Piedmont" and "Valley-flat" phases of the "Fluvial Environment" as given by Twenhofel (1932, p. 785-795; 800-811).

SOURCE OF SEDIMENT

The Sangre de Cristo Mountains to the east of the Española Valley (Fig. 2) are composed of rocks of two distinct ages. (*See* Darton's geologic map of New Mexico published by United States Geological Survey in 1928.) Granite, gneiss, schist, pegmatite, and similar rocks of

pre-Cambrian age (Darton, 1928, p. 272-274) are overlain unconformably by sedimentary rocks of Pennsylvanian age which include limestone and minor amounts of shale and sandstone.

The Jemez Mountains to the west of the Rio Grande are underlain predominantly by volcanic rocks of Cenozoic age. One of these, the Chicoma volcanic formation, includes "several thousand feet of andesite and latite lavas with some basalt, rhyolite and volcanic breccia" (Smith, 1938, p. 939). This formation is older than the Santa Fe and is probably "equivalent to the Miocene volcanics of the San Juan Mountains in Colorado" (Smith, 1938, p. 958). In most places the Chicoma volcanic formation is overlain unconformably by volcanic rocks of Quaternary age.

In the southern half of the Española Valley the Santa Fe formation contains an abundance of granitic gravel and arkosic sand. A few limestone pebbles are present. At most localities pebbles of volcanic rock are absent. These facts indicate that the Santa Fe formation was derived from the Sangre de Cristo Mountains to the east (Smith, 1938, p. 955-956). Near Chimayo (T. 21 N., R. 10 E.) arkosic Santa Fe gravel contains a few pebbles of volcanic rock. Such pebbles are not necessarily of western derivation (from the Jemez Mountains) because they could have come from outcrops of Picuris tuff (Cabot, 1938, p. 91) which are now either concealed beneath later deposits or have been removed by post-Picuris erosion. The slightly water-worn pebbles of andesite porphyry which are found in the Santa Fe river gravel to the west of Buchman were probably derived from the low-lying Chicoma volcanic center to the west.

AREAL DISTRIBUTION OF LITHOLOGIC TYPES

In general bouldery gravel is found only near the eastern limit of the formation from Chimayo to Chupadero (Pl. 1). As one goes westward from this contact the beds are finer and finer grained until one reaches about the longitude of Pojoaque and Cuyamungué. Northward from the above-mentioned villages runs a belt of rather fine-grained material which extends as far north as the Arroyo Seco where the belt turns slightly to the northeast (parallel to the strike of the rocks) and continues to the Santa Cruz River. To the west of this belt the formation is somewhat coarser-grained, although nowhere is it as coarse as near its eastern margin. Near the Rio Grande the Santa Fe is mostly sand and silt although layers of pebbly fan gravel can still be found interbedded with the Santa Fe river gravel to the west of Buchman.

ANCESTRAL RIO GRANDE

The gravel which crops out to the west of Buchman is interpreted as the deposit of a large, through-flowing river on the basis of the following

evidence (Bryan, 1938, p. 205-208): (1) The abundance of large wat worn fragments of resistant rock in contrast to the angular stones in surrounding fan deposits; (2) the presence of greenish clay (flood-pl deposit); and (3) the geographic location of this gravel with respect the bordering fan deposits of the Española Valley and to similar ri gravel in adjoining areas to the south (Fig. 2). The well-roun boulders of quartzite and volcanic porphyry, found near Buchman, too greatly water-worn to have come from the surrounding fans Santa Fe time and must have been carried by the late Tertiary ri from extensive outcrops of quartzite and volcanic rock in northe New Mexico.

The hypothesis that the Santa Fe formation was laid down in sever contiguous basins, the axis of which was marked by a through-flowi river, is based on field studies by Bryan and others (Bryan, 1938; Bry and McCann, 1937; Denny, 1940; Smith, 1938). River gravel is fou at the south end of White Rock Canyon, throughout the Santa Domin Valley where good exposures of river gravel are found in road cuts alon the Santa Fe-Bernalillo highway about 5 miles north of Algodones, and scattered outcrops throughout the Albuquerque and Belen Valleys. Th gravel shows a slight decrease in size from north to south.

The river gravel is locally associated with lava flows which appear have confined the course of the river to some extent (Fig. 2).

The controlling base-level for the deposition of the Santa Fe formatio in the Española Valley was the ancestral Rio Grande. This base-level was rising, probably as the result of tectonic disturbance at an unde termined point down river. In the southern part of the Española Valle the abundance of fine-grained material in the formation may be part due to damming of the ancestral Rio Grande by lava flows, of whi more than 1200 feet are exposed in White Rock Canyon to the sou of Buchman (Bryan, 1938, p. 208).

ORIGINAL EXTENT OF THE FORMATION

Only the eastern part of the original basin of deposition of the Santa Fe formation is exposed in the southern half of the Española Valley. Th fact is brought out in structure sections G-H and I-J because, as point out above, all the material, to the east of the outcrops of river gravel, w derived from the east. The formation must have originally extend some distance to the west of Buchman. Smith (1938, p. 956) states th there were low highlands "at the Chicoma volcanic center" duri Santa Fe time. At its eastern edge the formation is not very coa grained except at a few localities. The rather gradual change in text from the center of the original basin eastward to the present marg

suggests that the formation once extended a considerable distance farther to the east, perhaps nearly to the position of the present summits of the Sangre de Cristo Range. The small number of limestone pebbles in the Tertiary gravel, in spite of the relatively large areas of Pennsylvanian limestone to the west of the summit of the range, suggests that relatively early in the epoch of Santa Fe deposition these areas were more or less completely covered by detritus and, therefore, most of the Santa Fe gravel came from the pre-Cambrian rocks near the crest of the range. (*See* Darton's geologic map of New Mexico published by the United States Geological Survey in 1928. The areas of Magdalena limestone shown are somewhat exaggerated.)

CLIMATE OF SANTA FE TIME

The climate of Santa Fe time was probably semi-arid to humid with a rainfall somewhat greater than that of the present, which is 7 to 18 inches a year in the valleys (Cooperrider and Hendricks, 1937, Fig. 2). The great abundance of vertebrate remains attests to a more humid climate than that of the present as does the absence of saline deposits such as gypsum from the Tertiary beds. On the other hand the absence of carbonaceous matter in the finer-grained sediments, the presence of mud cracks, the unweathered character of most of the detritus, and the abundance of calcium carbonate suggest a semi-arid climate.

CONCLUSIONS

The Santa Fe formation contains alluvial fan and river gravel, sand, silt, clay, tuff, and intraformational breccia. The formation was deposited as coalescing alluvial fans which, during the late Tertiary, spread westward from the relatively low ancestral Sangre de Cristo Mountains toward the flood-plain of a southward-flowing permanent river, the ancestral Rio Grande. Gradients were low. To the west of the river there was a small highland area, the Chicoma volcanic center (ancestral Valles Mountains). Sand dunes were common along the eastern side of the flood-plain of the river. The climate was semi-arid to humid. Occasional showers of volcanic ash were spread over the surface, to be locally transported by rain wash and deposited near and on the river and plain. Considerable vegetation was present in and near the flood-plain and also on the bordering highlands. An abundant vertebrate life inhabited the area, at least for part of the year.

Since the Pliocene the formation has been tilted westward and broken along many normal faults. Much material has been either eroded away or covered by later deposits. Extensive erosion has been in progress since at least the middle of the Pleistocene.

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