STRATIGRAPHY AND ENVIRONMENT OF DEPOSITION OF MEMBER 9 OF THE RAWLS FORMATION, PRESIDIO COUNTY, TEXAS

by

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THESIS

Presented to the Faculty of the Department of
Geology of the University of Houston in Partial
Fulfillment of the Requirements for the Degree of

Master of Science

The University of Houston
Houston, Texas
May, 1976

PREFACE

Many people were instrumental in the completion of this thesis. Members of my advisory committee, Drs. Henry Chaftez, John Butler, James B. Stevens, and Victor Mote, were always available when called upon. To these people I offer my sincere thanks.

Financial aid via a grant from the Texas Bureau of Economic Geology and a Tenneco Foundation Scholarship allowed me to work full time on this thesis during my last year, this aid is heartily appreciated. Special thanks to M. Stevens who identified the vertebrate fossils collected from the study area. Thanks to my mother-in-law Mrs. Ralph Spence, who typed the final draft of my thesis. Lastly to my wife Barbara, whose help as field assistent, typist, editor, and innumerable other small projects, I offer my sincerest thanks.

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Abstract

Strata of member 9 crop out in the Santana, Redford and Presidio bolsons in the southern Bofecillos Mountains. Member 9 is correlative with the Tarantula gravels in the Rim Rock Country, the Delaho Formation in the Big Bend National Park, and with the basal parts of many of the bolson deposits which crop out along the Rio Grande. Approximately 90 meters of coarse-grained sedimentary strata and intercalated volcanic flows compose the member. Volcanic strata included in the member are the youngest known in this part of west Texas. The depositional environment for the sedimentary strata is interpreted as having been a series of coalescing alluvial fans that filled fault block basins which were formed along the trend of the Redford-Lajitas fault zone. The source for these strata was the older Tertiary volcanic flow rocks exposed around the flanks of the topographically high Bofecillos Volcano. A transgression of textural facies (distal over proximal) within the member indicates that that these strata were deposited during a period of tectonic quiescence. Renewed faulting in the area terminated the accumulation of member 9 strata. Strata deposited after this second period of faulting compose the Redford-Presidio bolson-fills. Erosion since the introduction of a regional drainage system during the Pleistocene(?) has resulted in stripping away most of the originally

deposited member 9 strata; only those strata contained within grabens formed during post-member 9 tectonic activity have been preserved.

This thesis was presented to the faculty of the Department of Geology in May, 1976.

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INTRODUCTION

Purpose

The purpose of this study was to determine the environment of deposition and source area for strata composing member 9 of the Rawls Formation in Presidio County, Texas; and to re-evaluate the stratigraphy of the late Tertiary-Quaternary bolson deposits in this region of west Texas.

Scope

In the study area, McKnight (1968) mapped and described strata representing two periods of deposition within bolson structures. He concluded that there is an unconformity with 3° of angularity separating the two units. However, for mapping purposes, he used the presence or absence of intercalated volcanic flow rocks to differentiate two bolson-fill units. The oldest of these has the youngest volcanic flows known in this part of west Texas intercalated with the sediments and was mapped by McKnight (1968) as part of the Rawls Formation (Tr9 and Tr9f). This older bolson-fill unit is the subject of this report. McKnight (1968) mapped the younger bolson-fill strata as Redford-Presidio bolson-fill (Qtf). These strata are only cursorily treated in this paper.

Because both "units" were aggrading sequences within bolson structures the term "bolson-fill strata (Qtf)" will be used to designate those deposits mapped as such by McKnight (1968). Problems of the relations of these two units will be discussed in more detail in a later section of this text.

Location

The study area is located in the southeastern part of Presidio County, Texas (Figure 1). Included in this study are those outcrops of member 9 strata bounded on the south and west by the Rio Grande, on the north by latitude 29°30', and on the east by the Brewster-Presidio county line. The defined area occupies parts of the Lajitas and Redford quadrangles.

Access

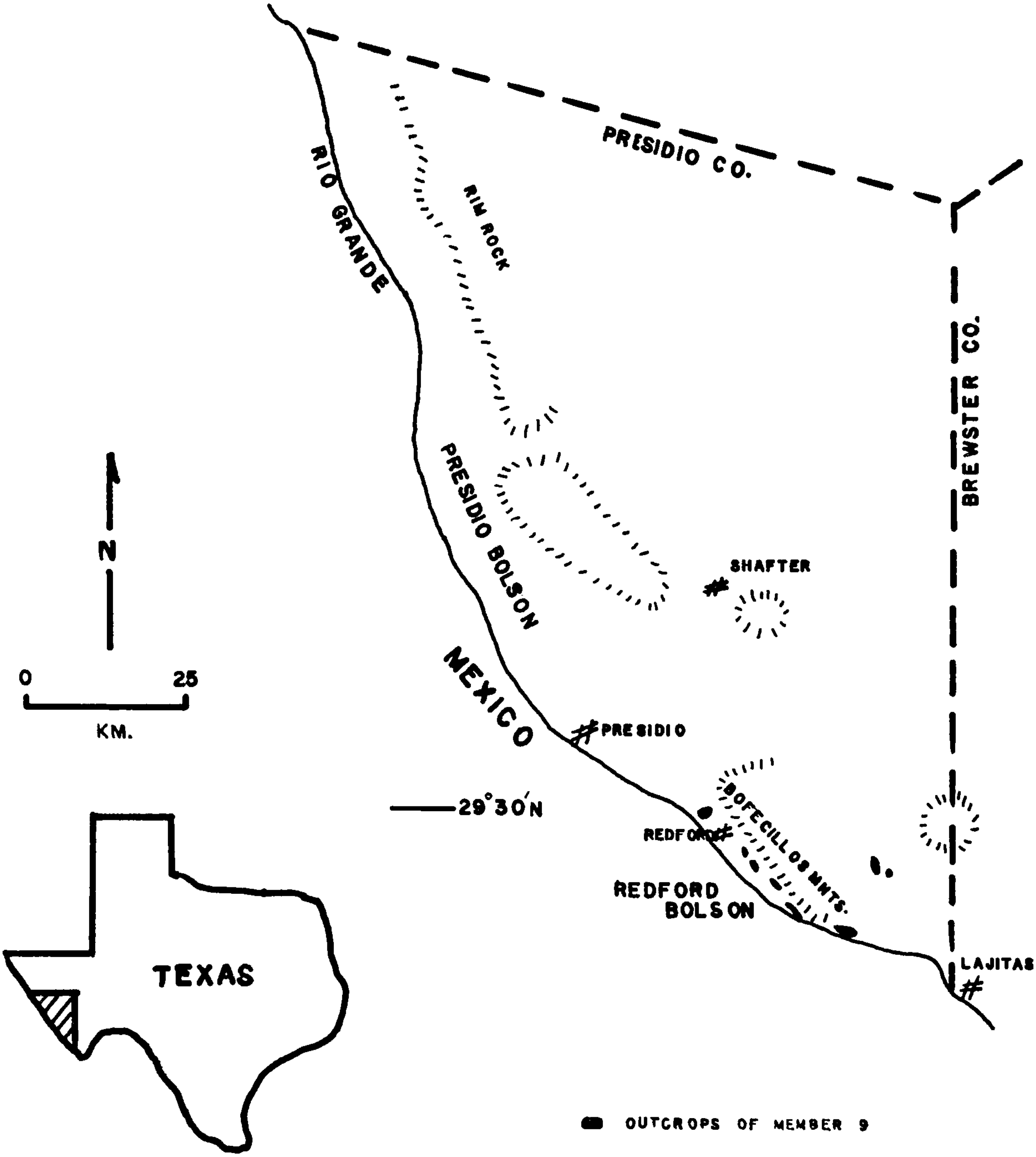
Access to the southern part of the study area can be gained by Texas Route 170 which parellels the Rio Grande and connects the Texas border towns of Study Butte and Presidio. The northern part is accessible by numerous graded roads located on the Big Bend Ranch, many of which are not traversable with two-wheel drive vehicles.

Climate and Vegetation

The study area is located in the arid, Trans-Pecos region of west Texas. The annual precipitation in the area is approximately 25 cm and occurs most commonly as downpours during the late summer and early fall; these thunderstorms often result in flash floods. Temperatures range from well over 40° C on many summer days to below freezing during the winter months. Presidio, former site of a United States weather station, often recorded the highest daily temperatures in the United States, particularly during the spring and summer months.

Vegetation in the area is typical of arid-desert regions of the southwestern United States and the Chihuahua desert; this includes catclaw, lechuguilla, ocotillo, cactus, mesquite, creosote bush, and grasses. Locally, around springs and on the Rio Grande flood plain, thickets of cottonwood and cedar are found.

Figure 1. Map showing location of the study area
(modified from Groat, 1968)


PRESIDIO CO.
BREWSTER CO.
RIO GRANDE
RIM ROCK
PRESIDIO BOLSON
SHAFTER
MEXICO
PRESIDIO
N
0
25
KM.
29°30'N
BOFECILLOS MNTS.
REDFORD
REDFORD BOLSON
LAJITAS
TEXAS
OUTCROPS OF MEMBER 9

Land Use

Farming of cantaloupes, onions and cotton around the towns of Lajitas and Redford on the Rio Grande flood plain provides the major source of income for the local inhabitants. Large expanses of rugged pastures support small numbers of cattle, goats, and sheep. The Rio Grande and wells provide the only dependable source of water for most of these pastures. Deer are common in this part of west Texas and therefore hunter's fees are an additional source of income for ranch owners.

Physiography

The Bofecillos Mountains are located within the Basin and Range Physiographic province. McKnight (1968) divided the area into four basic types of physiographic land forms. The dominant physiographic feature in the area is the ancient Bofecillos Volcano which forms the center of the Bofecillos Mountains. Erosion of this near circular structure and several small domes in the area has produced a radial drainage pattern of deeply incised streams. Tilted fault blocks (Plate 1A) are prevalent along the Rio Grande in the northwest-southeast trending Redford-Lajitas fault zone. Erosional lowlands are the most common physiographic land form north and east of the town of Lajitas. Breached bolsons along the Rio Grande form the lowest erosional surfaces in the study area (Plate 1B). The flat surface eroded on the bolson-fill strata dips gently away from the mountains toward the Rio Grande. Elevations in the study area range from 730 meters to 1490 meters within a distance of 5 kilometers.

METHODS AND DISCUSSIONS

Procedures

Reconnaissance of the area was made during the spring, summer and winter of 1974. Most field work was completed during the summer of 1975. A subsequent visit to the field area was made during the fall of 1975 in order to resolve problems that arose during the writing stage of this thesis. The majority of the analyses of samples were completed using techniques performed in the field.

Samples were taken at more than fifty localities. Upon selecting a site to be examined, a number of systematic sampling and describing operations were conducted. These operations included: (1) the determination of sorting of the unit; (2) measurements of maximum clast size; (3) recording directional measurements on paleocurrent indicators; (4) lithologic pebble counts; (5) measurements of roundness and form of clast; (6) completion of a detailed description of bedding characteristics; and (7) collection of oriented samples for later laboratory examination.

A total of 14 representative conglomerate samples were collected, slabbed, and their texture and fabric described. Ten thin-sections of various sandstone beds and conglomerate matrix material were examined for sorting, size, and mineralogy using a petrographic microscope. X-ray diffraction methods were used to determine the mineralogy of eleven oriented clay samples and one sample of evaporite crystals.

Sampling Locations

Collecting stations were chosen to provide good areal control and to include the best outcrops. The best outcrops occur along sidestreams of the Rio Grande which cross member 9 strata from north to south before entering the river. Once a suitable station was chosen, its location was marked on a 1:60,000 aerial photograph, a 1:24,000 U.S.G.S. topographic sheet and a Texas Bureau of Economic Geology map of the Bofecillos Mountains area.

Outcrop Descriptions

The general descriptions of the outcrops are important in determining the distribution and relations of the facies. It is from these observations that the environment of deposition of the strata is determined.

Special emphasis in this part of the study was placed on the determination of (1) bedding thicknesses, (2) percentage conglomerate versus sandstone versus mudstone as discreet beds, (3) bedding contacts and continuity, (4) channel width-to-depth ratios, (5) types and abundances of cross-stratification, and (6) the fabric of the strata. Two measured sections (Appendix A) and fifty-one described stations were examined from which the above listed data were obtained.

Size Measurements

Bluck (1964) and Blissenbach (1954) have shown that by comparing the maximum clast sizes from various locations on the surface of an alluvial fan one can determine the distance and the direction of transport of the clasts. This method can be used to infer the location of the source area.

The size of a clast can be measured in a number of ways. One method is a linear measurement of a chosen dimension, which is used directly as measured, or which is combined with other linearly measured dimensions to yield an approximation of the area or the volume of a clast. While the latter is probably the best measure of size, it is not commonly used because of the inconvenience of measurement. Most workers have chosen to use either the long dimension (Bluck, 1964), or the intermediate dimension (Sneed and Folk, 1958) of a clast as a measure of size. If the clasts cannot be removed from the outcrop, Miall (1970) has suggested measuring the apparent long dimensions of the clasts exposed on a vertical outcrop face. Miall's (1970) method of clast-size determination has many of the same problems as the determination of grain size in thin-section, which has been extensively studied (Chayes, 1958, and 1965; Friedman, 1965; and Irani and Collis, 1963). Using Miall's (1970) method, the size obtained for each clast will be smaller than the size determined by removing the clast from the outcrop; but this does not appear to present a problem in delineating changes in size with distance from the source area. Different workers have suggested measuring various numbers of clasts; in recent investigations, Bluck (1964) measured ten clasts, and Miall (1970) twenty-five clasts. Because induration of much of member 9 strata made the removal of clasts for size measurements difficult, I chose to measure the apparent long dimension of the fifteen largest clasts exposed at the sampling site. The measured clasts were located within a circle ten feet in diameter that was centered around a randomly chosen point. At some stations is was nescessary to measure more than 100 clasts to insure that the fifteen largest were included.

Sorting

Determination of the degree of sorting is an important part of any study of sedimentary rocks. Different environments of deposition are capable of producing different degrees of sorting. In unconsolidated sediments sorting values are generally obtained by measuring the size of the gravel constituents with a caliper, sieving the sand fraction, and pipetting the mud fraction. This method presents problems when one tries to combine the numerical percentage of the coarse fraction to weight percentage of the fine fraction to obtain a "whole-rock" sorting value. Another problem related to the use of this method is that the size of the sample needed for analysis increases geometrically as the size of the largest clasts increases (Krumbein and Pettijohn, 1938). Sampling member 9 strata for standard size analysis is not feasible for this reason. "Whole-rock" sorting analyses of coarse-grained strata are rare (Miall, 1970). When the strata are indurated, as were most that I dealt with, two alternatives exist. Either one can measure the size of only the larger clasts (Mackin, 1937); or measure the size of all the larger clasts, estimate the percentage of the matrix material, and collect a sample that can be thin-sectioned and point-counted. Then these two sets of data can be related by the equation given by Miall (1970). I chose, as most workers have, to determine the degree of "sorting" by using only the coarser-than-2 cm size fraction.

At each station, using a method similar to the ribbon technique suggested by Van der Plas (1965) for thin-section work, 100 clasts, whose apparent long dimension was greater-than-2 cm, were measured. Later, an equation which determines sorting by the method of moments (Folk, 1974) was used to determine the sorting values from the raw data. "Sorting" values obtained by this method are probably lower (better sorted) than the value other methods would have yielded. This is because the smaller-sized clasts are selectively weathered from the outcrop (Stevens, 1969), and because only the coarser-than-2 cm size fraction was included in the analysis. All measurements for sorting determinations were conducted using the sedimentation unit as a basis for sampling (Otto, 1938). The only other statistical parameter determined was the mean, as all other parameters "would be of doubtful value" (Stevens, 1969).

Roundness and Form

Roundness and form are intricately related. Thus they will be discussed under a single heading.

Roundness measurements of pebble and larger-sized clasts have been widely used as indicators of distance, vigor, and direction of sediment transport. Clast form has been shown to change with distance of transport (Miall, 1970) and environment of deposition (Dobkins and Folk, 1970); although differing views for the former have been presented by Krumbein (1942).

Roundness and form are both dependent on size and lithology; furthermore, roundness, when measured quantitatively, is closely related to form for low roundness values (Flemming, 1965). Because of these interrelations, it is possible to measure both parameters on the same set of clasts.

Most of the quantitative methods for measuring roundness are modifications of the method described by Wentworth (1919). Non-quantitative, visual comparison charts (Krumbein, 1941) are also widely used. I felt that using a quantitative approach to measuring roundness would introduce the least chance of operator error, or bias, into the system and would better indicate subtle differences in roundness.

The method described by Stevens (1969) was used in this study because much of the material I worked with had high roundness values (very angular), which makes the use of Folk's (1970) method somewhat inadequate. The procedure was as follows: (1) the clast was oriented so as to view the maximum projection plane (MPP) (Wadell, 1933); (2) next, using a plastic overlay with a series of inscribed circles, the diameter of the largest circle that could be inscribed on the MPP surface was determined; (3) then, the diameter of the circle whose radius of curvature just fit the sharpest corner on the perimeter outline of the MPP was determined (Figure 2). The diameter of each circle had previously been converted to the log 2, so that the diameter of the smaller circle could then be subtracted from the larger circle diameter resulting in a roundness value. At each station the roundness values of twenty-five clasts with long dimensions between 32 and 64 mm (-5 to -6 phi) were calculated. This size was chosen because the lithology of clasts in this range were easily identifiable and present in the strata of all facies. The mean and standard deviation were then determined and compared with data from other stations by a t-test.

The terms shape, form and, to a lesser extent, sphericity (Wadell, 1932), are generally used interchangeably, although their meanings are different. Form, as defined by Folk (1974), is "the measure of the relation between the three dimensions of an object". Clast form was determined on the same set of clasts used in the study of roundness. The procedure for determining form was to hold each clast in order to view the MPP, and then to measure the longest dimension of the clast with a standard laboratory caliper. Next, the length of the longest dimension perpendicular to the true long dimension was measured (intermediate dimension). Finally the length of the longest dimension perpendicular to the MPP (short dimension) was determined. No axis need pass through any common point, although the axes must be mutually perpendicular.

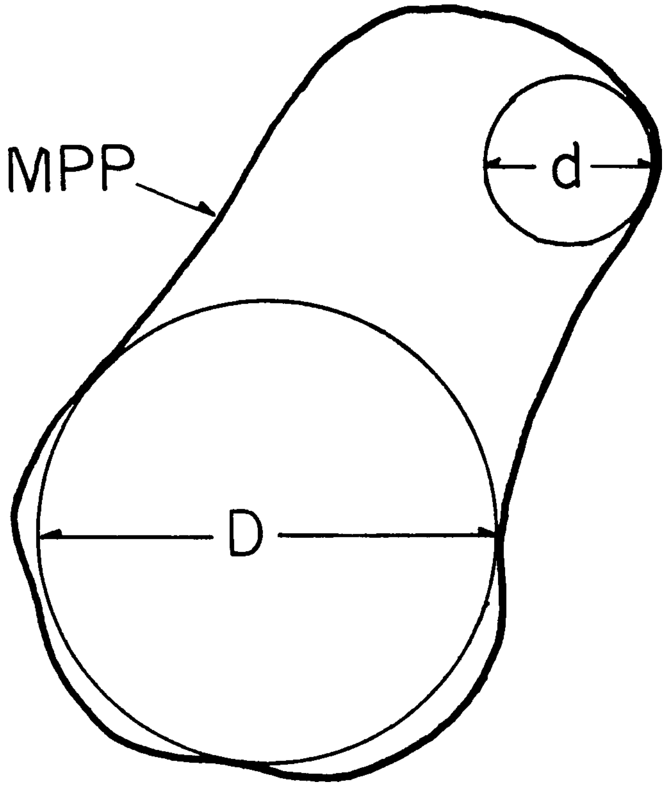
The equations used for calculating the axial ratios from which form is determined, are given below (Folk, 1974):

Equation 1: $Y = S / L$

Equation 2: $X = (L - I) / (L - S)$

Where X and Y are axes on a triangular graph, L is the long dimension, I

Figure 2. Method used to determine the roundness of pebble-sized clasts. (modified from Stevens, 1969)



ROUNDNESS = D-d

is the intermediate dimension, and S is the short dimension.

Once the X and Y coordinates of each clast had been determined and plotted on a triangular graph (Dobkins and Folk, 1970), an average form for each station was computed. For each station the number of clasts within each "form cell" was computed and compared with the data from other stations by a Chi-square test. This statistical test was used to detect any significant differences in form between stations. Using the same dimensions previously measured, the maximum projection sphericity (MPS) (Sneed and Folk, 1958) was computed using the following equation:

Equation 3: $$\sqrt[3]{S^2 / (L * I)} = MPS$$

Where L, I, and S are the same variables as in equations 1 and 2. These values were then plotted on a similar triangular diagram, and the mean MPS computed.

Paleocurrent Indicators

Imbricated pebbles, cross-stratification, and the orientation of channel axes have all found wide use as paleoslope indicators in recent and ancient sedimentary basins.

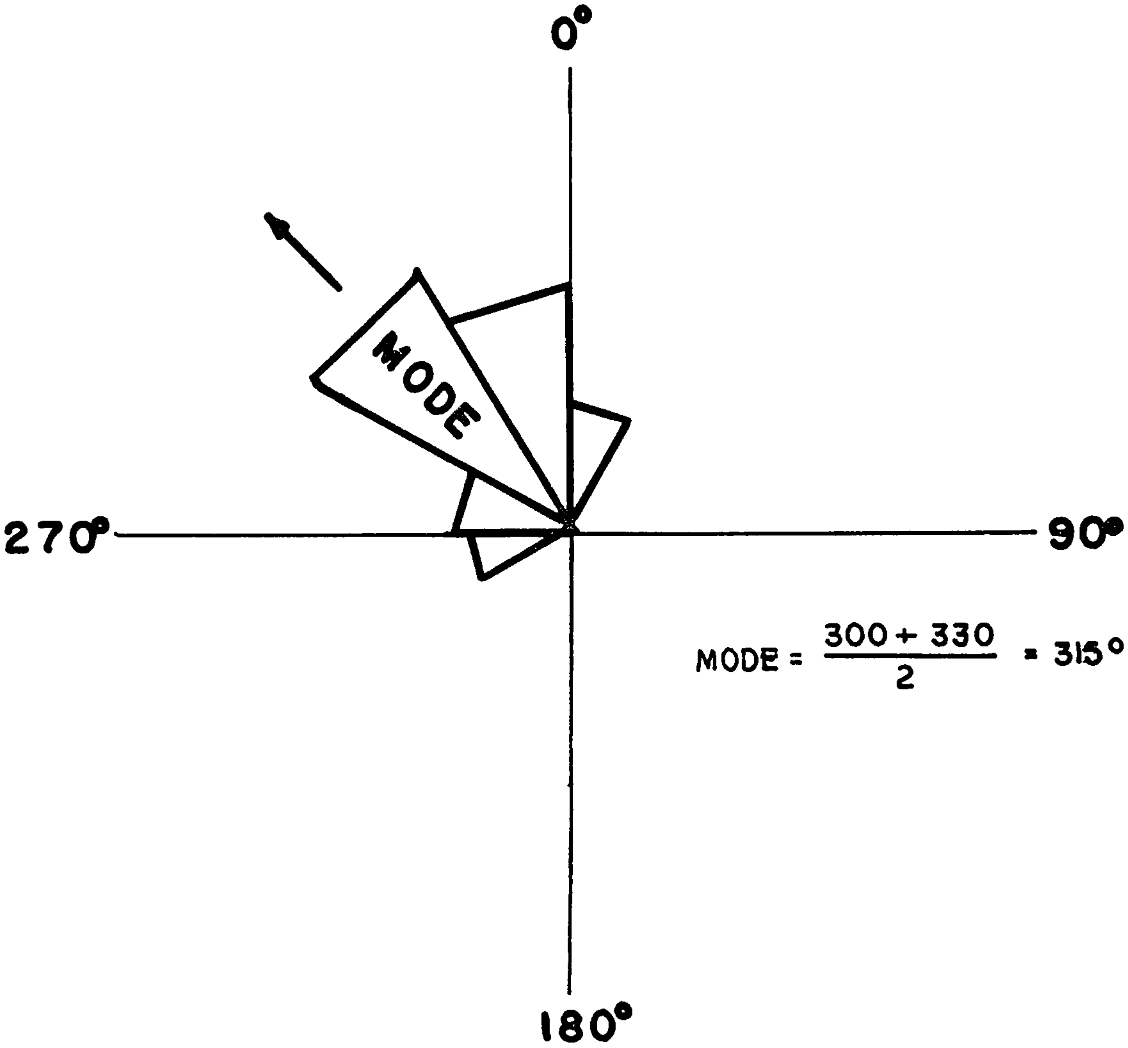
Imbrication of clasts, or shingling, occurs in two forms: isolate and contact (Laming, 1966). Contact imbrication occurs when a clast is deposited on a gravelly stream bottom. In this situation the clast will come to rest in contact with other clasts in the position that is most stable against further transportation. For those clasts whose form is platy, this position is with the MPP dipping upstream. For those clasts whose form is elongate, the long dimension will be oriented perpendicular to the directional flow of the stream current. Isolate imbrication occurs when clasts are deposited on a sandy bottom so that clast-to-clast contact is at a minimum. The mechanism for producing isolate imbrication is not fully understood; however, Bagnold (1954) relates the formation of isolate imbrication to shear stress on the clasts, either at the sediment-water interface or shortly after burial. Nevertheless, isolate imbricated clasts have the same axial alignments as contact imbricated clasts.

A modified version of the method outlined by Miall (1970) for determining imbrication direction in indurated conglomerates was used in this study. Only those clasts in the -3 to -7 phi size range, whose form appeared platy, and that were sufficiently weathered out to allow for accurate directional measurements, were studied.

After the general dip direction of the clast had been determined, a directional reading was taken with a Brunton compass. The readings obtained were then grouped into 30° classes and a rose diagram constructed to determine the modal (strongest) direction (Figure 3). The mean direction and magnitude (Appendix B) were then calculated using a vector-analysis program given by Curray (1955). The mean direction was then considered the direction of sediment influx into the basin.

Post-member 9 faulting affects the reliability of the directional readings as true indicators of the paleoslope. However, after examination of the problem, it was concluded that as long as the dips of the strata were below 20° (as all were) the correction factor for faulting was insignificant and within the allowable error ($\pm$ 5 degrees), considering the field method employed for determining the original dip directions. The significance of any error that may have been introduced due to faulting is further

Figure 3. Rose diagram used for determining the modal direction of imbrication readings.


0°
270°
90°
180°
MODE
MODE = $\frac{300 + 330}{2}$ = 315°

reduced by grouping the readings into 30° classes. Therefore, all dip directions were used as originally taken in the field.

Cross-stratification and channel axes, though not abundant, were used as flow-direction indicators in an attempt to supplement imbrication data. Directional readings were taken in the direction of the maximum dip of planar cross-stratifications, and along the axis of trough cross-stratifications. The data gained from these measurements were treated in a manner similar to the imbrication data.

Lithologic Pebble Counts

Miall (1970) has shown that lithology does not vary within a single fan, but that lithologic variations are common between fans. Intuitively, I felt that pebble counts of lithologies would prove valuable in distinquishing strata of individual fans within a bajada, which might be present in the Bofecillos Mountains area. During early reconnaisance, clasts of various lithologies found within member 9 strata, and samples of the surrounding Tertiary volcanic flow rocks were collected. Most clasts collected from member 9 were volcanic in origin and my initial attempts to satisfactorily classify these clasts were unsuccessful. Butler (oral communication, 1974) suggested that arbitrary classes be formed, into which the clasts could be assigned using field-identification techniques. A total of 16 clast rock types were used (Appendix C); for many of which a source rock was known.

At each station 100 clasts, approximately -6 phi in size, were assigned to one of the 16 lithologic classes. The percentage of each lithologic type was computed and an Q-mode cluster analysis run to determine which stations were most closely associated according to their lithologic assemblages.

Thin-section Examination

Ten thin-sections were made from selected sandstone beds and matrix material of the conglomerates. From these thin-sections the lithology, mean grain size, and the sorting of the finer material were determined.

The mean grain size of the sample was determined by recording the apparent long dimension of 100 grains less than 2 mm in diameter. This was accomplished by making traverses across bedding planes on a one-millimeter grid. As the traverses were made, the size of each grain the crosshair landed on was measured and recorded. These values were then transformed to phi units and a mean grain size was determined.

Little work has been done concerning sorting of volcanic litharenites in thin-section. Size determination from thin-sections has been discussed by Chayes (1951), and was found to be dependent on the form of the grains. Griffiths (1967) has suggested measuring size on one mineralogy and states that results obtained on various mineralogies are questionable. No work that I am aware of has dealt with sorting determined on rock fragments in thin-section. Because rock fragments were by far the most common constituent in all slides examined, I chose to make a visual estimate of sorting using a chart taken from Folk (1974).

The thin-sections examined were initially stained for potassium and calcium-sodium feldspars using a modified version of the method given by Bailey and Stevens (1960). The lithologies of 100 sand-sized grains then were recorded using a standard Clay-Adams laboratory counter. The same technique applied during point counting for the determination of grain size was employed for grain counts of lithology. The constituent grains were grouped into one of five mineralogic categories (Appendix D) and the percentages of each tabulated and manipulated in the manner described by Folk (1974); plotted on a triangular graph and a clan name derived.

X-Ray Diffraction

Ten oriented slides of clay-sized material were analyzed using a Norelco X-ray diffractometer with Cu K alpha radiation. The method outlined by Carrol (1970) was employed for making the slides and analyzing the diffraction patterns. One sample of evaporite crystals was also analyzed by X-ray diffraction techniques.

Computer Analysis

Computer programs devised by myself and supplied by Dr. Butler of the University of Houston Geology Department were used to make basic statistical computations and to test the significance of the results obtained.

THE RECENT: BASIS FOR ENVIRONMENTAL INTERPRETATIONS

The geometries of the sedimentary packages, facies relations, sedimentary structures, and stratigraphy of modern alluvial fans and fan complexes are well documented. It is the comparison of the characteristics of member 9 strata with the findings of others who have worked with modern alluvial fans and bolson deposits, on which the environmental interpretations made in this study are based.

Alluvial fans are cone-shaped deposits of alluvium formed where a high gradient stream issues from a mountain onto the lowlands. Fans are distinctive terrestrial deposits that are known from the Pre-Cambrian to Holocene. Fans in the rock record have been found which exceed 65 kilometers in radius with vertical sediment accumulations of tens of thousands of meters.

As one examines the distribution of fans forming today it becomes apparent that they form under a variety of climatic conditions; recent fans are forming in both humid and arid regions (Bull, 1972). Two conditions are considered necessary for the formation of alluvial fans; first, relief is required, and secondly, sporadic and abrupt runoff of water must be prevalent. It follows that areas of extensive faulting may be potential sites for the formation of these deposits. Abrupt, sporadic runoff, the wady flow of Glennie (1970), may occur for several reasons. Heavy seasonal rains (Gole and Chitale, 1966), cloudburst in arid regions (Hooke, 1967), and the spring thawing of ice covered areas (Ryder, 1971); are all capable of producing wady type flows. In the opinion of most of those who have studied alluvial fans, the optimum conditions for the formation of these deposits occur in semi-arid deserts.

Identifiable alluvial fan deposits are more common at present than any time in the past. This may be due in part to the failure of workers to identify ancient fans in the rock record and/or the fact that in the recent past there have been unusually large amounts of land area. Also, because fans are continental deposits they are susceptible to erosion and therefore many older fans have probably been destroyed by peneplanation (Bull, 1972).

Processes and Responses

The geometry of an alluvial fan can best be described as a half cone. From the apex of the fan the surface dips toward the base, in which direction, the surface slope becomes flatter. A radial profile through a fan is concave upward; a profile at right angles to this is convex (Bull, 1972). Fan surfaces rarely dip above 10 degrees, although dips of over 20 degrees have been reported. Surface slopes in the range of 6 to 9 degrees appear most typical for the apex of alluvial fans (Blissenbach, 1954). The fan slope declines rapidly from the apex to the fan toe where flat-lying sediments are often found.

Generally fans are fed by a single trunk stream which drains a relatively small area. Hooke (1967) has discussed the inherent nature of fans to be dissected at their apex. He was referring to the entrenchment of streams where they first flow onto the fan surface. Near the fan apex the main channel will begin to bifurcate. Bifurcation continues down fan resulting in an ever increasing number of smaller and shallower channels. Further down fan a distributary pattern is well developed and resembles that found on modern deltas. At a point near mid-fan the gradient of the streams approaches that of the fan surface slope; this point is referred to as the intersection point (Hooke, 1967). From this point down fan, the streams essentially flow on the fan surface and have channel widths on the order of 20 times the channel depths. These shallow channels make up a larger braided stream that covers the entire fan surface with a series of channels that divide and rejoin in an anastomosing pattern. Finally, near the fan toe, few discernible channels exist.

The processes responsible for these morphologic and topographic changes down fan are relatively simple. As a given amount of water flows through a narrow canyon, it is restricted much like water flowing through a small orifice. Upon leaving this confinement the water will spread in the form of a fan; this is analogous to the plane jet flow at the mouth of deltas, such as the Mississippi (Bates, 1953). Because the volume of water decreases due to evaporation and infiltration, and the wetted parimeter (area covered by water) increases with distance from the mouth, both the depth and velocity of the water decrease down fan. These decreases are accompanied by the rapid dissipation of energy available for channel erosion and sediment transport. The braided stream pattern developes due to the volume of coarse-grained sediments and the steep gradient (Smith, 1970).

Modes of Deposition

Alluvial fans are often classified on the basis of the depositing agent, and therefore the resulting deposits. Blackwelder (1928), Bull (1962), and Hooke (1967), have all used this scheme. The two most important methods of transportation on modern fans are water, which behaves as a Newtonian fluid; and mud flows, which behave more like a plastic mass. These two end members are part of a continuous series of depositional agents that vary only with respect to viscosity and density. Although a fan may contain deposits produced by only one type of agent many contain deposits of both.

Mud Flows and Debris Flows--Mud flows occur chiefly on arid region fans. They are commonly found on the fan apex (Hooke, 1967). These deposits are generally confined to definite channels and therefore take on an elongate shape. Often these deposits will "jump channel" and form lobate tongues; if a flow is viscous enough to reach the mid-fan areas it will often spread over the fan as a sheet-like deposit. When a water flow loses water through infiltration, or if sediment entrainment reaches a point where deposition is irreversible, a highly viscous (1000 poises) mass results. Mud flows are capable of transporting clasts weighing several tons (Wilson, 1970), and size sorting by deposition affects only the largest clasts. Because of these traits, mud flows produce poorly sorted, non-stratified deposits, which commonly lack erosional bases and contain light-weight material that normally would have been carried off by a stream-flow.

Mud flows deposited are generally uniform in thickness throughout their extent. Individual mud flows can reach five meters in thickness, with sequences of flows forming deposits of great thicknesses (Hooke, 1967). Mud flow deposits usually contain abundant bubble cavities, which are formed by the entrapment of air in the low viscosity flow, and contain clasts that are floating in a mud matrix. Polygonal desiccation cracks are often associated with these deposits. Blackwelder (1928) lists the criteria necessary for the formation of mud flows as the presence of unconsolidated material, abundant clay, and steep slopes which induce sloughing. Mud flows are most readily formed when the annual rainfall is 25 to 40 cm. These deposits are common in the rock record (Nielsen, 1969) and are the only type of deposits found on some modern fans (Bull, 1962).

Associated with mud flows are sharp crested natural levees, which form as the result of the migration of clasts to the outside of the flow and the piling up of sediment at the front of the advancing flow. Upon erosion of a mud flow deposit, these ridges will often remain as the only evidence as to the nature of the original deposit. Mud flows are best recognized by the lack of an erosional base and high clay content; although Passega's CM plots have been used to distinquish mud flows from other types of deposits (Hooke, 1967).

Debris flows are an intermediate type depositional agent between mud flows and water. They have many of the same traits as mud flows. "Debris flow deposits", as used in this paper, refers to mud-rich, poor-sorted sediments which lack significant erosional bases, are poorly stratified, and contain clasts that are in point contact, and show little preferred orientation.

Water-Laid Deposits -- There are basically three kinds of water-laid deposits. Terminology for these deposits is varied; the classification used by Hooke (1967) will be used in this report. These include stream-flood, sheetflood and sieve deposits. Stream-flood deposits and stream-channel deposits are typically confined to definite channels and therefore take on an elongate shape. These deposits are usually better sorted than mud flows, but not as well sorted as other types of water-laid deposits (e.g., Bull (1972) determined the average sorting, Inman's standard deviation, on many California fans as 2.0). These deposits occur in the upper-fan areas where channels are most prominent. Stream-flood deposits are typically cross-stratified, with trough cross-stratification dominating. Bull (1962) reports the average clay content to be 17% in stream-channel deposits. These deposits are often massive, pebbly sands in which individual beds may range from centimeters to several meters thick (McGowen and Groat, 1971). Large scale cut-and-fill structures are numerous in stream-channel deposits and oriented longitudinal gravel bars may be seen in the filled channels. Imbrication of clasts is common if the pebble form is platy or bladed. Stream-channel deposits make up a large part of the sediment package on fans with high rain fall.

Sheet-flood deposits occur in the mid-and-lower-fan regions (Blissenbach, 1954). Here the lack of well-defined channels allows the flow to take on an anastomosing braided stream pattern, which at flood stages can cover the lower fan with a sheet of sediment-laden water. Because of the shallow water depth and braided pattern, individual beds are only centimeters thick and not traceable for any distance down fan. Cut-and-fill structures are common, but small in scale; most sediments deposited in this environment exhibit planar cross-stratification, although trough cross-stratification is common. Horizontal laminations dominate the most distal ends of the fan where water energy is low. The resulting overall sediment package is a sheet of moderately sorted sand which is traceable laterally for great distances. Clay content of these deposits averages only 6% (Bull, 1962).

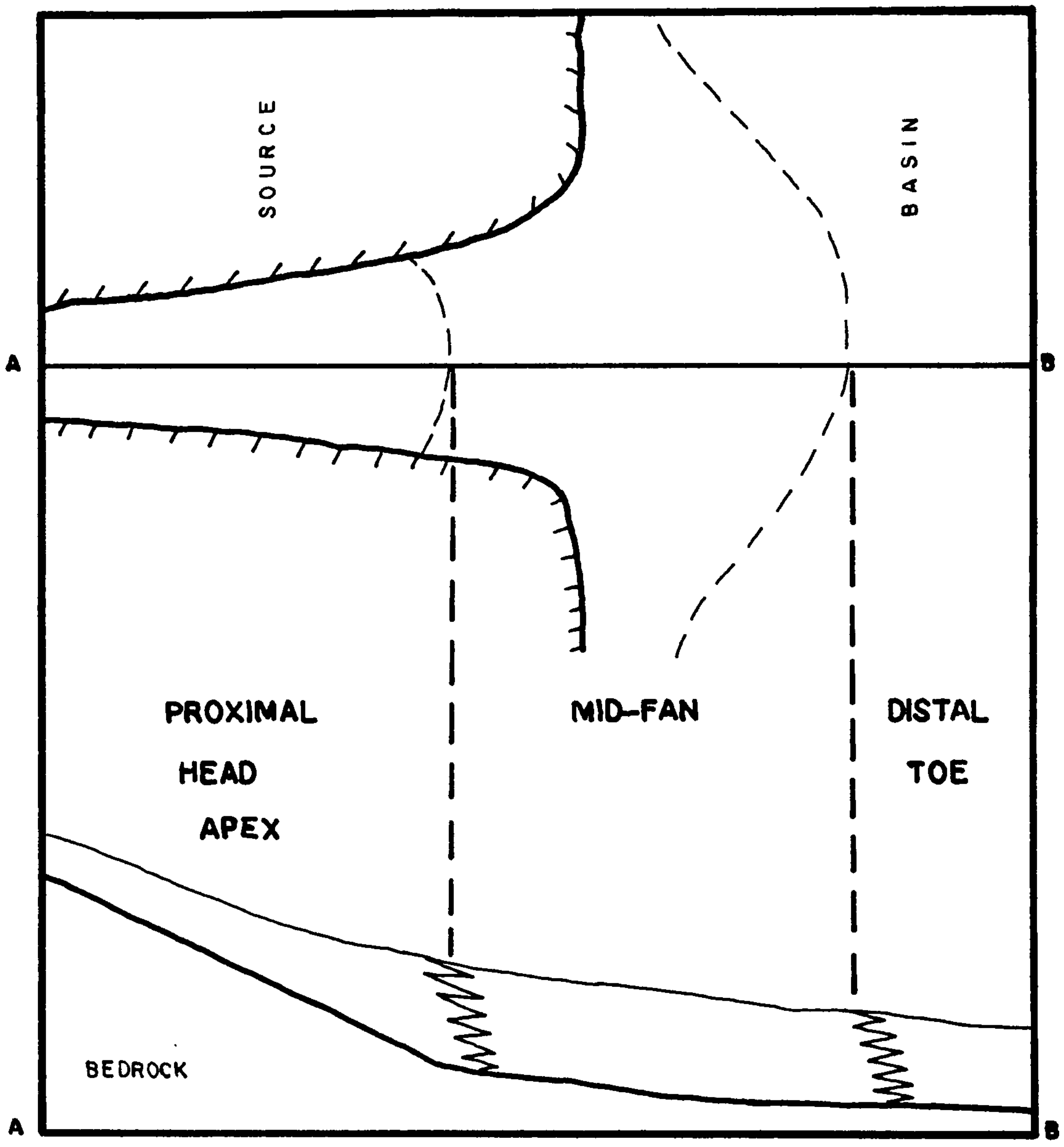
Sieve deposits (Hooke, 1967) are a special type of water-laid deposit. Sieve deposits are easily recognizable on modern fans. If the source area is supplying mostly coarse detritus, with a paucity of finer sizes, sieve deposits may form. When a stream carrying coarse sediment comes to a break in slope it will deposit its load. During subsequent periods of flow this initial deposit will enhance the deposition of sediment at the same point, by allowing the water to be infiltered while retaining the coarser sediment. This process works much like a standard laboratory sieve, hence its name. If there are abundant detritus of all sizes the sieve would become clogged and under go dissection (Hooke, 1967). These deposits on modern fans appear as a well-sorted cuspate shaped ridge of large clasts. After the mechanics for the formation of sieve deposits were discovered in the lab, a study was conducted by Hooke (1967) on modern fans that revealed that these type deposits are quite common. However, no mention of definite sieve deposits in the rock record are known from the literature. With time, sieve deposits probably closely resemble mud flow deposits because of fine sediment infiltration. The best method for distinquishing between the two are: maximum clast size will seldom be over one meter in a sieve deposit; mud flows have natural levees; and sieve deposits are not traceable for great distances upslope.

Fan Facies

Alluvial fan deposits have commonly been divided into three facies. These divisions of the strata have either been based on the distribution of grain sizes on the fan or on the most common mode of deposition of the fan strata. Terminology for the various facies is varied among the investigators in this field of study. The terminology of McGowen and Groat (1971) will be used in this report, although their criteria for the recognition of the facies have been modified. Figure 4 shows the facies position on the fan, and the terminology used by most investigators.

Proximal facies -- The proximal facies is located nearest the source area and includes the apex and upper mid-fan of a typical alluvial cone. This facies is based on the presence of at least 90% gravel as discreet beds, which are often interbedded with sands. Most mud flow and debris

Figure 4. Distribution of facies and geomorphic terminology used by various workers for alluvial fan deposits. Upper part, plane view of an alluvial fan. Lower part, cross-section of the same fan. (modified from McGowen and Groat, 1971)


SOURCE
BASIN
A
B
PROXIMAL
HEAD
APEX
MID-FAN
DISTAL
TOE
BEDROCK
A
B

flow deposits are found in this facies (Bull, 1972), as are the largest percentage of stream-channel deposits. The geometry of beds within this facies are elongate down fan and uniform in thickness. Large cut-and-fill structures are also common. Toward the source area proximal facies deposits are often interbedded with talus-slope debris (McKnight, 1968), down slope, the deposits interfinger with and are gradational into mid-fan facies deposits.

Mid-fan facies -- The mid-fan facies occupies the mid-fan area of a typical fan and contains deposits characteristic of that area. Outcrops which contain not more than 90% nor less than 10% gravel deposits as discreet beds are placed in this facies. This facies contains predominately water-laid deposits, which are the result of deposition in braided streams. Small scale cut-and-fill structures are common; the dominant sedimentary structures are planar and festoon cross-stratifications. Beds deposited in this facies have great lateral extent and are sheet-like in form. Individual beds are on the order of only a meter thick. The mid-fan facies grades laterally into the distal-fan facies down slope.

Distal fan facies -- The distal facies boundaries are based on the occurence of not more than 10% gravel as discreet beds. This facies is located in the geomorphically lowest parts of the fan surface where beds on the order of a few centimeters in thickness are found. Sedimentary structures are predominantly horizontal laminations, although small-scale festoon cross-stratification is common. Well-developed channels are generally absent, and thin discontinuous beds of alternating fine sand and mudstone comprise the bulk of the deposits found in this facies. These deposits reflect deposition in the most tranquil, lowest energy environment. Distal facies deposits are often interfingered with other continental deposits such as other alluvial fans, playa, lacustrine, flood plain, or desert dune (eolian) deposits (Bull, 1972).

Summary of Diagnostic Criteria of Alluvial Fan Deposits

Most fans have some or all of the following characteristics which are the product of a unique depositional system, and it is these characteristics that are used to recognize ancient alluvial fans.

1. Beds (texture) that reflect a rapid fluctuation of energy.
2. Elongation of beds down slope with overlapping beds in cross-sectional profile.
3. Rapid down fan decrease in particle size.
4. Lateral relations with other environments, which are generally continental.
5. Cone-shaped geometry as deduced from exposures or paleocurrent indicators.
6. Presence of a narrow range of locally derived clasts.
7. Presence of mud flow, debris flow, and sieve deposits.
8. General lack of fossils, and those that are found are indicative of a continental sedimentary environment.
9. Sediments that are generally poorly sorted and composed of large, angular clast.

REGIONAL STRATIGRAPHY AND GEOLOGIC HISTORY

Previous Work

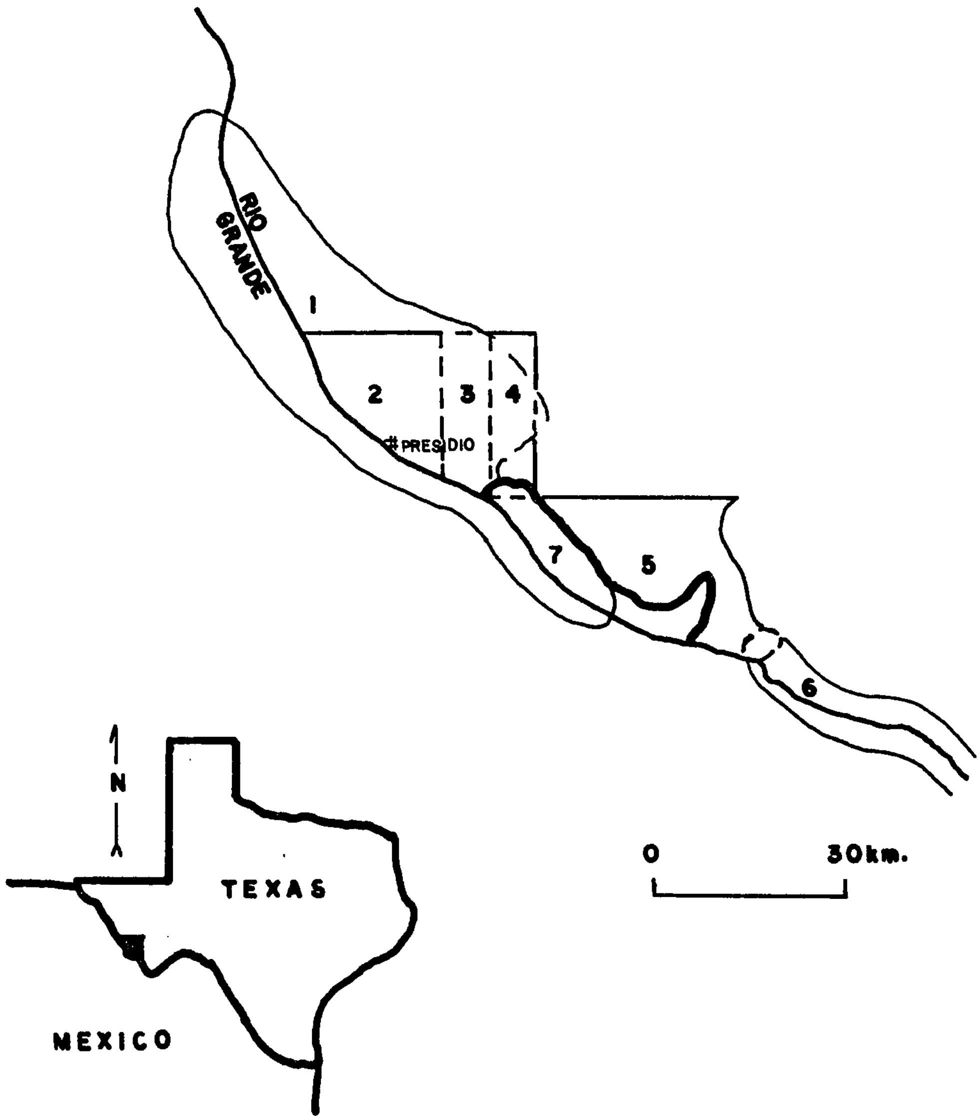
Parry (1857), as a member of a United States-Mexican boundary survey team, was the first geologist to describe the strata in the Bofecillos Mountains. With the discovery of mercury deposits along Terlinqua Creek, numerous geologists made visits to the Bofecillos Mountains area. Among these were J. A. Udden, whose "Sketch of the Geology of the Chisos Country" (1907) presented the first regional tectonic picture that included the study area. Graduate students at the University of Texas have mapped and described two fifteen-minute quadrangles northwest of the town of Redford. These works include Lampert (1953), Zinn (1953), McCarthy (1953) and Dietrich (1954). The International Boundary Commission (1955) mapped a very small portion of the southeast corner of the study area. Dietrich (1965) mapped and described the geology of the Presidio area; his work later served as a basis for McKnight's (1968) mapping in the Bofecillos Mountains area. Groat (1970) mapped and described the Presidio and Redford bolsons, but did not include member 9 strata in his study. The locations of these studies with respect to my study area are shown in Figure 5.

The detailed stratigraphy of this part of west Texas was worked out slowly due to the inaccessability of the area, and because detailed petrographic work was not used as a tool to differentiate the volcanic flows in the area until the early 1950's. Goldich and Elms' (1949) "Stratigraphy and Petrography of the Buck Hills Quandrangle" was the first significant stratigraphic study in this part of west Texas and has served as a basis for extending the stratigraphy into adjacent areas.

Figure 5. Locations of previous works that have included parts of the study area.

1. Groat (1968)
2. Dietrich (1965)
3. McCarthy (1953) and Dietrich (1954)
4. Lampert (1953) and Zinn (1953)
5. McKnight (1968)
6. International Boundary Commission (1955)
7. This study

(modified from McKnight, 1968)


RIO GRANDE
1
2
3
4
PRESIDIO
5
6
7
N
TEXAS
MEXICO
0
30km.

In this part of west Texas correlation of strata over great distances can best be made by radiometric dating of volcanic rocks and the study of vertebrate fossils from sedimentary strata. However, very little age dating has been applied to volcanic strata of the Bofecillos Mountains area, and vertebrate fossil-bearing sedimentary strata are scarce.

Approximately 1380 meters of strata ranging in age from Pleistocene to Cretaceous crop out in the Bofecillos Mountains. These strata were deposited during two distinctively different geologic episodes.

Cretaceous Strata

The oldest strata in the Bofecillos Mountains consist of limestones, shales, and sandstones, which were deposited in a shallow marine environment. These strata are equivalent to the Gulf and Comanche Series of Central Texas (McKnight, 1968). Exposures of the oldest strata are found in the centers and on the flanks of several dissected domes and in the erosional lowlands north and east of the town of Lajitas. These strata were deformed into broad anticlines and synclines during the Larimide orogeny (McKnight, 1968).

Tertiary Strata

After the withdrawal of the Cretaceous seas the area was reduced to a peneplane (McKnight, 1968). The second period of deposition began during the Tertiary Period. The strata deposited during this depositional episode consist of a thick sequence of Tertiary volcanic flows and interbedded terrigenous continental sediments. In the Bofecillos Mountains approximately 900 meters of late Tertiary through Pleistocene (?) volcanic and sedimentary strata are exposed. These strata have been divided into six formations which make up the Bofecillos Group. These are, in stratigraphic order:

Redford-Presidio bolson-fill	youngest
Rawls Formation	↑
Fresno Formation	│
Mitchell Mesa Formation	│
Chisos Formation	│
Jeff Conglomerate	oldest

<u>Jeff Conglomerate</u> -- The Jeff Conglomerate (Eifler, 1951) is present throughout most of west Texas. The Jeff was deposited before or early during Tertiary volcanism, and probably represents a lag deposit which accumulated on the peneplane surface that had developed on the deformed Cretaceous strata (McKnight, 1968). In the Buck Hills, a conglomerate stratigraphically equivalent to the Jeff and below the oldest Tertiary tuffaceous and volcanic strata of that area (the Pruett Formation) does contain extrusive igneous rock fragments (Goldich and Elms, 1949). A basal Tertiary conglomerate of similar lithology, which crops out in the lowlands north and east of Lajitas, has been mapped as Jeff by McKnight (1968).

<u>Chisos Formation</u> -- The Chisos Formation (Udden, 1907) ranges from 150 to 250 meters thick and is exposed in several dissected domes and deeply incised canyons in the Bofecillos Mountains. The Chisos is dominantly volcanic conglomerates, volcarenites, tuffaceous mudstones, and tuffs; but also contains several volcanic flows of regional extent, which are given formalized standing as members. These are the Alamo Creek Basalt, Bee Mountain Basalt, Mule Ear Spring Tuff, and the Tule Mountain Trachyandesite.

<u>Mitchell Mesa Formation</u> -- The Mitchell Mesa Formation (Goldich and Elms, 1949) is probably the most useful marker bed in the Big Bend Region. It is a single ash flow covering 5100 square kilometers in the United States and Mexico. The Mitchell Mesa is a moderately to well-indurated, grey-to-cream, welded-to-non-welded, vitric-crystal tuff (McKnight, 1968) containing phenocryst of chatoyant sanidine, glassy quartz, and fragments of tuff. The Mitchell Mesa Formation averages 11 meters thick in the Bofecillos Mountains and weathers to a distinctive orange color.

<u>Fresno Formation</u> -- The Fresno Formation (Maxwell and Dietrich, 1970) unlike the older Tertiary age formations of the area, is not of regional extent. The source of the Fresno flows was the Bofecillos Volcano (McKnight, 1968), which forms the center of the Bofecillos Mountains. Probably 370 meters of tuff and associated flows accumulated around the vent. Away from the vent area, flow rocks give way to sedimentary strata as the most common rock type. In these areas the name Tascotal Formation is appropriate (Dietrich, 1965). Tuffs in the Fresno Formation often have a distinctive green or blue color.

<u>Santana Formation</u> -- Approximately 180 meters of ash flow tuff, the source of which probably lies in Mexico, were named and described by Maxwell and Dietrich (1970) after reconnaissance in the Bofecillos Mountains. The Santana Formation, in most places, is a single ash flow, which forms the cap rock for several prominent meses in the southern and western parts of the study area. In the study area the Santana is a cream-colored rhyolite tuff that contains abundant vesicular basalt fragments that weather out leaving lensoidal pits, which are characteristic of the Santana strata.

Rawls Formation -- Rawls was the name derived from the old Rawls Ranch, and applied by Goldich and Seward (1948) to the black basalts capping Tascotal Mesa. Maxwell and Dietrich (1970) redefined the Rawls Formation to include volcanic and associated sedimentary strata in the Bofecillos Mountains that "lie above the Santana Tuff or in the absence of the Santana, the lowest lava or tuff unit that overlies the Santana".

Dietrich (1965) divided the Rawls into three members in the Presidio area. McKnight (1968) recognized the increased complexity of the Rawls Formation nearer its Bofecillos source area, and divided the Rawls into nine informal members (Table 1) numbered in ascending order. Most members consist chiefly of volcanic flows, the composition of which is within the latite-basalt range. Although minor faulting had taken place during the earlier part of the Tertiary Period, the increased tectonic activity near the end of Tertiary volcanism produced many fault-block basins that received large volumes of coarse-grained sediments from the surrounding highlands. The uppermost Rawls member, member 9, unlike members one through eight, consist of a thick sequence of intercalated volcanic flows and sedimentary strata.

Strata of member 9 are correlative with Dietrich's (1965) sedimentary rocks in the upper member of the Rawls Formation in the Presidio area. Outcrops of member 9 also occur north of the study area in the southern part of the Tascotal Mesa Quandrangle (Dietrich, 1965). Vertebrate fossils found in member 9 strata, structural relations, and stratigraphic position, all indicate that the member may be in part correlative with the lower member and Smokey Creek member of the Delaho Formation (Stevens, 1969) in the Castolon area; with the Tarantula gravels (Deford and Bridges, 1959) in the Rim Rock Country; and with the basal parts of many bolson deposits along the Rio Grande. Outcrops of member 9 can also be seen across the Rio Grande River in Mexico.

TABLE I

Rawls Formation

Member		Index Rock
9	Tr9b	basalt
8	Tr8a	trachyandesite
7	Tr7at	mafic ash-flow tuff
6	--	not present
5	Tr5a	trachyandesite
4	Tr4bp	trachybasalt porphyry
3	Tr3lp	latite porphyry
2	Tr2at	rhyolite ash-flow tuff
1	Tr1b	basalt

(modified from McKnight, 1968)

Table I. Stratigraphy and index rocks of the Rawls Formation in the Bofecillos Mountains.

(Plate 1C). Arenal (1964) mapped and described this area, but from his map and description the extent of the member cannot be determined.

Bolson Fill (QTf) -- The youngest strata, excluding Rio Grande and terrace deposits, are those that filled the Redford and Presidio bolsons (Plate 1d). These deposits are restricted to a narrow graben system formed by faults in the northwest-southeast trending Redford-Lajitas fault zone. These deposits reach a thickness of at least 300 meters in the Presidio area (Dietrich, 1965). The lowermost strata in the bolsons, according to Dietrich (1965), angularly overlie member 9 strata; but from my examination of this contact the relation between the two cannot be confidently determined. This problem is discussed in detail in a later section. Groat (1970) studied the fill deposits and related their origin and age to similar bolson deposits to the northwest near ElPaso, and in New Mexico. In the Hueco Bolson, Strain (1964) found vertebrate fossils of Aftonian age that led Groat (1970) to conclude that the ages for the upper part of the Redford and Presidio bolsons are also Pleistocene (?). The fill strata were locally derived from the surrounding mountains, and become finer grained toward the center of the basin. No volcanic flow rocks are known to lie above or within the fill strata. McKnight (1968) believes that parts of the fill strata and member 9 are correlative. His conclusion is correct but his reasoning appears questionable based on observations I made. This problem will be discussed under another section.

Quarternary gravels -- Coarse-grained gravels (Plate 2a) similar in texture and composition to member 9 strata, mantle the flat surfaces eroded on the Redford, Presidio, and Santana bolson-fill strata. The gravels were deposited on terraces that developed at several elevations by the planing action of laterally migrating sidestreams of the Rio Grande (Groat, 1970)

As many as four gravel sheets have been differentiated in the Bofecillos Mountains area on the basis of elevation and induration of the deposits.

Locally, near the center of the Presidio and Redford bolsons, deposits of the Rio Grande are common. Gravel deposits of the Rio Grande are distinquishable from other gravels by their texture and lithology. The youngest "deposits" in the study area are those presently flooring the modern Rio Grande and its sidestreams.

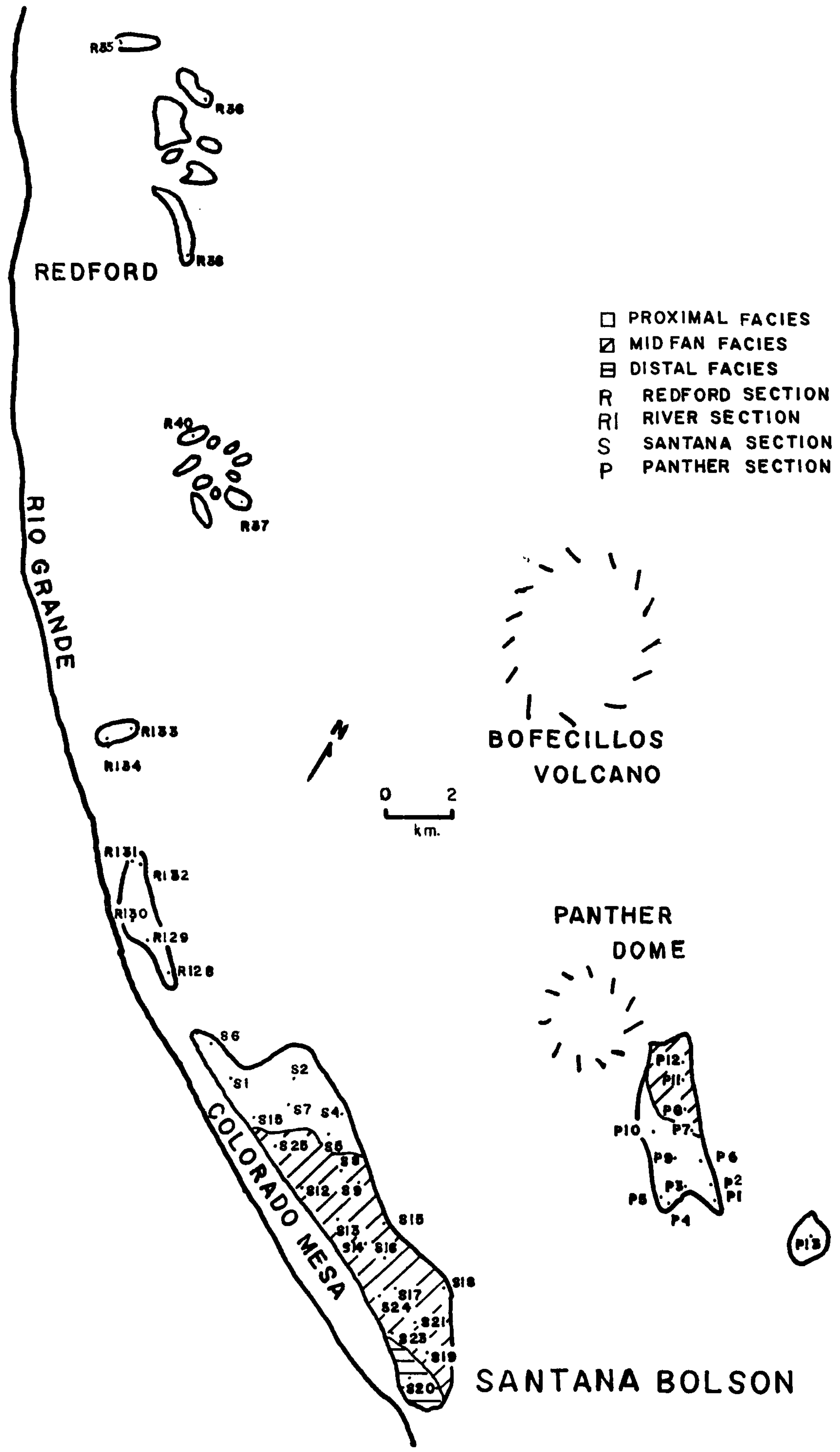
MEMBER 9 STRATIGRAPHY

Those strata that are included in member 9 can be logically divided into two distinct groups. These are the volcanic flow rocks and the sedimentary rocks. In the following discussions the term "member 9" will be restricted to outcrops that contain sedimentary rocks unless otherwise specified. Member 9 strata crop out in the Santana Bolson, in fault blocks on the flanks of Panther and Primero domes, in a small unnamed graben along the Rio Grande west of Colorado Mesa, and as a series of low rolling hills northwest of the town of Redford (Figure 6). In future discussions these outcrops will be referred to as the Santana, Panther, River, and Redford sections, respectively.

Sedimentary Strata--A minimum of 90 meters of strata were deposited in the Panther section; this is probably the thickest preserved section. The Redford section may be thicker, but the lower contact is not exposed so the total thickness cannot be determined. At most places member 9 strata have an eroded upper contact. McKnight (1968) has reported a discordant contact of three degrees between member 9 and Redford Bolson-fill strata (Qtf) west of the town of Redford; but my examination of this area has shown this contact is not between Redford Bolson-fill (Qtf) strata and member 9 strata, but between "bolson-fill strata" and sedimentary strata of the Fresno Formation exposed on the flanks of Torneros Dome.

This relation can be demonstrated by "walking" the outcrop. Approximately two kilometers from the exposure examined by McKnight, the same strata he thought to belong in member 9 are overlain by several flows that belong within members of the lower Rawls Formation (members 1, 2, and 4).

Figure 6. Map showing location of member 9 outcrops, facies distributions, and locations of sampling stations.


REDFORD
RIO GRANDE
PROXIMAL FACIES
MID FAN FACIES
DISTAL FACIES
R REDFORD SECTION
RI RIVER SECTION
S SANTANA SECTION
P PANTHER SECTION
BOFECILLOS VOLCANO
N
0 2 km.
PANTHER DOME
COLORADO MESA
SANTANA BOLSON

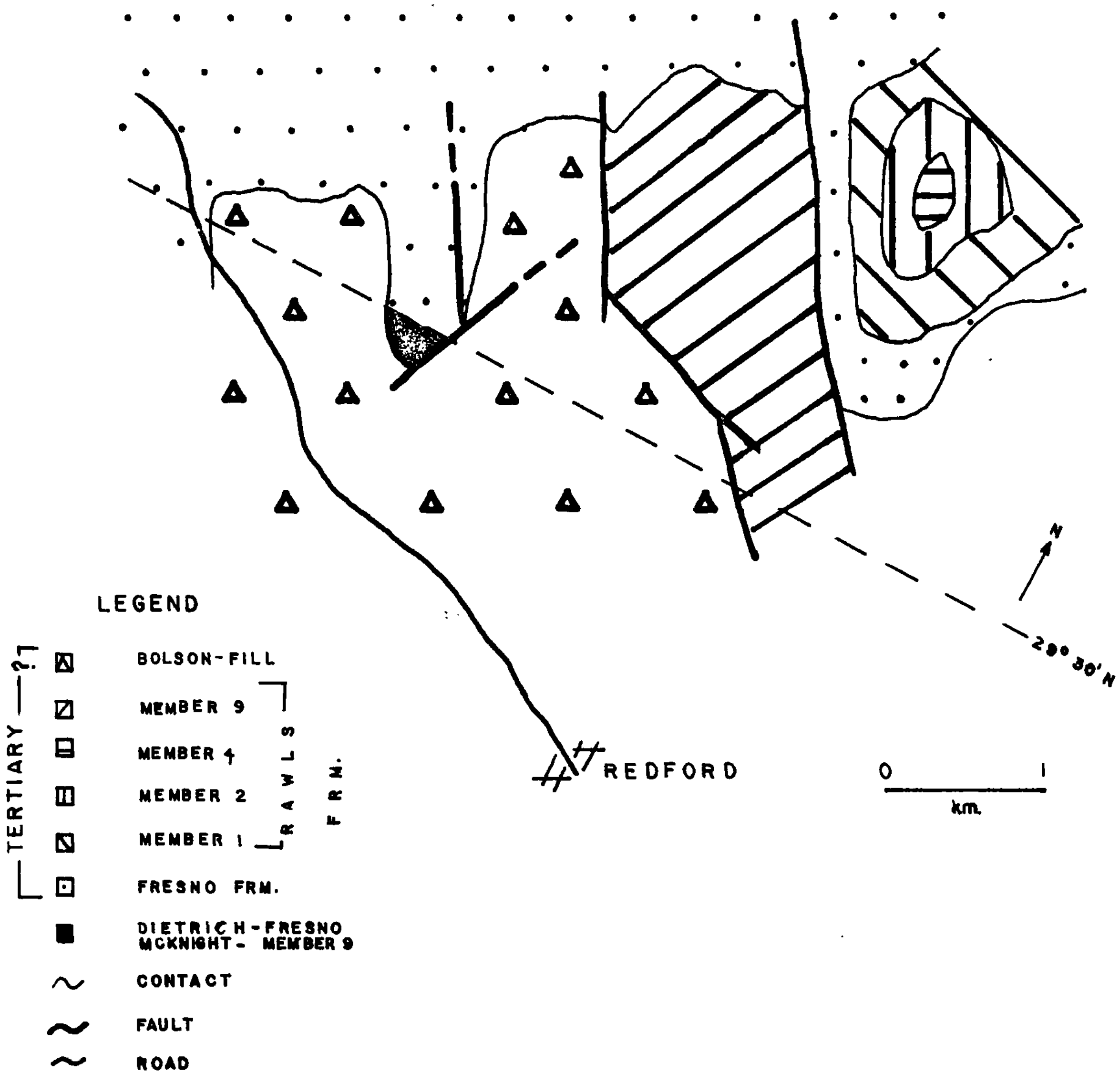
McKnight (1968) did not recognize this relation because this exposure is a kilometer or more north of his study area (Figure 7). Lithologic pebble counts made at the outcrops in question further substantiate this conclusion (Figure 8). Previously Dietrich (1965) had correctly assigned these strata to the Fresno Formation.

Due to pre-member 9 erosion and the localized nature of many of the older flows, member 9 strata may rest on strata of any older formation. The oldest strata immediately overlain by member 9 belong to the Boquillas Formation, which is exposed on the flanks of the Solitario. Laterally, the relations of the member to other deposits is difficult to determine due to erosion or termination of member 9 strata by faulting. A single outcrop of talus material, possibly stratigraphically equivalent member 9, has been noted about 4 kilometers north of highway 170 up Burro Creek. Other than at this single location the lateral relations are indeterminable.

Detailed facies relations within member 9 strata are also difficult to determine. The best outcrops occur along actively degrading sidestreams of the Rio Grande. The gradient of these streams ranges from 11 to 28 meters per kilometer (Groat, 1970). Due to the attitude of member 9 strata, one usually moves down section when following a stream course in a northward direction. Due to this relation, the mapping of time equivalent facies is impossible. The facies boundaries shown in Figure 6 are not time equivalent, but are drawn along textural changes observable at the outcrop.

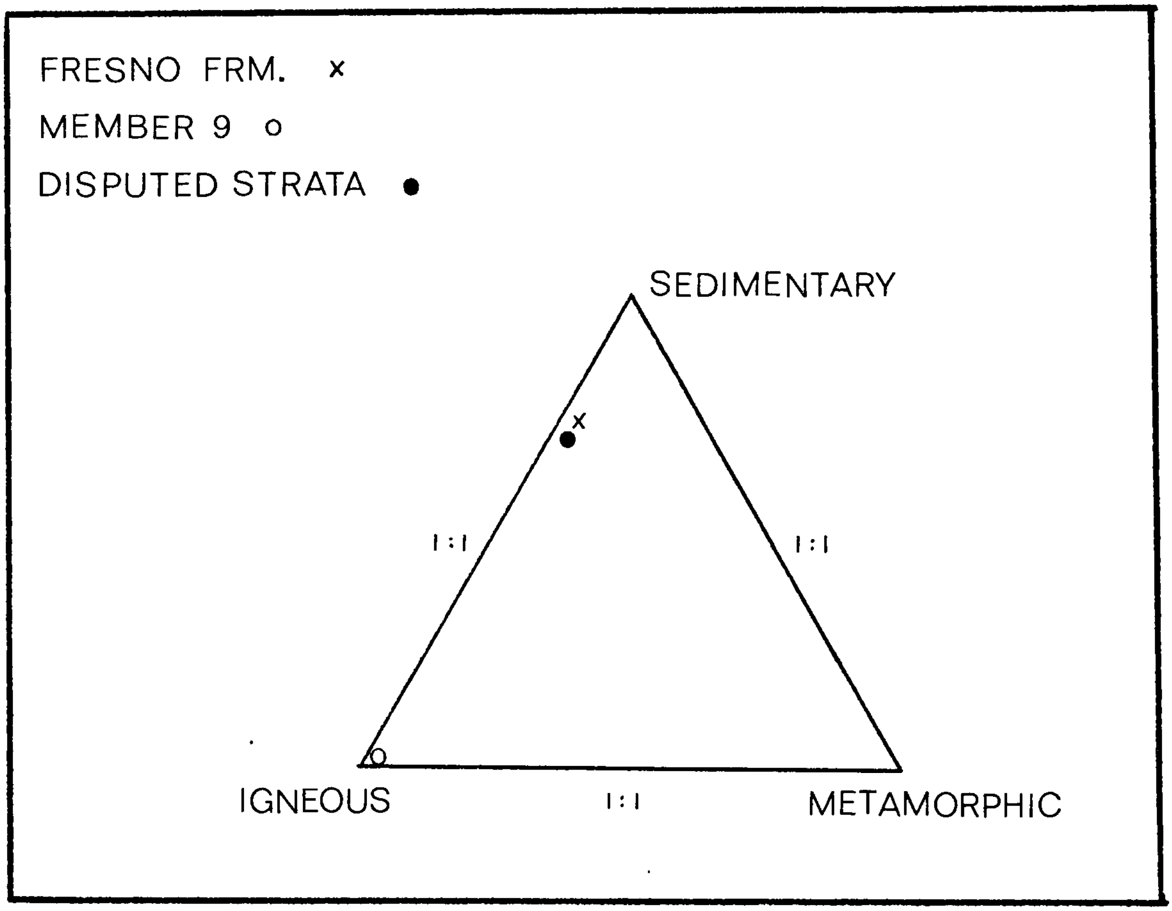
Igneous Strata--As many as three basalt flows are intercalated within member 9 sedimentary strata. Basalt is used as a field term as no petrographic examination was made of these dark volcanic rocks. These flows

Figure 7. Map showing the geology along the boundary of McKnight's (1968) and Dietrich's (1965) study areas.



N
29° 30' N
REDFORD
0
1
km.
LEGEND
TERTIARY
?
BOLSON-FILL
MEMBER 9
MEMBER 4
MEMBER 2
MEMBER 1
RAWLS FRM.
FRESNO FRM.
DIETRICH-FRESNO
MCKNIGHT- MEMBER 9
CONTACT
FAULT
ROAD

Figure 8. Plot of lithologic pebble counts used to resolve the stratigraphic position of some coarse-grained strata northwest of Redford, Texas. (triangular diagram after Folk, 1974)


FRESNO FRM. x
MEMBER 9 o
DISPUTED STRATA ●
SEDIMENTARY
1:1
1:1
IGNEOUS
1:1
METAMORPHIC

range from 3 to 15 meters thick and have resulted in the development of reddish-porcelaneous baked zones in the upper one to three meters of sedimentary strata beneath the flow. Commonly these flows are characterized by faint white splotches that McKnight (1968) attributes to the devitrification of the groundmass.

A single six feet thick dike of black basalt cuts member 9 sedimentary strata in the Santana Bolson. This intrusive rock is similar in appearance to the flow rocks within member 9, which suggests a common origin and near synchronous emplacement. The dike is traceable for approximately 18 meters.

The presence of these basalt flows within the sedimentary strata is helpful in distinquishing the member from other coarse-grained clastic rocks in the Bofecillos Mountains area. However, the absence of interbedded flow rocks cannot be used as evidence for excluding some strata from the member. In those areas where the basalt flows were continuous, the flows were used as time lines for determining the inter-member stratigraphy. Generally no correlation of flows between widely separated fault blocks was attempted. However, three flows are present in the Santana section and three flows are present in the Panther section. On this basis physical correlation of these flows was made on a one-to-one basis over a distance of 5 kilometers. If this correlation is correct, then it appears that at least these two basins were formed during the same period of tectonic activity. This is known because both basins had accumulated approximately three meters of sedimentary strata before the first flow was extruded.

Based on ages determined from vertebrate fossils from two separate fault blocks, it appears that the flows are restricted to the oldest strata. Based on these same fossils the age for the end of Tertiary volcanism in the Bofecillos Mountains can be established as middle Miocene.

MEMBER 9 FACIES DESCRIPTIONS

Early workers who were concerned with the stratigraphy within bolson-fill sediments have described deposits that grade from coarse, angular conglomerates near the mountain fronts, to mudstones in the basin centers. Most workers who have studied the deposits within the Redford-Presidio bolson complexes have recognized similar gradational textural changes.

Zinn (1953) may have been the first to apply the term "facies" to textural subdivisions within the Presidio Bolson-fill. Later, Dickerson (1966) mapped a conglomerate-sandstone facies and a claystone facies of the Presidio Bolson-fill in the Hot Springs area. Dietrich (1965) noted the textural changes with increased distance from the mountain fronts within the Presidio Bolson-fill strata, but he did not subdivide the strata into separate facies. McKnight (1968) recognized and mapped two subdivisions of member 9 sedimentary strata (Tr9 and Tr9f) in the Bofecillos Mountains based on textural and color changes, but he did not apply the term facies to these subdivisions.

Proximal Facies

Proximal facies deposits dominate the preserved member 9 strata, accounting for 75% of all exposed outcrops. The Redford and River sections are composed entirely of proximal facies deposits (Plate 2B). Proximal facies deposits crop out in the stratigraphically lower parts of the exposed sections and in those areas closer to the source. Approimately 60 meters of proximal deposits are exposed in the Panther section. This is probably the maximum preserved accumulation of proximal facies deposits. These deposits overlie flows of member 8 of the Rawls

Formations and contain a basal boulder conglomerate three meters thick which was deposited before the first member 9 basalt was extruded. Between stations P7 and P8 (approximately 45 meters above the base of the member) the gradational contact between proximal and mid-fan facies deposits occurs. The gradational transition between facies takes place over a vertical distance of 12 meters. Deposits of the proximal facies tend to form low rounded hills typical of coarse grained conglomeratic strata exposed in semi-arid regions. Many outcrops are not suitable for making detailed descriptions due to a covering of lag material, slope wash, and because a thick weathering crust often develops on the outcrop (Plate 2C).

The weathering crust develops due to the repeated wetting and drying of the clay matrix present in the rock. In most samples, montmorillonite composes from 15 to 25% of the rock by volume, and is the principal binding agent for proximal facies deposits.

Textural classes of the deposits range from conglomerates through muddy conglomerates to conglomeratic sandstones, with muddy-sandy conglomerates the most common textural class (Figure 9). Clast sizes range from boulders one meter across at station P6 to dominantly medium-size pebbles at station RI29 (Plate 2D and 3A). The clasts are generally subangular (average 3.44, ranging from 4.91 to 2.52, angular to subround), and show little preferred orientation. Sorting is generally poor (average 1.16 phi, poorly sorted) for the fraction that is coarser-than-2-cm. Thin-sections of the matrix material of the conglomerates show that the finer-size fractions are also poorly sorted.

As previously mentioned good exposures occur only along the courses of actively degrading streams. Exposures in the study area range from 0.5 to 45 meters, with good exposures approximately 5 meters high. In

Figure 9. Plot of the texture of member 9 proximal facies deposits. (triangular graph after Folk, 1974)

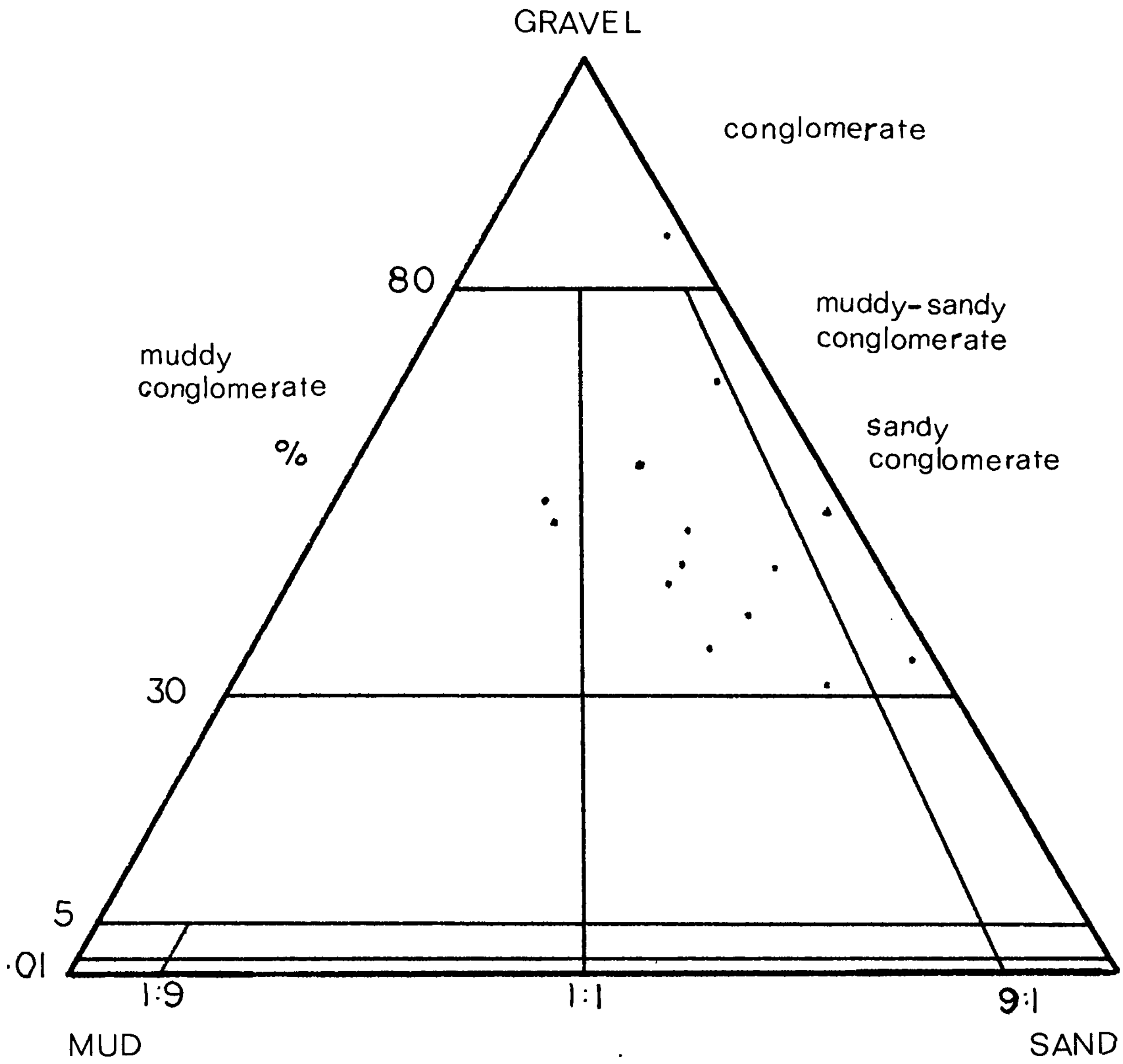
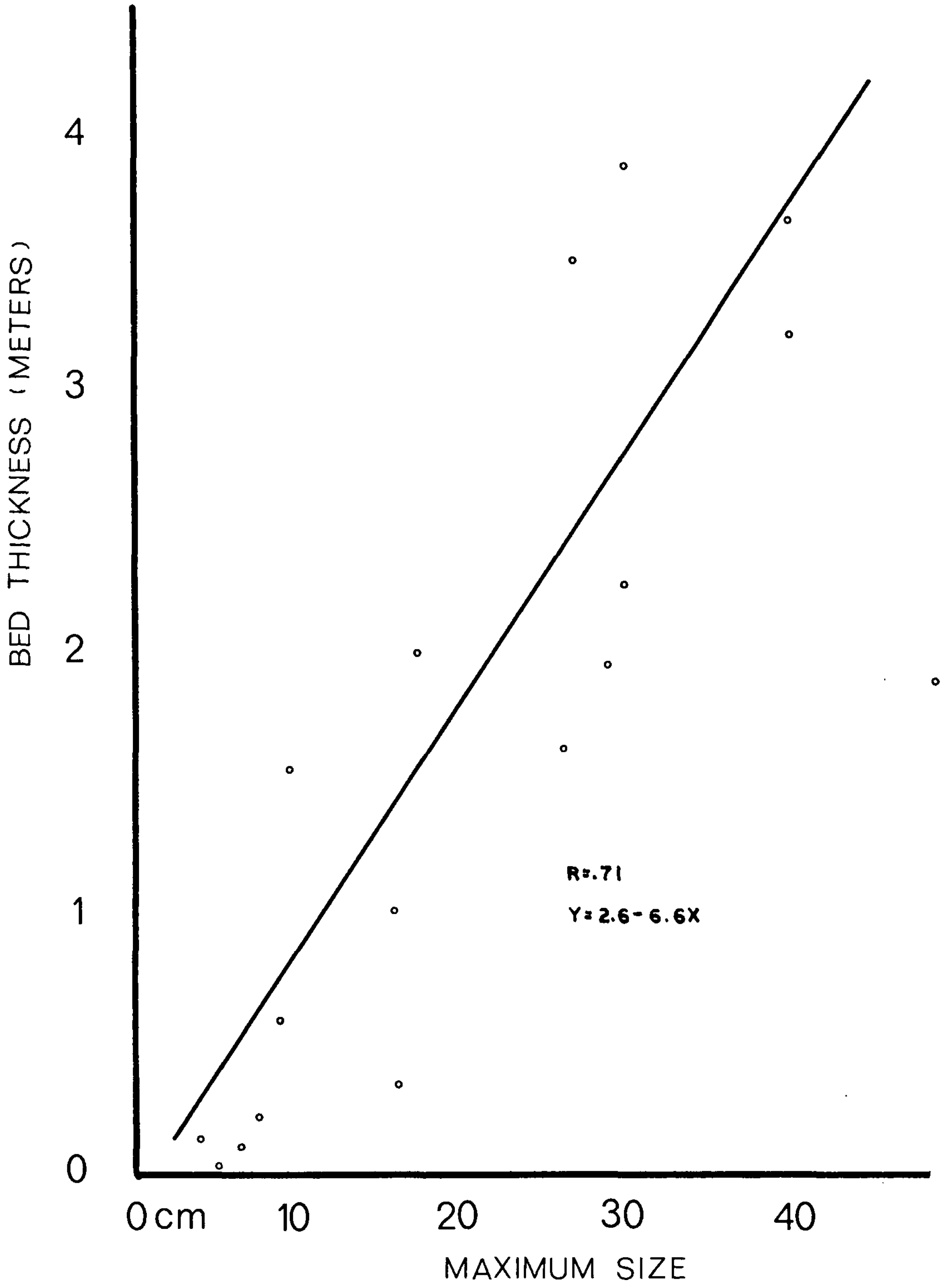

GRAVEL
conglomerate
80
muddy-sandy
conglomerate
muddy
conglomerate
sandy
conglomerate
%
30
5
·01
1:9
1:1
9:1
MUD
SAND

Figure 10. Plot of maximum clast size versus bed thickness.


4
3
2
1
0
BED THICKNESS (METERS)
0 cm
10
20
30
40
MAXIMUM SIZE
R=.71
Y=2.6-6.6X

the Panther section, due to deep rapid downcutting by Madera Creek and the presence of a basalt flow which serves as a cap rock, outcrops stand 45 meters above the stream floor. But even under these circumstances a a 1 to 10 cm thick weathering crust covers all but the lower few feet of the exposure. Individual beds range from 30 cm to over 6 meters in thickness. An observation made in the field and shown graphically in Figure 10 is that there is a good correlation between the sizes of the maximum clasts and bed thickness. This relation has also been noted by Bluck (1964) in alluvial fan strata. Additionally many outcrops exhibited the sedimentation couplet described by Steel (1974), which consists of a conglomerate unit deposited as a debris flow overlain by a better sorted sandstone unit deposited in the waning stages of the depositional event. The thickness of the conglomerate beds remains constant for great distances but the sandstones pinch and swell often disappearing laterally after 9 to 12 meters. In the River section, where the Rio Grande has thoroughly dissected member 9 strata, individual conglomerate beds can be traced laterally for .4 kilometers of more (Plate 3B).

Channeling is minor except in coarse units that are texturally sub-mature (Plate 3C). Most beds exhibit slightly erosional to non-erosional basal contacts; the maximum relief observed in an erosional contact was 4.6 meters. Channel width-to-depth ratios are approximately 4 to 1. The largest channel noted was at station S6 in the Santana section; this channel is 9 to 12 meters wide and 4 meters deep. The size of the channel fill material indicates that high flow velocities were obtained in these narrow channels. At station RI36 an erosional contact showed boulder conglomerates of member 9 which had filled a channel eroded into a member 9 basalt flow.

Much of the conglomerate material represents deposition in the form of debris flows. This conclusion is based on the lack of erosional bases, high mud content, lack of stratification, large clast sizes and geometery of the beds. Clast are generally not floating in a mud matrix and exhibit some preferred orientation. Because of the small modal clast size at some locations it is concluded that size sorting of the larger clast was possible and that the viscosity of the depositional agent was probably not significantly greater than that of water. Sequences of debris flows form deposits that are over 45 meters thick, each flow represents one episode of deposition. As the sediment-laden flows, analogous to turbidity currents, left the confinement of the stream canyon they spread over the fan surface as flows of uniform thicknesses. Because of water loss through infiltration and the decrease of the fan slope the flows deposited their load very rapidly. Deposition in this manner is not condusive to size sorting or the formation of sedimentary structures.

Rarely was mudstone present as discrete beds, though one such occurence was noted at station R33. There a bed of mudstone about 10 cm thick was swirled around large clasts within a coarse debris flow conglomerate; the mudstone appears to have been ripped up and transported a short distance as a unit. This material was probably originally deposited up fan as a mudflow. This bed of mudstone could not have retained its identity if the depositional agent were a Newtonian fluid, which further substantiates that most proximal facies deposits are debris flow in origin.

Mid-Fan Facies

Outcrops of mid-fan facies deposits occur in the stratigraphically higher parts of the Santana and Panther sections, as well as in fault contact with proximal facies deposits in the River section (Plate 4C). Mid-fan facies account for 25% of the exposed member 9 strata. Typical exposures along active sidestreams stand 6 meters or more vertically. In the Santana section where faulting has tilted the strata to a maximum of 16°, dip slopes often form on the surface of the more indurated conglomeratic beds.

The mean maximum clast size in the mid-fan facies is generally smaller (average -7 phi) than in the proximal facies and the clasts are better rounded (average 3.14 rho, subangular). Sedimentary units are more distinct and better sorted (Plate 4D) (moderately sorted for sands and .9 phi, moderately sorted, for the conglomerates). Colors of the strata vary from light-grey to pale-pink depending on the amount of iron oxide as silt-sized material present in the matrix (Groat, 1970). It is on this color difference that McKnight (1968) erroneously mapped most mid-fan facies as Quaternary-Tertiary bolson fill (Tr9f). The transition zone from gravel to sand as the dominant textural class seems to be a natural boundary for the subdivisions of the mid-fan facies. These sub-divisions will be discussed separately.

Mid-fan Conglomerate Sub-facies -- Deposits of the mid-fan conglomerate sub-facies generally crop out stratigraphically lower than deposits within the sandstone subfacies, although sediments of both facies were being deposited simultaneously. Good exposure of the conglomerate subfacies occur at station S5 in the Santana section and in the Panther section about two kilometers south from the point where a jeep trail enters Panther Canyon. Bedding thicknesses range from 15 cm to 3 meters. At most outcrops, a sequence of beds that consist of a 1.5 to 3 meters thick, sandy, coarse-to-fine pebble conglomerate separated by a thinner .3 to.6 meter thick bed of pebbly sandstone; is rhythmically repeated. Bedding

Unfortunately, outcrops permitting three-dimensional views of sediment bodies are rare, which makes interpretation of the geometry of the sediment packages difficult. Sedimentary structures are generally absent or masked by weathering phenomena; and, therefore, most outcrops appear as homogeneous massive boulder beds. Crude horizontal bedding consistently dominates the observable sedimentary structures. Occasionally, beds of fine-pebble conglomerate or sandstone will exhibit large scale planar cross-stratification sets that range in thickness from 12cm to .8 meters (Plate 3D).

Station S5 was located at the junction of two large modern sidestreams and allowed a rare opportunity to study the three-dimensional geometry of the conglomerates and sand bodies. Gravel deposits (Plate 4A), interpreted as longitudinal bars, were up to 14 meters long and had thicknesses from one-half to three meters. The sizes of clasts within these bars grade from boulders at the bar head to planar cross-stratified, granular-sized material at their down current end. Sandstone occured in the upper parts of graded channel-fill sequence, at the down current end of longitudinal bars (Plate 4B), and as isolated pockets within the conglomerate deposits. Occasionally, a stringer of fine-pebble conglomerate would be moderately sorted and cemented with large sparry calcite crystals, but this type of deposit was rare. The texturally mature streamflood deposits are the result of reworking of debris flows by channeling during the maximum and wanning flood stages. The sand-sized materials are interpretated as having been deposited in the wanning stages of the depositional event when the compentency and capacity of the current were rapidly decreasing; however, some sandstone beds exhibit low depositional angles indicative of upper flow regieme velocities.

at most places is poorly defined and is generally detected by a slight shift in the modal size of the clasts rather than by sharp erosional contacts. Large scale cut-and-fill structures (Plate 5A) are common in the conglomeratic sub-facies with channels that commonly have width-to-depth ratios of approximately 14 to 1. At station S5 in the Santana section remnants of six channels are present, each truncated by a younger cut-and-fill event. Channels commonly are filled with sandy coarse-pebble conglomerate or fine-pebble coarse sandstone, which exhibits crude festoon and planar cross-stratifications. Conglomerate deposits occur as longitudinal bars, massive channel-fill material, and as isolated pockets within conglomerate beds. Sandstone occurs as channel-fill deposits, isolate pockets and as gradational tops and downstream ends of logitudinal gravel bars.

The fabric of the strata in this subfacies is generally clast-to-clast contact with pronounced imbrication of platy clasts. Most beds contain a high percentage (5 to 20%) of very slightly calcareous muds as an interstitial binding agent, but beds with fine pebble-sized material as the dominant modal class are commonly cemented with sparry calcite. At some locations deposits are so well indurated that the rock breaks across clasts rather than around them. These deposits are the best-sorted material (.7 phi, moderately sorted) found within any facies.

Many outcrops consist of alternating horizontally bedded conglomerates and planar cross-stratified sandstones. Dip angles of the cross-strata are generally in the range of from 13° to 25°. Some of the cross-stratifications are up to .6 meter long. Most planar laminae are terminated sharply at their upper and lower contacts (Plate 5B). These cross-stratified sandstones were deposited as transverse bars that migrated across the fan surface in large braided streams.

Station P11 in the Panther section consisted of a basal three meters of predominantly high-angle planar cross-stratified sandstones and medium-pebble conglomerates which are overlain by 2.4 meters of horizontally bedded muddy medium-pebble conglomerate. This sequence of beds is repeated in the upper part of the outcrop. The changes in texture do not represent deposition under varying flow regimes but are interpreted as a migration of textural facies that were deposited simultaneously. This is deduced from the observation that many planar cross-stratified sandstone beds can be traced laterally into horizontally bedded conglomerate units which were deposited as longitudinal gravel bars.

Sandstone Sub-facies--When sandstone deposits are more common than conglomeratic deposits as the main textural class, bedding and sedimentary structures become more distinct. Good exposures of the sandstone sub-facies occur along highway 170 between stations S14 and S17. There, due to differential induration of the conglomerate and sandstone beds, tilted member 9 strata crop out as a series of small ridges. Bedding thicknesses in this sub-facies range from 15 cm to 2 meters with 1 to 1.5 meter beds most common.

Sorting values for the deposits range from .76 phi to 1.26 phi (moderate to poorly sorted) for the conglomerate beds to moderate and poorly sorted for sandstone units. The conglomerate beds are generally grey in color, have a medium-pebble size modal class, and are bound by a slightly calcareous sandy mud. The finer-grained sandstone units are usually pale-pink in color, and always contain gravel-sized clasts. Erosional bases (Plate 5C) are common, with beds pinching and swelling laterally, but generally remaining traceable for .4 kilometers or more.

Approximately 15 meters above the highest proximal facies deposits in the Santana section, the ratio of sandstone to conglomerate beds is about 1 to 1, and therefore marks the transition zone between subfacies. Conglomerates, although still forming discrete beds, are less abundant and localized within channels, and in the basal parts of sandstone beds. Orientation of clasts is not as apparent due to a paucity of clasts with platy form. This change in clast form is solely the result of lithologic changes that occur higher in the Santana section.

Sedimentary structures in the lower part of this subfacies consist of planar cross-stratifications that vary in thickness from 15 to 45 cm; and horizontal laminations, which occur with equal frequency (Plate 5D). At station S19 pebbly sandstone units that consist of four to five sets of planar cross-stratified beds are approximately 14 cm thick and exhibit high depositional angles, indicative of low flow velocities during deposition (Busch, 1965).

Many sandstone beds are massive with the exception of small gravel-floored U-shaped scour channels, which generally have width-to-depth ratios of approximately 3 to 1. The gravel in these channels typically is only a few clasts thick. The structureless appearance of these sandstones is probably the result of their having been deposited very rapidly; this would not be conducive to size sorting, which would facilitate the formation of sedimentary structures. The lack of differential color staining of the strata would also make the detection of any sedimentary structures that might be present most difficult. In the stratigraphically higher parts of this subfacies the ratio of sandstone beds to conglomerate beds is approximately four to one. The sandstone beds average approximately 1.5 meters thick and are laterally continuous; conglomerate beds become thinner and less abundant, averaging only 0.3 to 0.6 meter thick and often disappear laterally within a hundred meters (Plate 6A). Horizontal laminations and festoon cross-stratifications are the most common sedimentary structures; but locally, planar cross-stratification may prevail. Graded beds in the sandstone subfacies are present but are not common. This is probably due to erosion that preceded each depositional event removing the upper parts of previously deposited beds. This would make the detection of graded bedding difficult.

Soft sediment deformation is common in the finer parts of this subfacies. For example, at station S24 a bed of granular conglomerate has sunk into an underlying bed of "pink" structureless sandstone. Two structures that are interpreted as clastic dikes were noted in this subfacies. At station S12 a 7 to 15 cm thick clastic dike of medium-coarse sandstone has been injected into a medium-fine pebble coarse sandstone bed. The second such structure (station S8) consisted of a very fine pebble conglomerate that has intruded a bed of similar texture. This "dike" stood seven cm above the outcrop surface and was traceable for ten meters. In neither case was the source horizon exposed.

Evidences of bioturbation are extremely rare. At station S22 a circular burrow approximately seven cm long and 1 cm in diameter was found within a bed of otherwise structureless "pink" sandstone. The burrow was filled with a sandstone of slightly different texture than the burrowed strata. This indicates that some of the massive "pink" sandstones in this facies represent more than one depositional episode.

At other localities in the mid-fan sandstone subfacies, irregularly-shaped, light grey to white, two to four cm long nodules of calcium carbonate are found dotting the outcrop and littering the slopes. Groat (1970) and Hawley and Giles (1966) attributed similar nodules in other bolson-fill strata to a stage in the development of caliche horizons. Generally in association with these nodules were what appeared to be root tubes or burrows which were reoresented by calcium carbonate clasts. These trace fossils were up to ten centimeters long and had the same grey-white color as the caliche nodules. LeMone and Johnson (1969) attributed similar fossils in the Santa Fe Formation of New Mexico to root tubes of succulent(?) plants. Trace fossils similar to these also occur in the Presidio Bolson (Groat, 1972). Wood fragments, although extremely rare, were found within deoosits of this subfacies. Fragments of vertebrate fossils are most common in the sandier mid-fan facies deposits, but were found in strata of all facies.

Lithology of the clasts within the mid-fan sandstone subfacies was found to be similar to time-equivalent proximal facies deoosits in those areas where this relation could be worked out. The most distal mid-fan facies deposits contain a higher percentage of light-weight tuffs as pebble-sized clasts and a higher percentage of quartz grains (11% as opposed to 4%) in the sand fraction. Beds with modal classes in the fine pebble range are commonly moderately sorted (.71 phi) and cemented with sparry calcite.

Generally no characteristic weathering pattern was developed on member 9 strata, however at several localities unusual patterns were noted. In the Santana Bolson near stations S11 and S12, outcrops of a slightly pebbly muddy-coarse sandstone exhibited a weathering pattern similar to the "popcorn" pattern described by Groat (1967). Another unusual weathering pattern was noted at station S24. There a "honey comb" pattern had developed on those outcrops that face into the direction of water flow in an unnamed creek. No explanation is given to explain these phenomena.

Distal-Fan Facies

Distal facies deposits are composed of less than 10% conglomerate as discrete beds. The only outcrops of distal facies deposits found in the study area were located in the Santana section. In this section they account for 15% of the exposed strata, but they represent only 5% of all member 9 strata. The transition from mid-fan facies to distal facies is gradational, and takes place over a vertical distance of approximately seven meters and a lateral distance of one kilometer. Good exposures occur about one kilometer south of state highway 170 on the west side of Panther Creek (stations S20 and S21) (Plate 6B). Where no active streams cross these deposits they form low rolling hills, which are unsuitable for detailed work. Outcrops of distal-fan facies deposits are often covered with a "puffy", soft, powdery, light-pink to grey-white cover of clayey sand. This "puffyness" is attributed to the swelling of expandable clays. Color of these strata range from light pink for silty sandstone beds to "chocolate" brown for claystone layers. The binding agent for the coarser material is generally a slightly calcareous, silty clay. Mineralogy of the clay-sized material as determined from x-ray diffraction patterns, is a sodium-calcium montmorillonite.

Bedding thicknesses range from $\frac{1}{2}$ cm to 2 meters. Gravel-sized clasts, although still present, are small pebble-sized and lithologically unidentifiable. Rare larger clasts, up to 15 cm in diameter, are generally light weight tuffaceous material. The gravel-sized material occurs in the basal parts of most beds and as discontinuous isolated lenses within the sandstone beds. The sandstone units generally appear structureless, but locally small-scale planar and trough cross-stratifications are common. Close examination of the outcrops showed that many beds were graded. These graded beds are composed of small 1 cm long clay clasts that constitute a basal conglomerate that grades upward into a muddy fine sandstone, which is capped with a thin clay drape. These graded beds are generally only 15 cm thick and are repeated many times in the section. Each graded bed is interpreted as representing one depositional event in which the sediments were deposited under an ever-decreasing flow regime. Minor scour channels attest to the lack of energy available for the erosion of deep channels (Plate 6C).

Due to the lack of outcrops, it is difficult to confidently trace beds laterally for any great distance. However, at least one bed of reworked tuff which is approximately one-half meter thick and exhibits a distinctive orange-yellow color can be traced for over .8 kilometer between stations S18 and S20. Similar beds were noted near station S14 in the mid-fan sandstone subfacies in the Santana section, immediately beneath a three meter thick basalt flow, and in a similar stratigraphic position in the Panther section at station P4. No correlation between the bed or beds in the Santana section and the bed in the Panther section was made except to note that the beds were probably deposited under similar environmental conditions.

At all locations visited, distal facies deposits were found to have an eroded upper contact. Near station S18 Pleistocene (?) boulder gravels fill a 90 meter wide channel eroded into the distal facies deposits by the Rio Grande. At other localities, Quarternary terrace deposits form a 0.3 to 1.5 meter thick sheet of gravel that angularly overlies distal facies deposits. Laterally, distal facies deposits are terminated either by erosion or more often by post-member 9 faults.

Playa Deposits

One outcrop of member 9 strata interpreted as having been deposited in a playa environment was examined. Station S24, in the Santana section, is composed of 90% mudstone, as thin, light-brown colored, mud-cracked, horizontally laminated beds which are up to seven cm in thickness (Plate 6D). In some areas the mudstone appears to have been bioturbated (Plate 7A).

Poorly sorted sandstones within the outcrop are often graded from pebble-sized material at their bases to mudstone at their upper surfaces. These sandstones are bound by a clay matrix and have minor amounts of calcium carbonate as a void filling. Occasionally, faint traction ripples can be detected within the sandstone beds.

Gypsum was found along joints that intersected the bedding planes and as small lenses which were concordant with the bedding planes of the mudstone deposits. The gypsum crystals are up to 1.6 mm long and form subhedral crystals. This single outcrop of playa deposits is approximately 3.7 meters high and in the process of being actively dissected by a small unnamed stream. Because of slope wash, the nature of the deposits cannot be recongized one meter above the stream floor without excavation.

The relations of these deposits to deposits of other fan facies is not clear from field evidence, as outcrops immediately surrounding the playa deposits are obscured by a cover of Quarternary gravels. Mid-fan facies deposits found near the outcrop suggests that the playa exposure is situated within a small fault block, even though no evidence to support the presence of a fault were found. The basis for this line of reasoning is that in a normal sequence of fan facies one would expect that the distal facies deposits would grade laterally into playa deposits, which are commonly located at the fan toe (Horne, 1975; Denney, 1965; Hooke, 1967). An alternative explanation is that the deposits represent deposition in a lake, which may have formed as a result of the overlapping of two alluvial cones. McGowen and Groat (1971) have described a similar feature which developed in this manner in the Van Horn Sandstone. Evidence to support the latter theory will be discussed in a later section. However, in either case this area was the site of an ephemeral lake for at least a short period during the filling of the Santana basin.

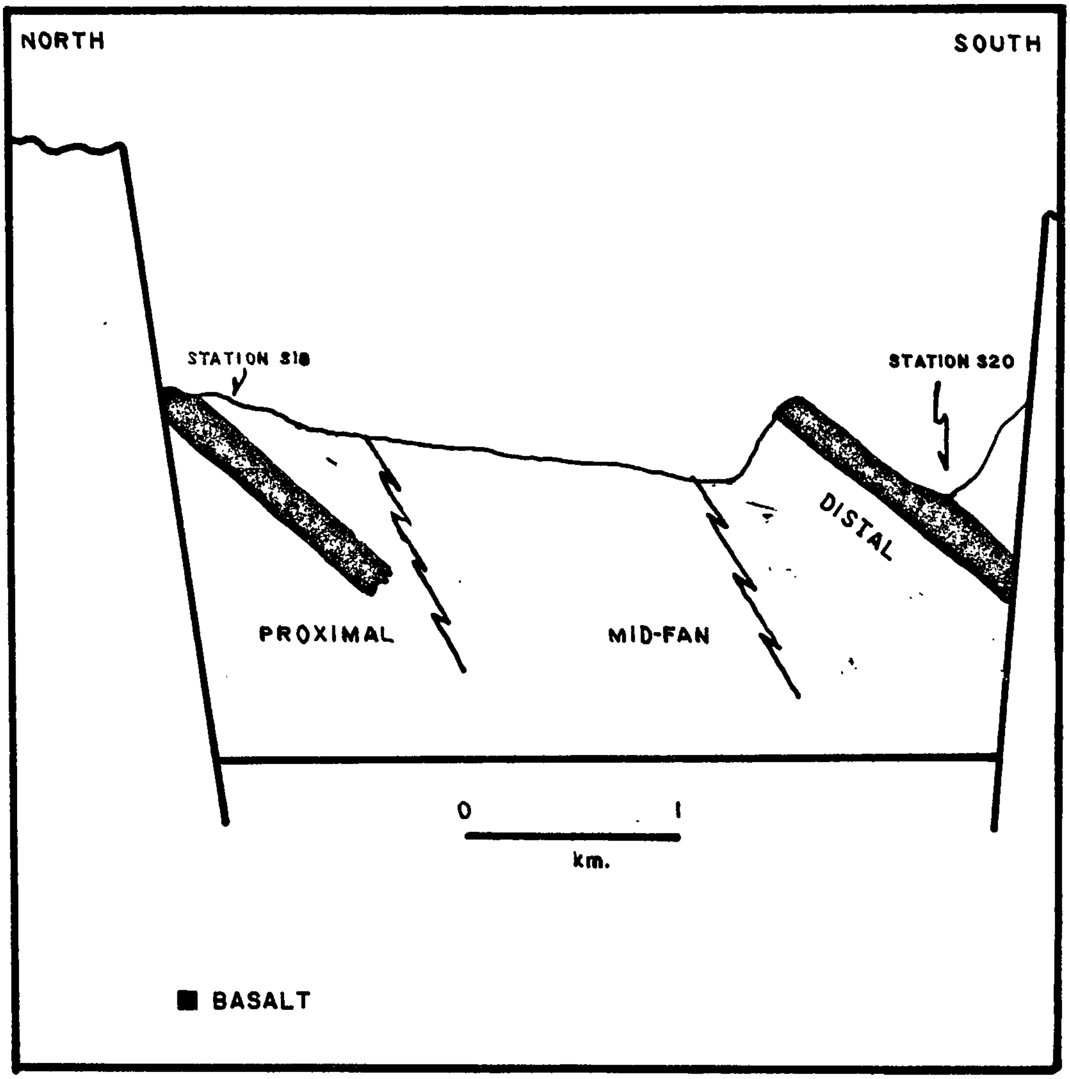
The playa strata were deposited at or near the toe of the alluvial fan in the most distal, tranquil parts of the depositional basin. Only during periods of unusually heavy run-off were coarse-grained sediments transported across the fan surface into the playa environment. The purity of some of the clay deposits and graded beds, indicate that a standing body of water may have occupied this area for some time after each storm period. Evaporite deposits, desiccation cracks and the presence of a fine-grained, quartz-"rich" (comparatively) sandstone between mud-cracks, which might be eolian, attest to the periodic drying of the lake bed.

Facies Relations

Isochronous outcrops at most places can be viewed only in two dimension, and therefore the relations of the various fan facies are drawn on "sketchy" observations. The River and Redford sections contain only proximal facies deposits. The Panther section contains both proximal and mid-fan facies deposits. Only in the Santana sections are deposits which represent all facies exposed, and therefore the facies relations are best exhibited in that section.

Figure 11 is a schematic diagram depicting the relations of the fan facies based on observations made in the Santana section. The proximal facies deposits are either terminated laterally by post-member 9 faults, or erosion. One isolated outcrop of talus material, which could be stratigraphically equivalent to member 9 strata, was noted in the study

Figure 11. Schematic diagram illustrating the facies relations in the Santana section.


NORTH
SOUTH
STATION S18
STATION S20
DISTAL
PROXIMAL
MID-FAN
0
1
km.
BASALT

area. Other than this single instance the lateral relations of the strata are indeterminate. Down slope, the proximal facies deposits grade laterally and vertically into mid-fan facies deposits. The mid-fan facies deposits in turn grade laterally and vertically into distal facies deposits. Distal facies deposits are either terminated laterally by post-member 9 faults or erosion. The relations of the playa deposits could not be confidently determined from the single outcrop observed.

In the Santana section the preserved facies are of approximately equal thickness; although the top of the distal facies deposits has been eroded. From the relations observed, it is concluded that the strata were deposited in a shallow basin during a period of tectonic quiescence. The deposits represent a normal migration of facies (distal over proximal) similar to that found in Holocene fans which are filling closed basins where erosion of the source area exceeds uplift.

From these observations it is estimated that an average alluvial cone depositing the sediments that comprise member 9 strata was approximately 5 kilometers long from its apex to toe, and covered an area of from 30 to 35 square kilometers.

SOURCE AREA

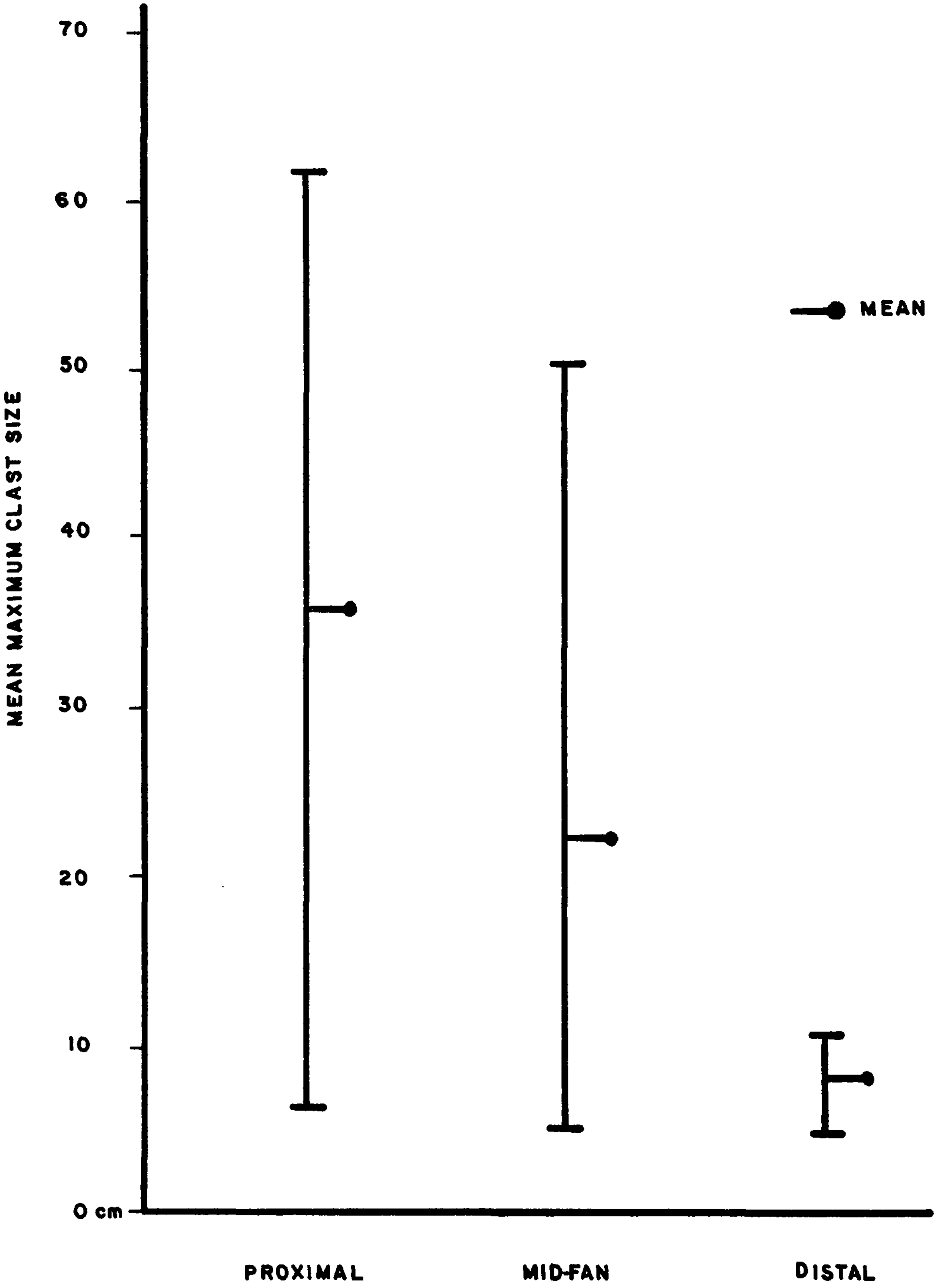
The examination of the morphology and morphologic changes of the clasts within member 9 strata were carried out, with the primary goal being to determine the distance and direction to the paleo-source area. Likewise, the data obtained from the examination of the lithology of the clasts, thin-section examination, and x-ray diffraction analysis, were examined with this same goal in mind. Certainly other conclusions about the inter- and intra-basinal depositional history were obtained from these studies. Nevertheless, they are presented under a common heading "Source Area", and will be presented in a manner which is oriented toward the significance of each phase to the interpretation of the location of the ancient source area.

Clast Size

Because the examination of isochronous outcrops are limited to two dimensions, and due to the juxtaposition of the fan facies by faulting, the use of size as an indicator of the direction of sediment influx into the basins proved fruitless. That is, it is nescessary to have three-point control, along a time line, to establish a source-to-basin line based on changes in grain size.

The most significant conclusion that can be drawn after examining the size data (Figure 12) is that the source area was not far from the preserved strata. This fact is indicated by the large size of some clasts found within the member. The maximum mean clast size is 61.7 cm (-9.3 phi) (station P7) and the largest single clast measured 101 cm (-10.0 phi) (also at station P7) (Appendix E). Using the values of the mean maximum clast size from each of the four sections and a plot of the

Figure 12. Plot of mean "maximum clast size" versus facies. Standard deviations: proximal-18.0 cm, mid-fan-13.9 cm, distal-3.6 cm.


70
60
50
40
30
20
10
0 cm
MEAN MAXIMUM CLAST SIZE
MEAN
PROXIMAL
MID-FAN
DISTAL

reduction of clast size across an alluvial fan surface with distance of transport given by Blissenbach (1954), the distance to the source area from each section can be extrapolated. To use this method, the size of the clast before transportation must either be known or approximated. During the course of field work for this thesis, visits to many of the source rocks were made and therefore the initial size of the material formed by weathering of the parent rock was known. In using this method, the source for the preserved member 9 strata was approximated to be no more than 10 to 12 kilometers.

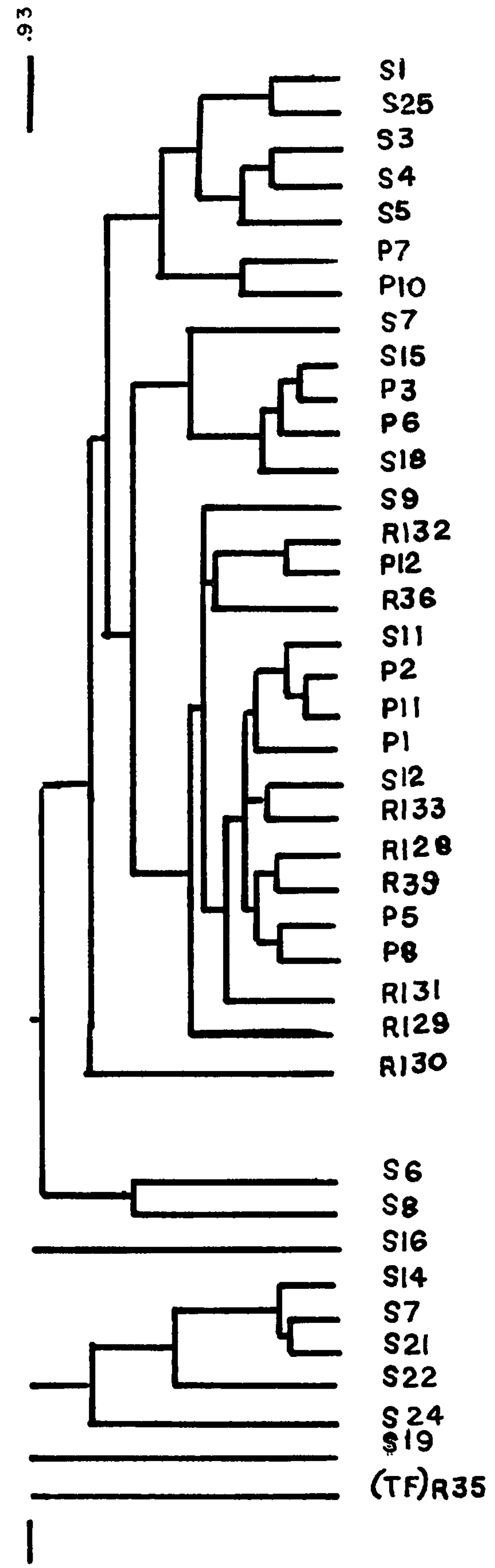
A crude differentiation, based on size, of the various facies can be detected in Figure 12. The mean largest clast size of the proximal facies deposits is 35.2 cm (-8.5 phi) with a median size of approximately 29 cm (-8.2 phi). Mid-fan facies deposits have a mean clast size of 21.3 cm with a median of approximately 18 cm (-7.5 phi). Distal facies deposits have a mean clast size of 6.0 cm (-5.9 phi) and a median of approximately 6 cm (-5.9 phi). These differences between proximal and mid-fan deposits (t=.836, d.f.=36) and between mid-fan and distal deposits (t=1.4, d.f.=23) are not significant at the 90% confidence level as determined by the "t" test. This lack of significance is not totally unexpected considering the gradational nature of the deposits and therefore the overlap in clast sizes present within each facies. However, a significant size difference is indicated from comparison of proximal and distal deposits (t=1.77, d.f.=19).

Lithology

The lithology of 100 clasts at each station was determined and the percentage of each type present, calculated. Sedimentary strata above, below, and stratigraphically equivalent to member 9 strata very often contain limestone clasts which were derived from either the Solitario, outcrops of Cretaceous limestones near the town of Shafter, or from several other breached domes near the study area. The absence of this lithology within member 9 strata is significant in excluding these areas as possible paleo-sources. Because all clasts within member 9 were volcanic and there were many which I could identify as having a probable local source; precludes all but a local source area. Thin-section mineralogy will be discussed in a later section, however it is appropriate to say here that the finer fraction also reflects a local volcanic source area. Identifiable clast found within member 9 strata include material eroded from the Santana Formation, Fresno Formation, and members 4, 5, 7, and 9 of the Rawls Formation, all of which are found within the Bofecillos Mountains. No lithology found within member 9 strata would warrant looking further than the Bofecillos Mountains area for a possible ancient source area. However, the geology across the Rio Grande is largely unknown, and therefore the study of clast lithologies cannot exclude the possibility that an ancient source area was totally or partially located within Mexico. One would expect that an international boundary would have little control on the distribution of volcanic flows and therefore it is felt that many of the same flows found in the Bofecillos Mountains also occur within Mexico. However, paleocurrent directions, deduced from imbricated clasts, indicate a source area for member 9 that lay in Texas. This conclusion is more fully elaborated on under the heading, "Imbrication and Cross-stratification".

The data obtained from the lithologic pebble counts were analysed using a Q-mode cluster analysis (Figure 13) in the hope of determining which stations were lithologically most similar; and therefore, which

Figure 13. Q-mode cluster analysis based on pebble counts of lithologies present at various stations. Data is in closed form.

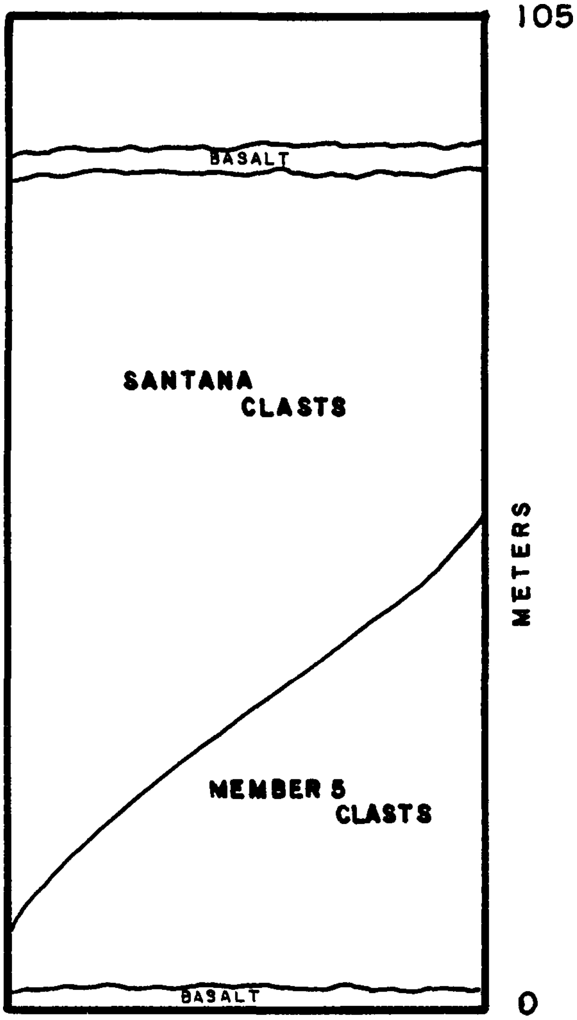

.93
S1
S25
S3
S4
S5
P7
P10
S7
S15
P3
P6
S18
S9
R132
P12
R36
S11
P2
P11
P1
S12
R133
R128
R39
P5
P8
R131
R129
R130
S6
S8
S16
S14
S7
S21
S22
S24
S19
(TF)R35

strata were deposited on the same fan. From this information only two groupings are shown at a distance of 9.33. Certainly a more detailed study of the lithologies present would have produced many significant findings, but a study of that nature was beyond the scope of this investigation.

Several stations do not belong within either of the two main groups. One of these was station R35, which was located at the boundary of Dietrich's (1965) and McKnight's (1968) mapping area. Earlier I have shown that this outcrop is not part of member 9, but part of the Fresno Formation. Two other stations (S16 and S19), which are approximately time equivalent, also fail to cluster with one of the two main groups. The reason these stations did not cluster is that they represent a transitional area between strata of the two lithologically different groups.

Figure 14 illustrates the vertical changes in lithologies within the Santana section. By observing the manner in which these changes take place, the cause can be deduced as to why the two stations (S16 and S19) failed to cluster with either of the two main groups. If the changes in lithology were due to unloading from a single source area, a gradational lithologic change with stratigraphic height should occur. Furthermore, the lithologies present within the basin should reflect a reversal in the source area stratigraphy. From Figure 14 one can see that both these criteria are satisfied and therefore, the above stated hypothesis would appear feasiable for explaining the depositional history of the basin. However, by examining the ratio of two distinct clast types present in this section the events responsible for the changes become apparent.

Figure 14. Diagram showing the variation with stratigraphic location, of the ratio of two distinct clast types present in the Santana section.


105
BASALT
SANTANA
CLASTS
METERS
MEMBER 5
CLASTS
BASALT
0

A basalt flow (Tr9b) which roughly divides the section in half, can be used as a time line. Below this basalt no Santana clasts are found; however, ten meters above the top of this flow the first Santana clasts are present. At station S16 (mid-fan facies deposits) equal amounts of "grey" conglomerate beds and "pink" sandstone beds crop out. Pebble counts made at this location show that the ratio of Santana clasts to member 5 clasts is approximately 1 to 1. However, pebble counts made from the "grey" conglomerate beds show the ratio to be approximately 1 to 19, and counts made from the "pink"-colored pebbly sandstone beds have a Santana to member 5 ratio of approximately 19 to 1 (Figure 15). This distribution of lithologies indicates a dual source area. Further up section at station S24 there are no member 5 clasts. From these observations it is clear that at least two alluvial fans were interfingering in this area, and that with time the sediment deposited on the fan whose trunk stream head was located on strata of the Santana Formation overwhelmed the other, probably smaller fan (Figure 16). This seems to be the more feasible explanation for the observed changes in lithology.

Generally the clasts present reflected a narrow range of lithologic types. The stratigraphically highest parts of the Santana section consist predominantly of clasts eroded from a single formation, the Santana. These deposits are more nearly monomict than other member 9 strata.

Because the first occurrence of interfingering takes place immediately above a basalt flow, several interesting possibilities exist that would explain some of the details of the sedimentary history of this basin; however, the fact remains that a coalescing of fans along their mid-fan areas was taking place. Interesting points raised, but not resolved are: (1) did one fan overwhelm the other by shear volume

Figure 15. Schematic diagram illustrating distribution of clast types near station S16 in the Santana section. This distribution of clasts of various lithologies indicates an inter-fingering of two alluvial fans.

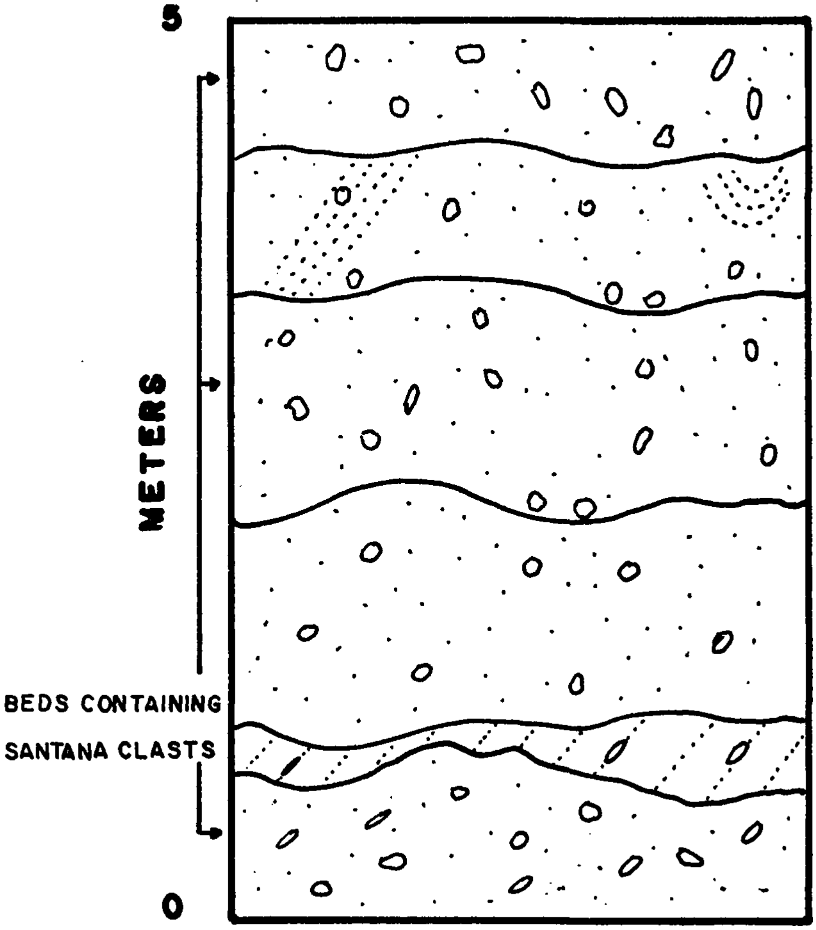
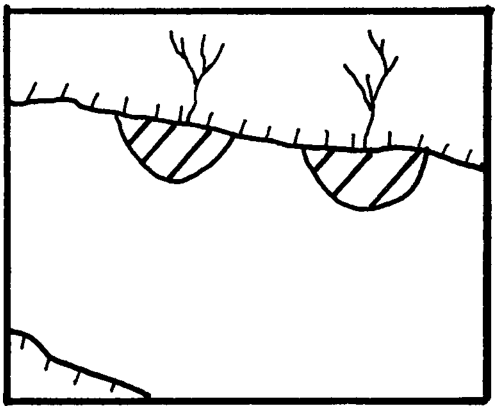

5
METERS
BEDS CONTAINING
SANTANA CLASTS
0

Figure 16. Three diagrams illustrating the filling of the Santana Bolson.

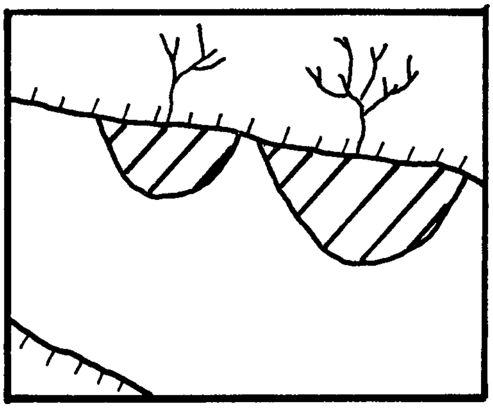
A. Two small alluvial fans building into the basin

B. One fan, begins to increase in size, perhaps related to its trunk stream eroding less resistant strata.

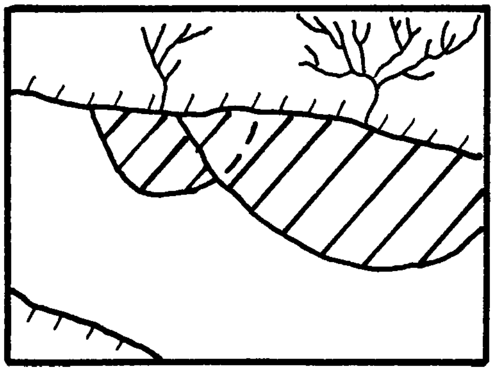
C. With time, one fan overwhelms the other by sheer volume of sediment input.



A



B



C

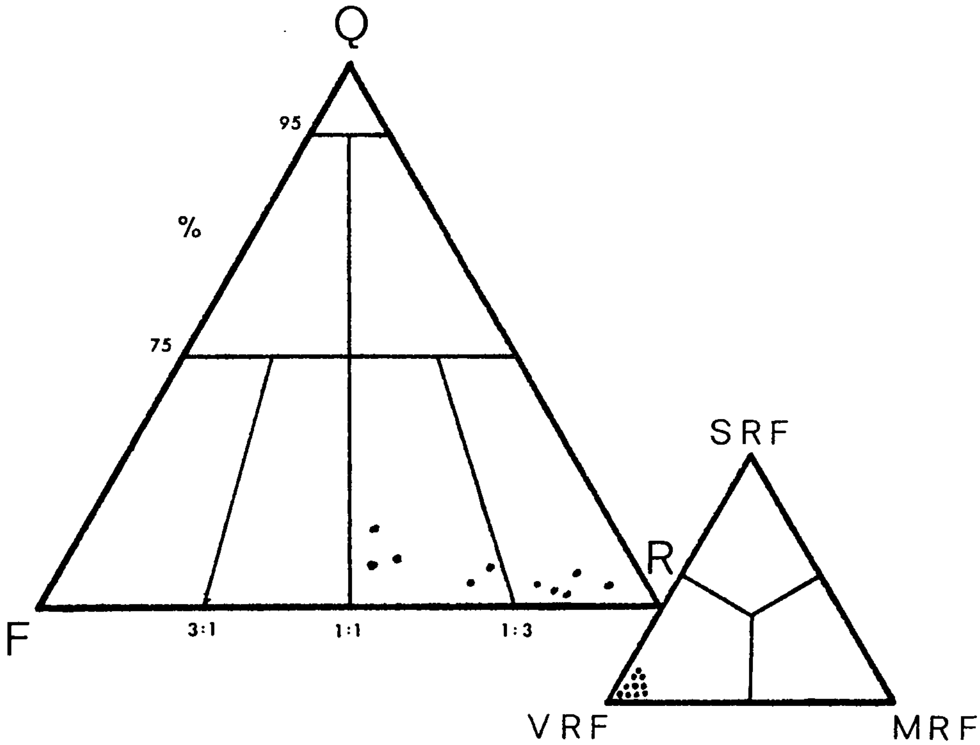
of sediment input, which may have occurred as a result of extrusion of a lava flow that plugged the drainage basin of the fan eroding member 5 strata, (2) did a period of faulting associated with the last episode of Tertiary volcanism result in disrupting the drainage basin of one of the fans while uplifting the source for the other, or (3) did stream capture play a part in reducing the drainage basin of one of the fans? Any or all the above are possibilities.

Thin-section

The mean grain size from thin-sections examined ranges from coarse-grained sand (.25 phi) to fine-grained sand (2.5 phi). Most thin-sections contain a high percentage of granular and larger-sized clasts, but these were not included in the point counts from which the mean grain size was determined. Sorting of the sand and finer sediments range from poor to very poor. Most samples are texturally immature; the others are submature, containing no clay-sized material. The submature rocks were generally cemented with large, equidimensional, passive (Folk, 1965), sparry calcite crystals. Lithologically the samples ranged from volcarenites (R39, P8, S13, P1, P2), to feldspathic volcarenites (S27, S5, S17, RI33, S19-A) (Figure 17).

The quartz grains are generally water clear, often embayed, and occasionally have crystal face terminations, indicating a nearby volcanic source area. Rounding of the quartz grains is generally poor, but occasionally a well-rounded grain was observed (probably the result of multi-cycle deposition). The quartz grains are generally confined to the finer sand-sized fractions. This is consistant with the observation that the quartz crystals within rock fragments were of a similar size; because, it is these rock fragments from which the quartz grains were

Figure 17. Plot of lithologic composition of thin-sections of member 9 sandstones. (triangular graphs after Folk, 1974) Triangles not to scale.


Q
95
%
75
F
3:1
1:1
1:3
R
SRF
VRF
MRF

derived. The percentage of quartz ranges from one to thirty percent of the grains in the slides examined, and are most common in the slides with fine sand-sized modal classes.

Fine-grained, volcanic rock fragments are the most abundant constituent and account for between 42% and 85% of the grains counted in the thin-sections. Feldspar grains are evenly divided in number between potassium and plagioclase feldspars, which together compose less than 20% of the mineralogy in most slides; however, in some slides one type may significantly dominate. The ratio of feldspar types might be valuable in working out the detailed stratigraphy of member 9 strata, but this would require the examination of an exceptionally large number of thin-sections. The feldspar grains are generally corroded and serratization is observed on some grains. Heavy minerals are opaque, and are more abundant in the finer-sand fraction than other size fractions. Occasionally, the heavy minerals are concentrated in placer deposits. The percentage of these minerals ranges from two to ten percent of the grain counts made.

No grains, regardless of mineralogy, are rounded to any significant degree. Deposits with a modal size in the fine-sand range (TS-S19, S17), generally contain a higher percentage of quartz and feldspar grains and a lower percentage of rock fragments. This reflects the breaking down of the rock fragments into their constituent minerals as their size was reduced.

The main binding agent, often composing 20% of the slide by volume, is a montmorillonite clay. The most common cementing agent was sparry calcite, which formed large equant crystals. In one slide (S19) calcium carbonate cement is found partially replacing rock fragments, quartz, and feldspar. In most thin-sections an unusual cement, which could not be positively identified with petrographic techniques, formed from one to fifteen percent of the precipitated cements. This cement has a low birefringence and forms intergrowths of stubby lath-like crystals which are commonly zoned. This cement is probably a type of zeolite. In some cases the unusual cement is found forming a fringing rim around individual clasts, indicating that it was precipitated before cementation by the calcite. Stevens (1969) reported similar cement paragenesis in the Delaho Formation in the Big Bend National Park.

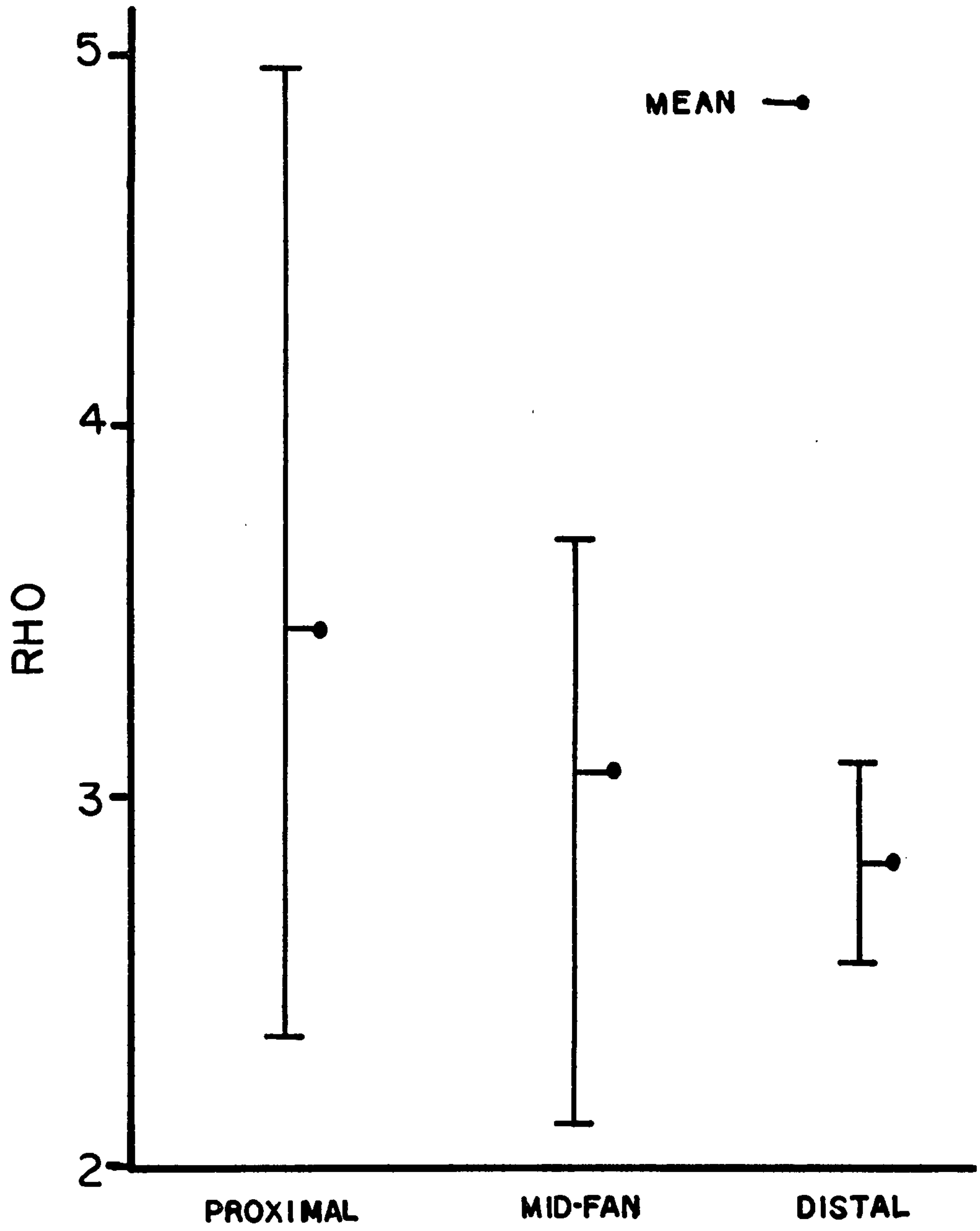
X-Ray Diffraction

X-ray diffraction patterns of clay material from member 9 strata were predominantly that of a sodium-calcium montmorillonite. Minor amounts of feldspar and quartz as clay-sized material are present in some samples. This clay suite strongly indicates a volcanic source area (Carrol, 1970). Crystals collected from station S27 (playa deposits) gave a diffraction pattern of gypsum.

Roundness

Very few studies have examined the rate of rounding of volcanic rocks with distance of transport. Kuenen, (1964) determined, from a flume study, that aphanitic volcanic rocks round as fast as limestone, which reach maximum roundnesses in less than 16 kilometers of fluvial transport. Roundness values of clasts within member 9 are generally high, ranging from angular to subround, depending on the type of deposit and facies. Deposits of the proximal facies are generally more angular than clasts from other facies (Figure 18). Roundness values of clasts from the proximal facies deposits average 3.44 rho (subangular), mid-fan facies deposits average 3.14 rho (subangular), and distal facies average

Figure 18. Plot of roundnesses of clasts versus facies. Differences between facies are not significant at the 90% confidence level. Proximal



MEAN
RHO
5
4
3
2
PROXIMAL
MID-FAN
DISTAL

2.75 rho (subround). The difference between the roundness values for these facies is not significant at the 90% confidence level; proximal to mid-fan (t=1.0, d.f.=36), mid-fan to distal (t=.15, d.f.=19), and proximal to distal (t=.25, d.f.=13) by the use of a t-test. No station contained clasts with an average roundness value of less than 2.16 rho (subround). When plotted on a graph taken from Blissenbach (1954) these values indicate less than ten miles of transport.

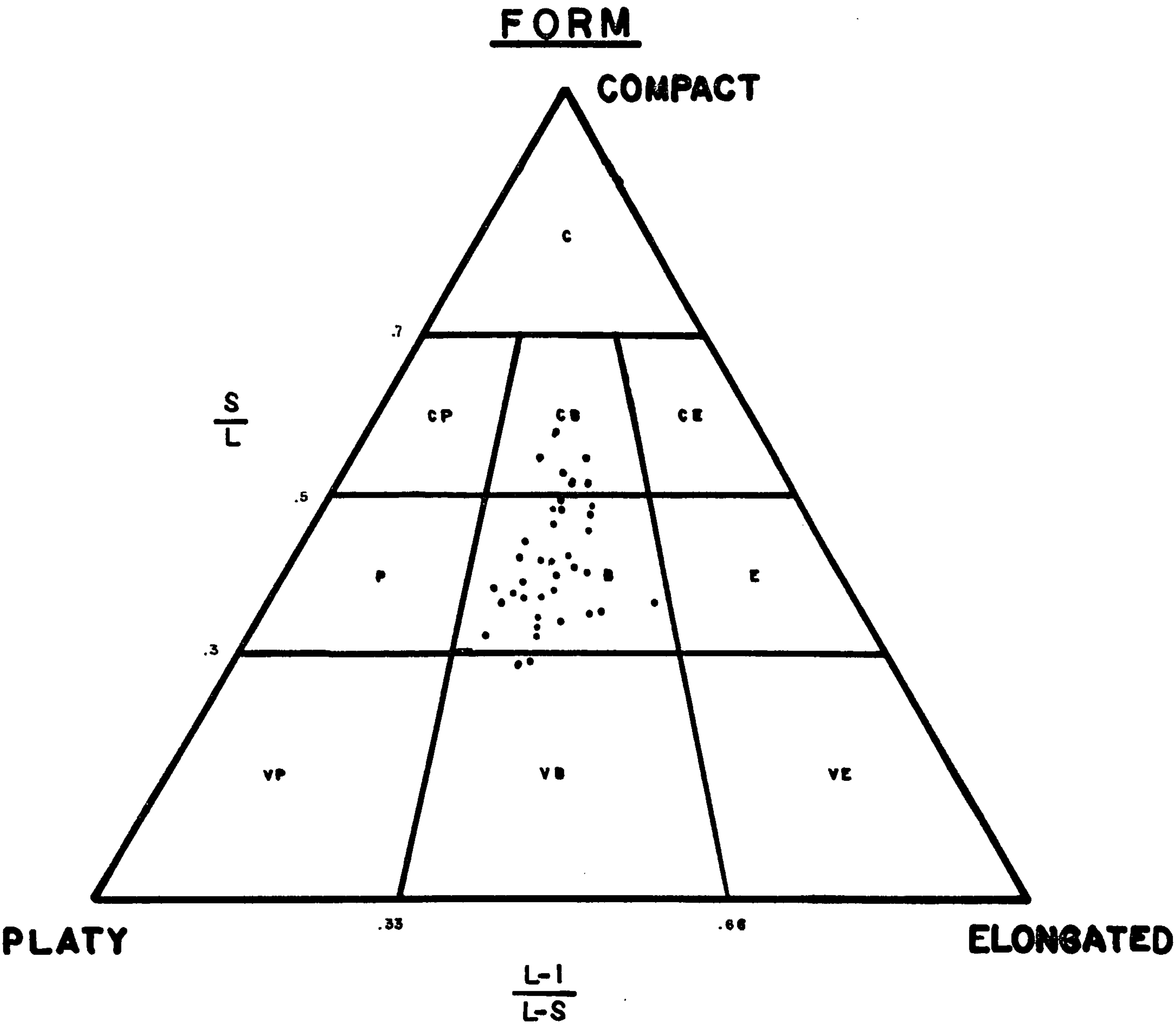
Form

Form proved useless as a tool in establishing a direction of sediment transport. No significant changes in clast form (as determined from a Chi^2 test of the data) were noted from proximal to distal fan facies deposits. This conclusion is similar to that reached by other workers concerning form of clasts found on alluvial fans (Blissenbach, 1954); however Bluck (1964) has reported form sorting on modern alluvial fans.

Most clasts fall into the bladed category (Figure 19). The form of most clasts was probably initially compact or subcompact. This conclusion is based on the lack of bedding or parting planes observed in the parent rock. Therefore, because the distance of transport was so short, one would expect that neither form sorting, nor physical changes of a clast's form would occur. However, my opinion is that form and form sorting are so poorly understood that the detection of actual changes in form is unlikely. It has been said that size sorting can take place with one swish of a miner's pan. Form sorting should also take place very rapidly because the form certainly controls the hydrodynamic characteristics of a pebble and therefore, to a great extent, its "transportability". It is possible that no form sorting has been noted in these or most strata

Figure 19. Plot of the mean form of clasts from each station. Most clasts fall into the bladed category. No significant differences at the 90% level, P=.10, between the form from various facies are suggested by a Chi^2 test.

Proximal-Mid-fan	X^2=7.39, d.f.=8
Mid-fan-distal	X^2=6.7, d.f.=8
Proximal-distal	X^2=8.3, d.f.=8


FORM
COMPACT
C
.7
S/L
CP
CB
CE
.5
P
B
E
.3
VP
VB
VE
PLATY
.33
.66
ELONGATED
L-I/L-S

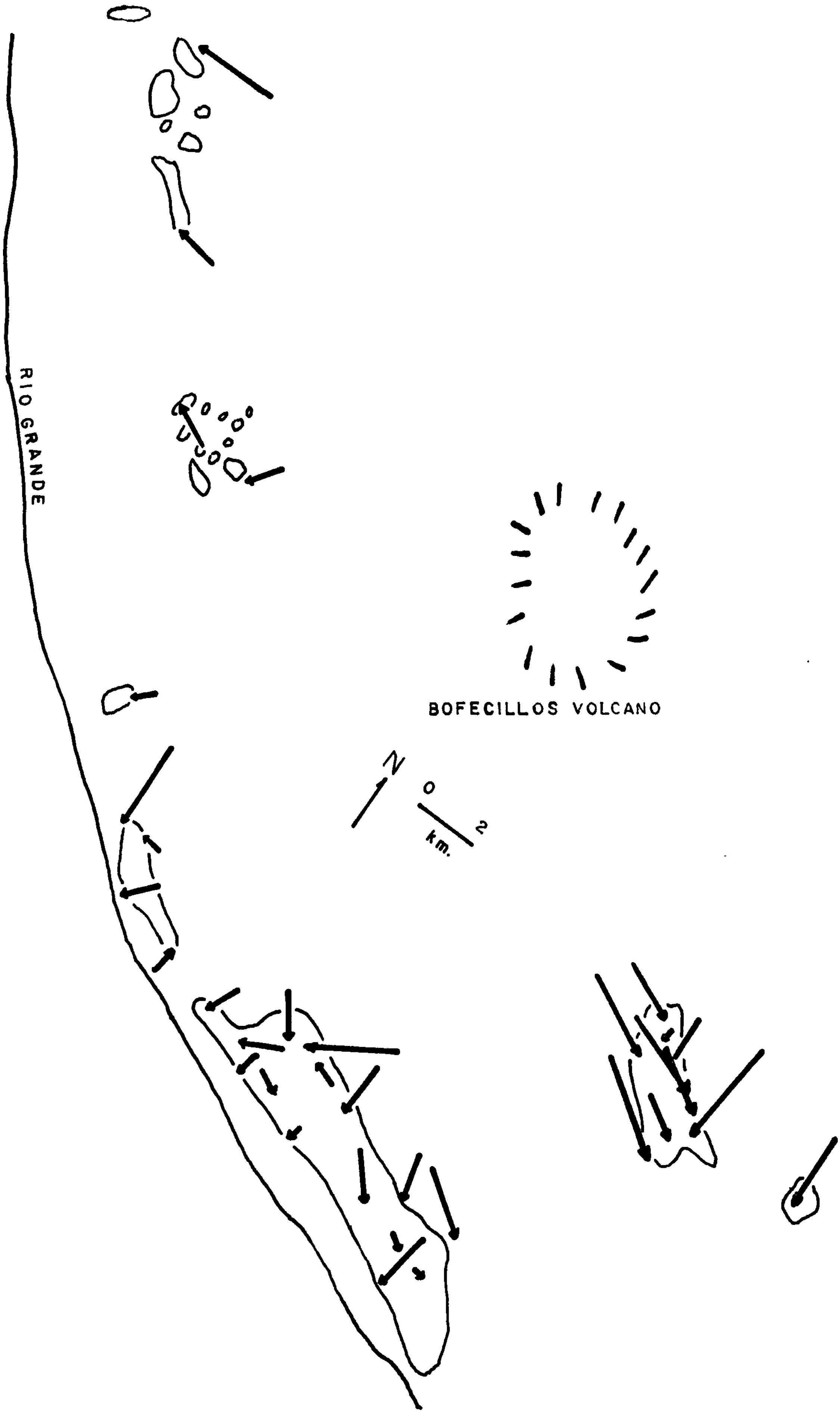
as a result of the criteria used in determining which clasts will be used in studying form. At present two variables, lithology and size, are considered important in selecting the set of clasts to be used for work concerning form. Lithology can be controlled easily; but, using commonly practiced field techniques, size cannot. For example, if one used the long dimension of a clast as a measure of size instead of volume, as I did, the differences in calculating the "true" size of a compact and elongate pebble with the same long dimension could be large. This size difference, between clasts with various forms, would certainly be adequate to nullify the ability of one to detect differences in form that might be present.

Imbrication and Cross-stratification

Measurements of paleocurrent indicators proved useful in reconstructing the paleo-slope in the Bofecillos Mountains, These indicators do not require three-dimensional areal control to establish a source-to-basin line. Figure 20 shows the mean imbrication direction and magnitude for each station. These data indicate that the source areas for member 9 strata centered around the Bofecillos Volcanic Vent. Sediment transportation directions into all depositional basins were away from this Miocene topographic high.

The paleocurrent data are significant in concluding that the source for member 9 strata was located in the present Bofecillos Mountains, and not another local topographic high such as the Solitario dome or an unknown area in Mexico. The mean directions do not deliniate individual fans from within member 9 strata. This is inconsistent with the findings of Laming (1966) and others. This leads me to believe that member 9 strata were deposited as a very large bajada complex in which sediment

Figure 20. Plot of mean imbrication directions. Notice that the direction of sediment transport diverge from the Bofecillos Volcano. Length of the arrows is proportionate to the percentage of clasts within 30° group (see appendix B)

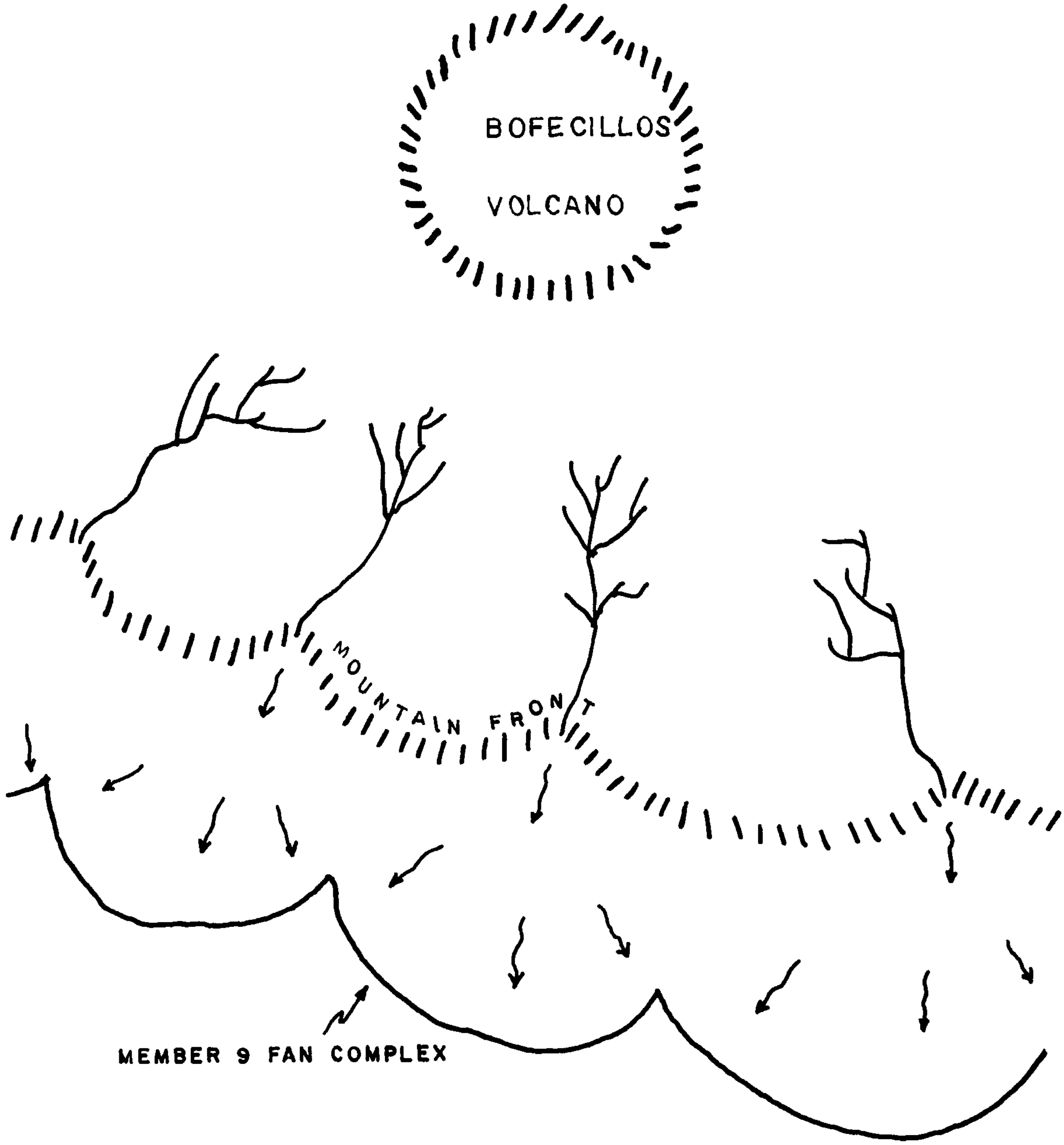

RIO GRANDE
BOFECILLOS VOLCANO
N
0
2
km.

dispersal loci were closely spaced (Figure 21). This situation would not be conducive to the formation of fully developed alluvial cones, and therefore one would not expect to find a full 180° change in paleo-slope directions across the cone surface. An alternative explanation is that very large fans with widely spaced loci of sediment dispersal existed, and therefore no pattern could be detected from the preserved outcrops. However, the overlap of mid-fan facies deposits of two different fans in the Santana section gives more credibility to the former hypothesis, as this overlapping of fans would not be expected in the later case.

Source Area Conclusion

From the study of clast lithologies and texture, it is evident that the sediments of member 9 strata were of local origin, and that the source probably lay within ten miles of the preserved outcrops. Paleocurrent data point to the Bofecillos Volcanic Vent area as the probable source. The Bofecillos Volcanic Vent was formed during the extrusion of the Fresno Formation lavas and tuffs (McKnight, 1968), and therefore was a topographic high during the Miocene deposition of member 9 strata. The volcano probably obtained relief of at least 300 meters above the local elevations and therefore greatly influenced the paleoslope. Streams flowed radially away from this topographic high and filled fault-block basins formed in the Redford-Lajitas fault-zone, which trends arcuate around the southern flanks of the volcanic structure.

Figure 21. Hypothetical sketch of closely spaced alluvial fans, filling grabens around the southern flanks of the Bofecillos Volcano.


BOFECILLOS
VOLCANO
MOUNTAIN FRONT
MEMBER 9 FAN COMPLEX

RELATIONS OF TR9, TR9F, AND QTF

Tr9 and Tr9f are the two subdivisions of member 9 sedimentary strata that were mapped by McKnight (1968) (Figure 22) based on color, mineralogical and textural differences that he observed in the field. McKnight (1968) states:

> "The term 'bolson fill' as used in this report is restricted to deposits that contain beds of 'pink' facies, even though much of the Rawls unit Tr9 were also aggrading sequences in bolsons. Except in the Santana Bolson, where interfingering 'gray' and 'pink' facies are mapped Tr9f, the 'pink' overlie the 'gray' and the bolson fill is mapped as a separate unit (bolson fill, Qtf)."

He later states:

> "In the Santana Bolson, typical 'gray' Tr9 conglomerate is intercalated with 'pink' conglomeratic sandstone typical of the bolson fill (Qtf) in alternating beds or groups of beds as much as 50 feet thick; this interfingering sequence is arbitrarily mapped as bolson fill in the Rawls Formation (Tr9f)."

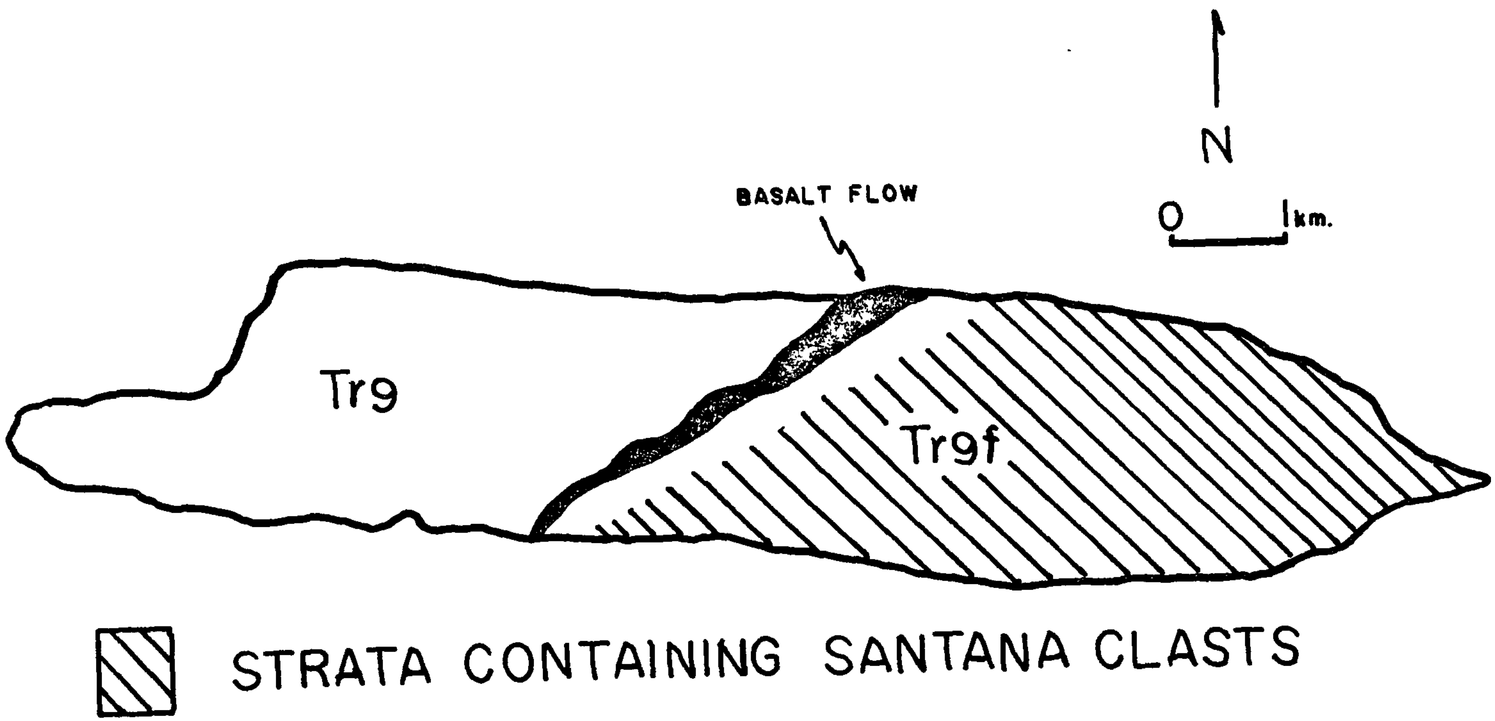
and also that:

> "The fact that the bolson fill of the mapped area is continuous with that of the Presidio area suggest that it was transported in from the northwest perhaps along the axis of the bolson."

Several lines of evidence can be presented that indicate some of his conclusions, with regard to the late Tertiary sedimentation in the area, are questionable. If the strata of Tr9f represent sediments derived from two different source areas, this difference should be reflected in the mineralogy and texture of these strata. Analysis of the clay

Figure 22. Diagram showing the relations of the two subfacies of member 9 sedimentary strata mapped by McKnight (1968). Tr9 strata crops out below the basalt flow, Tr9f strata crop out above the flow. Notice the close corellation of his "facies" boundaries with the first occurance of Santana clasts in the sedimentary strata.

SANTANA SECTION



mineralogy of Tr9f and other member 9 strata (e.g. Tr9) showed them to be montmorillonite. Some differences between the mineralogy of the sand fractions were noted; but these variations in texture and mineralogy are better explained by a local shift in the source area, than by derivation of some of the material from some distance to the northwest. Lithologic pebble counts made from strata of both subdivisions and a study of clast roundnesses, indicate that the source area for these strata was the Bofecillos Mountains.

If the source for the strata comprising Tr9f had been to the northwest, one would expect to find some indication of a limestone terrain. In that direction, large exposures of Cretaceous limestones and sandstones are now, and have been exposed since before the Miocene. This type of source area should be reflected in the presence of well-rounded clasts and grains of limestone, chert, siliceous sandstones, and other mineralogies common to that area. None of these was found. Also, if the bolson-fill strata (Qtf) were being transported along the center of the bolson, one would not expect to find the textural changes present in these structures from conglomerates near the mountains, to mudstones in the basin center. This distribution of textural facies excludes axial transport of large quantities of sediment by any large stream. Groat (1972) states:

> "McKnight (1968, p. 113) believes that the muds in the Redford Bolson were derived from upstream, from the Presidio Bolson but the presences of a wedge of coarser-grained deposits between the two areas does not support his interpretations."

Actually McKnight (1968) makes no mention of "mud", but talks of axial transport of all the "pink facies" strata. Further evidence contradictory to his conclusion is the existence of evaporite deposits in the Santana Bolson which attest to at least the locally closed nature of the basin for a period of its depositional history.

The observed textural and mineralogic differences in the Santana Bolson are best explained by facies changes within a coalescing alluvial-fan complex filling the Santana Bolson. Outcrops of Tr9f are stratigraphically higher than those mapped as Tr9, and their differences reflect the interfingering of two aggrading alluvial fans with local, yet distinguishable source areas. Evidence found in the basin indicates that with time one fan was successful in overwhelming the other. Mcknight (1968) mapped the oldest fan complex as Tr9 and the younger, stratigraphically higher, fan as Tr9f, because much of the strata exhibited the "pink" color that is dogmatically used in this area to recognize "bolson-fill".

The relation of member 9 strata to the strata filling the Reford and Presidio bolsons is not clear. McKnight (1968) reported a discordant contact of three degrees between the two units, with the bolson-fill strata (Qtf) overriding member 9 strata toward the mountain front. In an earlier section I have shown this contact to be between Redford Bolson strata (?) and sedimentary strata of the Fresno Formation. Dietrich (1965) also reports a discordant contact between the two units. From my observations the detection of discordant contact between the "two" units appears questionable for several reasons. First, the texture of the strata and the lack of good bedding would make the detection of an angular contact of such low values highly unlikely, and second, both units are composed of material lithologically and texturally indistinquishable without much detailed work, as both were derived from a common source area and become finer-grained in the same direction.

Much of the problem in the area is based on the fact that two periods of bolson fill were originally defined on the presence of an angular discordance, but this definition is either incorrect or insufficient to use in the differentiation of "two" units and therefore this criteria has not been used. Instead the "two" units are separated on the presence or absence of intercalated volcanic flow rocks.

I believe, as Dickerson (1966) concluded, that the "bolson strata" cannot realistically be divided into two distinct sedimentological episodes separated by a period of tectonic activity. No formalized definition of either member 9 strata or Redford Bolson-fill strata exists, which has resulted in confusion for those working in this area. I suggest that in the future the term 'member 9' be restricted to those bolson-fill strata which are intercalated with basalt flows and that the top of the member be placed at the top of the highest basalt flow. All sedimentary strata above member 9 should be termed Redford Bolson-Fill for those strata cropping out in that structure. These definitions are suggested as a working rule rather than in a formalized sense.

STRUCTRUAL GEOLOGY

McKnight (1968) gives an excellent insight into the type, age, and trends of faulting and other tectonic movement in the Bofecillos Mountains. He concluded that most faulting occurred after the deposition of member 9 strata citing strong field evidence to support his reasoning. My detailed examinations of member 9 strata support his findings. Member 9 strata are cut by numerous unmapped faults with little throw (generally less than 15 meters). The major faults, with displacements of over 150 meters, that form the present boundaries of the preserved outcrops of the member cut across facies, show fresh fault traces, and lack accumulation of talus material (Plate 7B). This observation suggests that the major faults are also post-member 9, although concievably they could have been active prior to deposition of member 9 strata. All faults observed showed normal displacements when relative direction of movements of the blocks could be ascertained. No faults found were truncated by member 9 strata. Faults generally parallel the trend of the Redford-Lajitas fault zone (trending northwest-southeast), with the down thrown block to the south.

At one locality in the Santana section, displacement of Quaternary gravel (Qg) was noted. This indicates, as Dietrich (1965) and McKnight (1968) concluded, that tectonic activity has continued into the Holocene epoch.

The relations of the textural facies within the Santana section demonstrate a migration of textural facies (distal over proximal) that indicates that after the basin was formed it was filled during a period of quiescence in tectonic activity.

Ages of sedimentary strata within member 9, based on vertebrate fossil remains found within separate fault blocks, indicate that deposition of the member took place from lower to middle Miocene over a period of at least five million years. This suggests that periods of sporadic tectonic activity may have been common and/or that much time is probably represented by hiatuses and erosional vacuities within the member.

FOSSILS

Two vertebrate fossils collected from member 9 sedimentary strata were identified by M. Stevens of Lamar University. A partial skull and jaw of an oreodont (Plate 7C) collected from the River section is identified as *Merychyus*, cf. *M. elegans*, typical of the middle Miocene (Hemingfordian). The other specimen, both halves of the mandible, collected from the Santana section (black dike collecting locality) is also an oreodont, *Phenacocoilus leptoscelos* (Plate 7D). This species is similar in morphology to fossil oreodonts collected and described from the Arikareean Delaho Formation of the Big Bend National Park, which suggests a similar age for at least part of Rawls member 9 (M. Stevens, written communication, 1976). More identifiable fossil finds, may of course amend these ages. Other vertebrate material collected, but of little use in establishing an age of the strata, include a poorly preserved jaw fragment of a camel containing several teeth fragments. At the present time middle Miocene age for the member is suggested.

GEOMORPHOLOGY

Low rolling hills are the most common physiographic expression of member 9 strata. This is characteristic of conglomerates that crop out in arid or semi-arid regions. Occasionally, due to rapid dissection and the presence of more resistent interbedded basalt flows, vertical cliffs up to 60 meters high are formed. Outcrops of member 9 are generally confined to grabens and the strata in these structures are presently topographic lows due to their less resistent nature compared to most rock types in the Bofecillos Mountains area.

ECONOMIC GEOLOGY

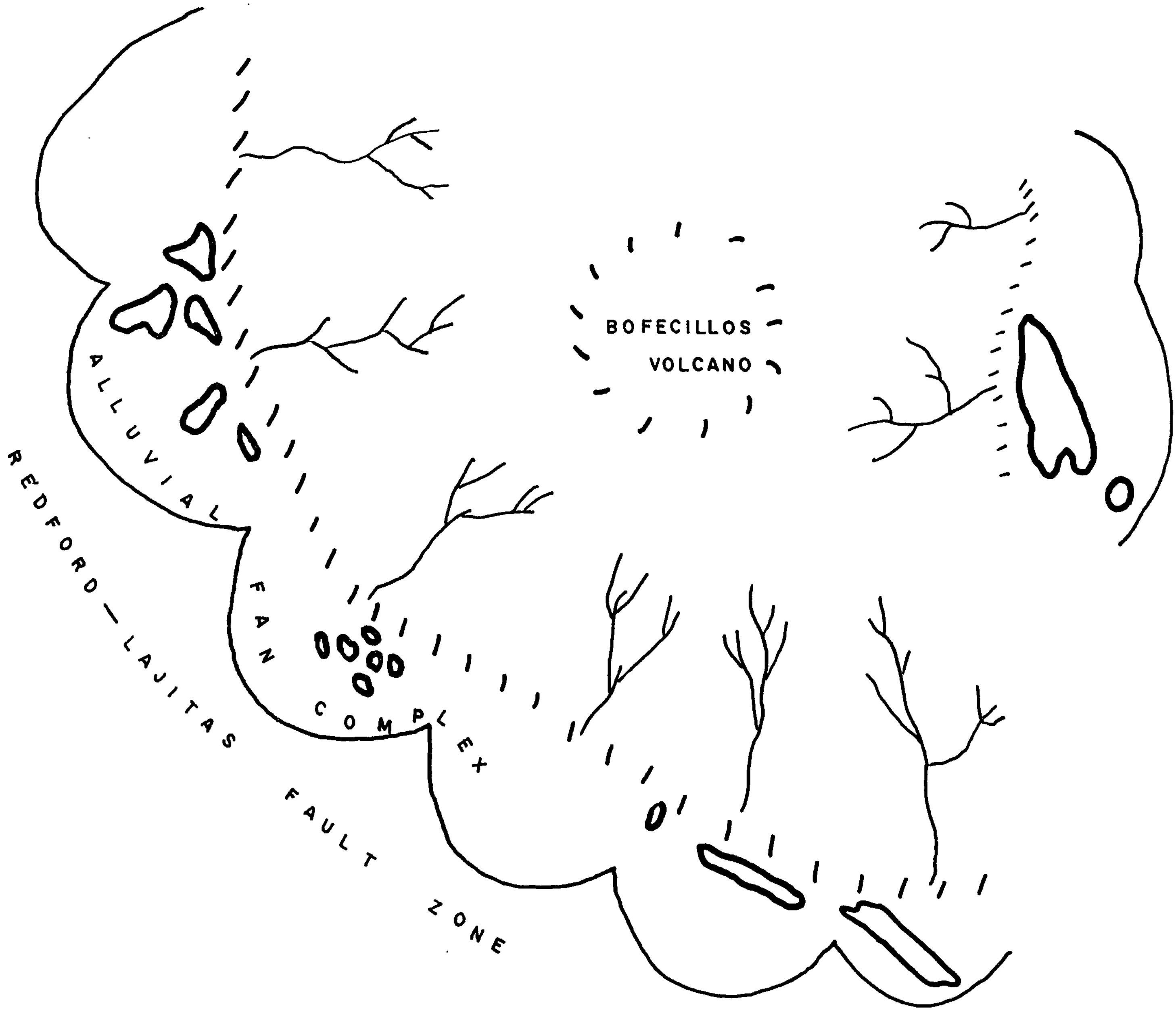
No minerals of economic value are present within menber 9 strata. The substance of highest economic value in an arid region is perhaps water. The porosity and permeability of member 9 strata are probably not sufficient to support a water well. Futhermore, most member 9 strata crop out along the Rio Grande, which affords a more dependable source of water for local pastures and irrigation of fields.

SUMMARY OF THE GEOLOGIC HISTORY

The Bofecillos Volcano was formed during the extrusion of the Fresno Formation lavas and tuffs during the early Miocene and was a major factor in the developement of the middle Miocene drainage pattern in the area. Streams with short courses and steep gradients were formed and flowed radially away this topographic high. A period of major tectonic activity during the early Miocene epoch formed numerous elongate grabens along the Redford-Lajitas fault zone which trends northwest-southeast around the southern flank of the volcanic structure. These faults block basins acted as depositional sites for the accumulation of a thick sequence of sedimentary rocks and intercalated volcanic flows. Relief, formed by the volcano and faulting, coupled with a semi-arid paleoclimate, similar to or slightly more humid than conditions found throughout the present desert southwest were conducive to the formation of an alluvial fan complex in this area.

Strata of member 9 represent the remnants of an extensive bajada complex that developed in this area during the Miocene (Figure 23). These sedimentary strata are intercalated with the youngest volcanic flows associated with Tertiary volcanism in this area. Member 9 sedimentary strata consist of approximately 90 meters of predominantly coarse-grained, angular, poorly sorted, immature, locally derived conglomerates and sandstones with minor amounts of mudstones; all of which were accummulated in shallow closed basins. The facies relations display a transgressive migration of facies (distal over proximal) toward the source area, which developed as the result of deposition during a period of tectonic quiescence.

Figure 23. Idealized Miocene physiography. Coalescing alluvial fan complex is shown filling grabens formed in the Redford-Lajitas fault zone. Renewed (post-deposition member 9) faulting has resulted in only those strata outlined in heavy lines being preserved.


BOFECILLOS
VOLCANO
ALLUVIAL FAN COMPLEX
REDFORD—LAJITAS FAULT ZONE

Strata of member 9 partially filled the Santana, Redford, and Presidio bolsons before renewed faulting resulted in the termination of the sedimentary events responsible for the accummulation of the member. Strata deposited after this episode of tectonic activity compose the Redford-Presidio bolson-fill (Qtf). The introduction of a through flowing regional drainage pattern during the Pleistocene(?) transformed the area from an aggradational to a degradational state. Erosion of member 9 strata has left only isolated outcrops which have been preserved within grabens formed by post-depositional tectonic activity, as evidence of the extensive bajada complex that existed in the area during the Miocene.

Vertebrate fossils found within the member establish a maximum age of Miocene for the formation of the Redford and Presidio bolson structures and place the end of Tertiary volcanism as middle(?) Miocene in this area.

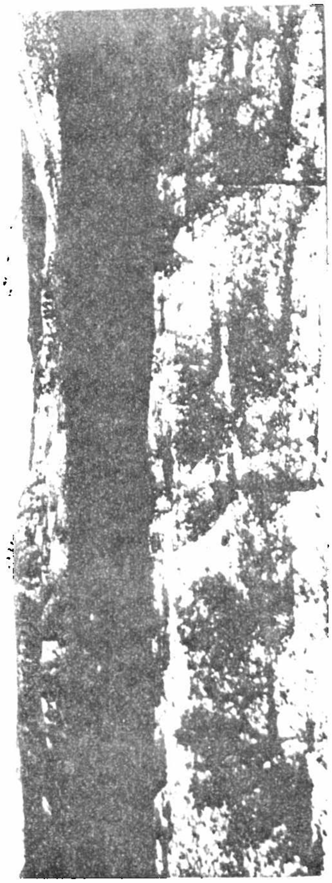
PLATES

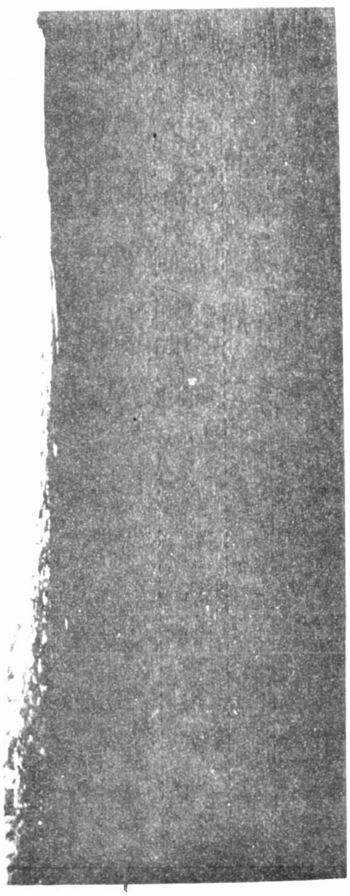
Plate 1. A. upper right. Eroded, tilted fault blocks in the Redford-Lajitas fault zone, produces a rugged topography. In foreground is an ephemeral braided stream that is choked with coarse debris.

B. upper left. Morning view across the dissected Redford Bolson-fill. Looking southwest toward Mexico.

C. lower right. View looking southwest across the Rio Grande from a point nine miles east of Redford. Member 9 strata can be seen in the low cliffs in the foreground.

D. lower left. Exposure of Redford Bolson-fill strata west of Redford, capped by a well indurated two meter thick terrace gravel.





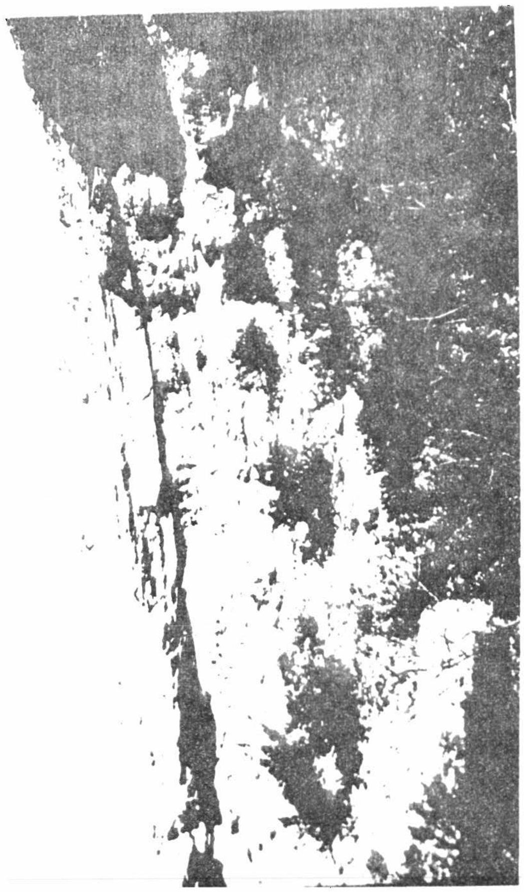
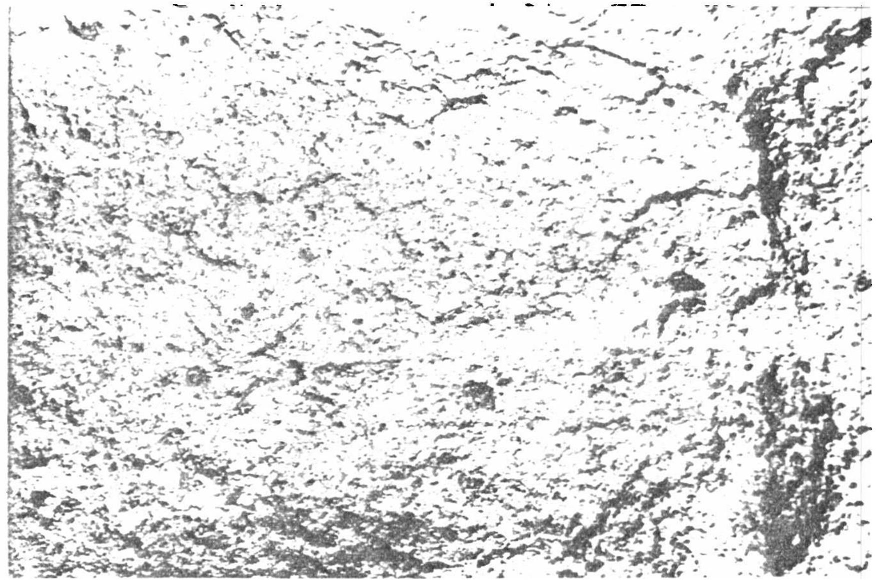


Plate 2. A. upper left. Clasts of three typical lithologies found flooring the modern sidestreams. Clasts like these are also abundant in member 9 strata, which makes differentiation of modern and ancient sediments difficult. These clasts are (R to L), 1) trachyandesite of member 5 (Rawls Formation), 2) basalt porphyry of member 4 (Rawls Formation), 3) Riebeckite (?) Rhyolite.

B. upper right. Outcrops of proximal facies deposits (low ridge in foreground) in River section, north of Texas Route 170 (foreground). View looking north, 9 miles east of Redford, Texas.

C. lower left. Weathering crust on proximal facies deposits in the River section. The crust developes due to the repeated wetting and drying of the clay matrix.

D. lower right. Coarse texture of muddy-sandy conglomerate near station P6. Boulders are large, angular and locally derived. The person is standing on a large member 9 basalt clast.



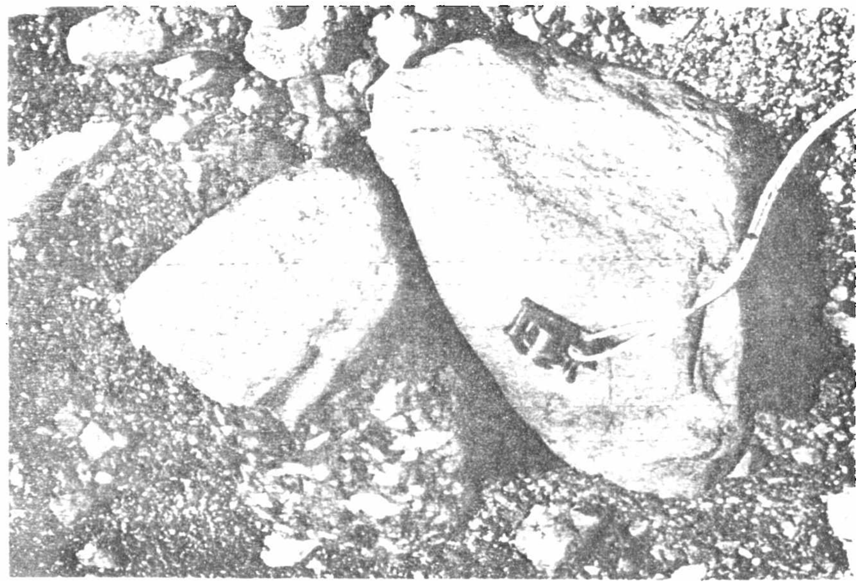


Plate 3. A. upper left. Large pebble muddy-sandy conglomerate (station RI29) proximal facies deposits.

B. upper right. Exposure of proximal facies deposits along the Rio Grande. Notice the two, one meter thick small pebble conglomerate beds in the middle of the outcrop. These beds can be traced continuously from left to right ($\frac{1}{2}$ mile) (arrows point to beds).

C. lower left. Deep, narrow channel in proximal facies deposits near station S25. The channel was cut into boulder conglomerates and is filled with a very pebbly, coarse, mature cross-stratified volcarenite.

D. lower right. Vague planar cross-stratification with steep dip angles and sharply terminated tops and bottoms in a fine pebble conglomerate. The rock is submature and cemented by calcium carbonate (quarter for scale).

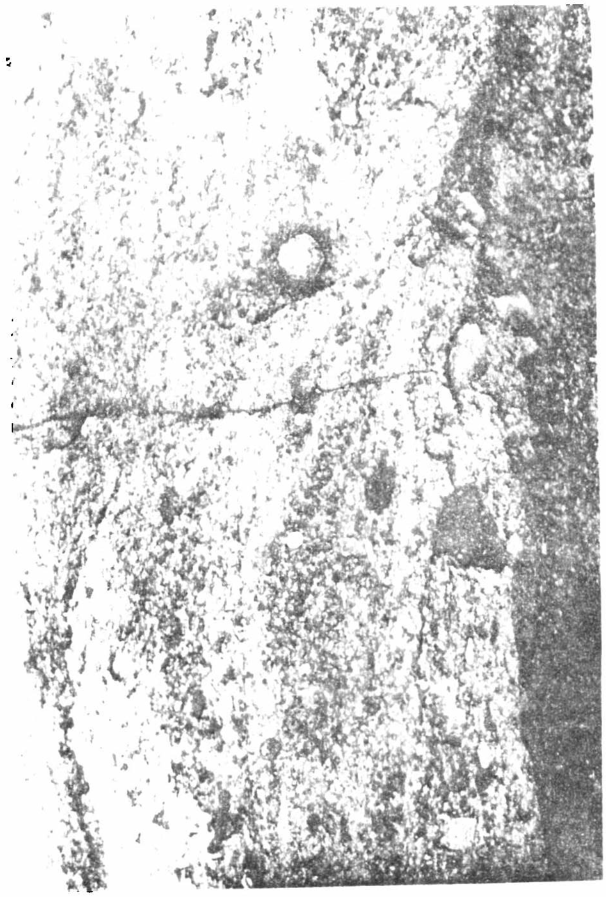


Plate 4. A. upper left. Longitudinal gravel bars and flanking sand-filled channels near station S3 (proximal facies). Gravel units consist of cobbles and pebbles. Sand units which separate some bars exhibit high angle planar cross-bedding (lower left) and thin toward bar tops (current from left to right).

B. upper right. Close-up of planar cross-stratified sandstone unit (immediately below hammar) at down-current end of longitudinal gravel bar.

C. lower left. Exposure of mid-fan sandstone subfacies deposits in fault contact with proximal deposits near station KI34. Outcrop consists of alternating two meter thick pebbly sandstones and medium cobble conglomerates. (exposure is approximately 30 meters high)

D. lower right. Close-up of horizontally bedded conglomerate shown in Plate 4-C.

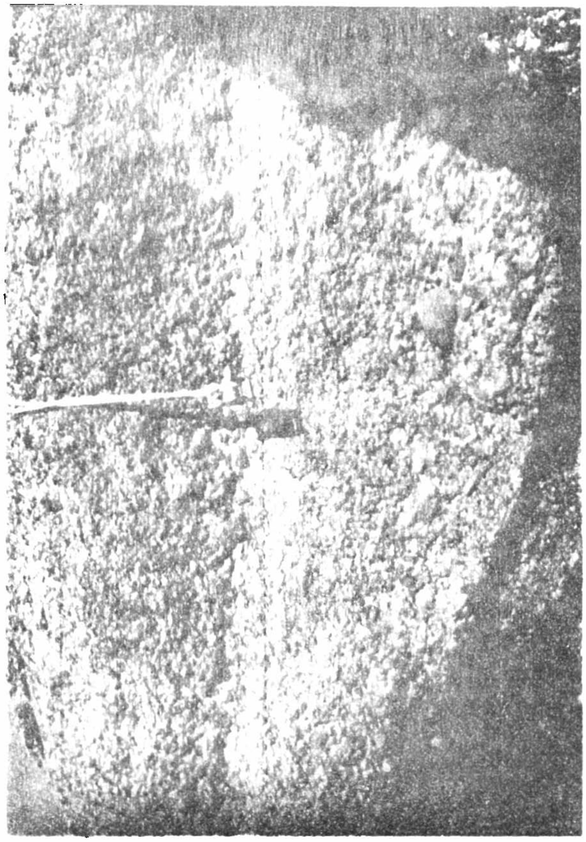
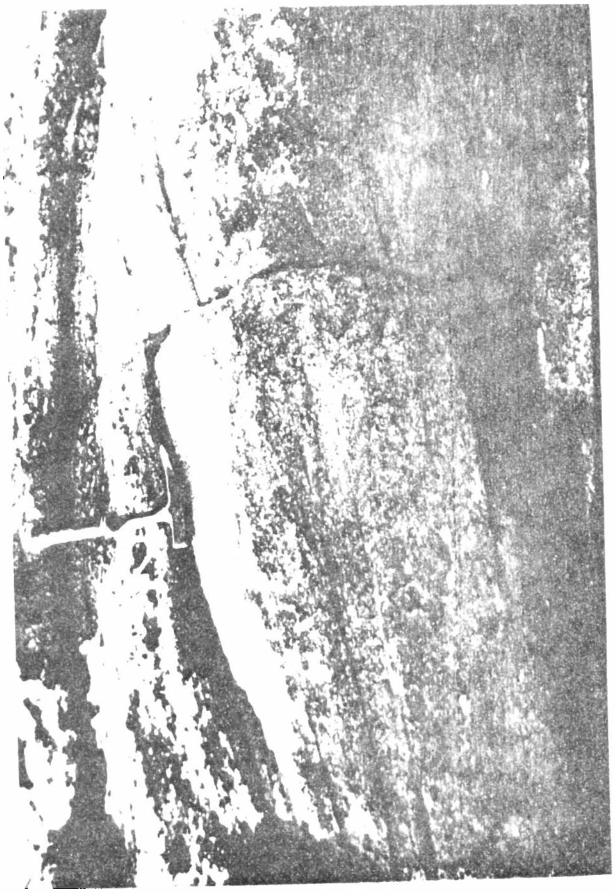


Plate 5. A. upper left. Horizontally bedded very pebbly sandstone which has filled a channel cut into a cobble conglomerate. The channel is approximately 2 meters deep and 3 meters wide. Channel axis orientation is into the picture toward the right.

B. upper right. Very large, high angle, planar cross-stratified pebbly sandstone in the mid-fan sandstone subfacies. Direction of current flow was from right to left (N to S). Unit is approximately 1 meter thick.

C. lower left. 3 meters of massive structureless pink volcarenite overlain by 2 meters of stratified sandy conglomerate, erosional contact. This sequence is rhymethically repeated at this station (S24).

D. lower right. Interbedded planar cross-stratified horizontally laminated coarse sandstones. Monomict conglomerate stringers are usually only one pebble thick and located at the base of sedimentation units. The clasts are derived from the Santana Formation.



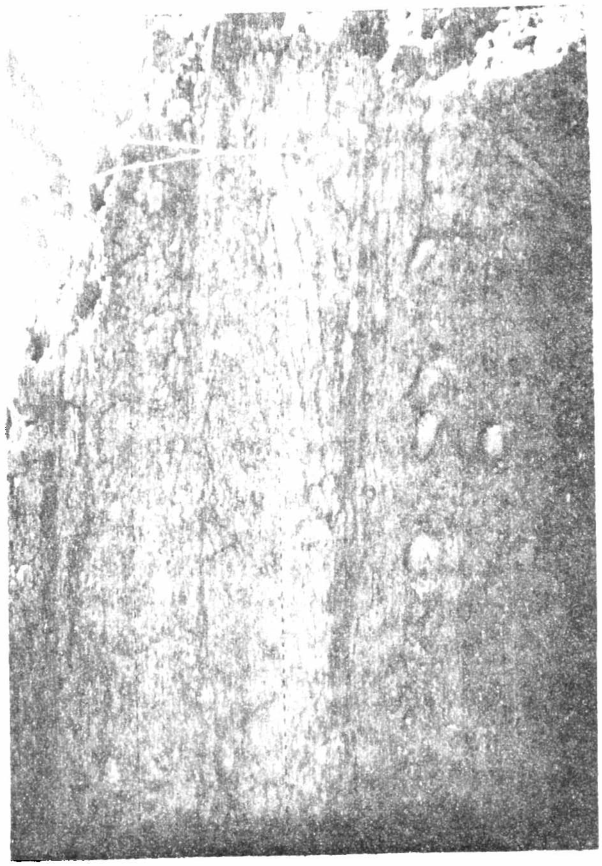


Plate 6. A. upper left. 5 meters of interbedded massive pink sandstones and discontinuous, more resistant, conglomerates in the mid-fan sandstone subfacies near station S16.

B. upper right. 12 meters of distal facies deposits near station S20. Outcrop consists of dominantly fine-grained volcarenites with minor conglomerate lenses (hammar level) and thin beds of mudstones (upper middle part of plate).

C. lower left. Abundant small scale cut-and-fill structures near station S21. The color differences in this picture are due to graded beds that consist of a small pebble basal conglomerate which grades upward into a thin mud drape.

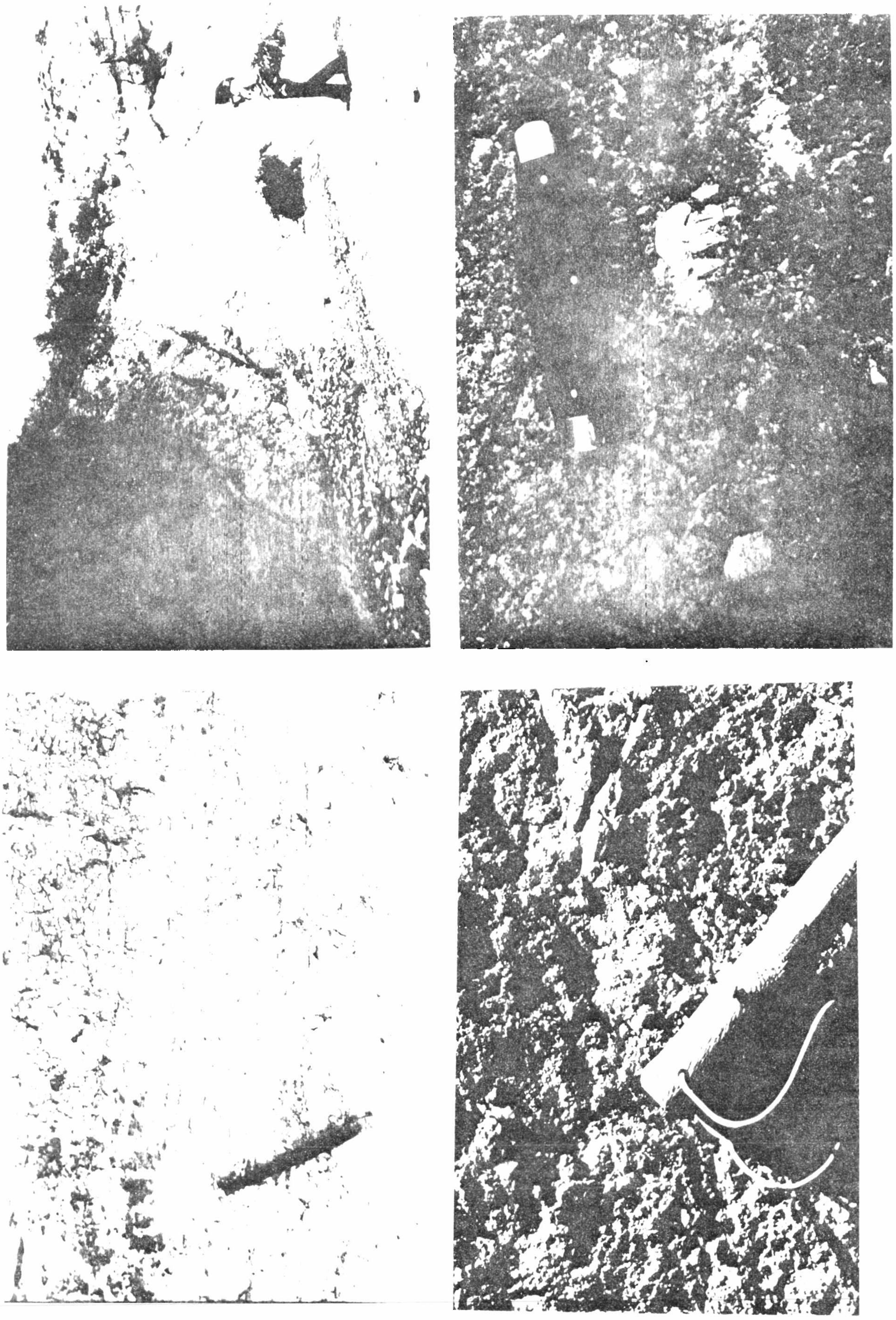
D. lower right. Exposure of playa deposits. Outcrops consist of 5 meters of predominately thinly bedded horizontally laminated mudstones, with some interbedded sandstones and gypsum.

Plate 7. A. upper left. Bioturbated playa deposits.

B. upper right. Boundary fault of the Santana section. Member 9 proximal facies deposits are down to the south (left). Notice fresh fault trace and lack of talus material, which indicate the faulting post-dates deposition of member 9.

C. lower left. Miocene oreodont, *Phenacocoelys leptoseclos*, early Miocene (Arikareean). Collected from black dike locality, mid-fan facies Santana section.

D. lower right. Jaw and teeth of *Merychyus*, cf. *M. elegans* (oreodont). Middle Miocene (Hemingfordian) collected from the River section.



APPENDIX

APPENDIX A

Measured Section 1
Station S18 to S24, member 9, Rawls Formation

Segment	Thickness (Meters)	Cumulative Thickness
Santana Formation		
Fault contact		
7. Black basalt with faint white splotches.	12.2	77.9
6. Pink, fine-grained volcarenite, baked red by overlying basalt flow.	0.9	65.7
5. Covered.	1.5	64.8
4. Sandy medium pebble conglomerate as discontinuous beds up 0.6 meters thick, poorly sorted, slightly calcareous muddy matrix, subangular clast of the Santana Formation dominate. Sandstone, volcarenite, in beds 0.5 to 2 meters thick, generally massive and pink in color. Minor amounts of light brown mudstone in beds 7 cm thick.	24.4	63.3
3. Equal amounts of massive bedded light grey, poorly sorted, subangular, medium pebble conglomerate containing dominantly Santana clasts and pebbly volcarenites, light pink in color, cross-stratified, in beds 0.6 to 2 meters thick. No member 5 clast present.	21.3	38.9
2. Dominantly large pebble conglomerate, light grey, well indurated, massive, some channeling. Calcite cemented,	15.2	17.6

Measured Section 1 (continued)

poorly sorted with subangular member 5 clasts in equal amounts with Santana clasts. Lower in unit no Santana clasts are found in the strata. Sandstones are moderately sorted, cross-bedded, coarse grained, volcarenites, light grey to pale pink in color.		
1. 2.4 meters of black basalt without white splotches.	2.4	2.4

Fault

Santana Formation

Measured Section 2

P2 eastward to top of hill

Segment	Thickness meters	Cumulative thickness
Top of hill		
9. covered	4.6	62.1
8. Large pebble conglomerate, massive, light grey, very poorly sorted, very high percentage mud component, all clasts are volcanic, sub-angular, and local in origin. Sandstone is interstitial component only, coarse-grained, poorly sorted, light grey, volcarenite.	1.5	57.49
7. Black basalt, containing sparse dark phenocrysts, similar to unit 1.	8.5	55.99
6. Alternating fine pebble conglomerate, light grey, poorly to moderately sorted,	2.7	47.49

Measured Section 2 (continued

moderately indurated; and very coarse-grained, sparry calcite cemented, slightly pebbly volcarenite, with erosional bases, in .3 meter thick beds, upper one meter baked red color.		
5. Yellow lithic tuff with stringers of white tuff, poorly indurated.	.49	44.79
4. covered	4.6	44.3
3. Light grey to white, poorly sorted, massive boulder conglomerates and medium pebble conglomerates with calcarious, sandy, mud matrix, poorly indurated, containing many large member 9 basalt clasts. Grades upward into similar beds with smaller mean clasts size. Scarce .3 meter beds of very coarse, sparry cemented, volcarenites and fine pebble conglomerate. All clasts are volcanic and subrounded.	34.6	39.7
2. covered	2.0	5.1
1. Basalt, black, dense with sparse black phenocryst.	3.1	3.1

Stream bed (base covered)

APPENDIX B

Imbrication Data

Station	Strength Percentage of Total	Direction North=0	No. of Readings
S1	46.2	58.5	16
S3	39.2	105.7	20
S4	71.9	49.0	25
S5	19.6	-76.7	23
S6	41.0	16.9	20
S7	46.6	-45.2	22
S8	48.8	-9.0	27
S12	22.4	180.0	4
S15	34.5	-18.3	25
S16	46.2	-42.6	21
S17	18.0	-61.1	20
S18	57.6	-58.7	20
S21	12.9	-90.0	4
S24	53.5	0.0	20
S25	29.6	-4.8	26
RI28	31.2	166.2	20
RI30	51.5	150.0	13
RI31	76.2	0.0	12
RI32	31.2	84.9	23
R36	68.9	93.3	16
R37	50.0	85.6	16
R38	43.7	90.3	13
R40	27.3	62.1	27
P2	96.6	-0.1	10
P5	84.9	-45.0	12
P6	81.9	-59.9	29
P7	75.6	-70.3	20
P8	45.6	-11.0	20
P9	40.3	-62.3	20

Appendix B (continued)

P10	82.0	-64.5	10
P11	17.2	-0.9	27
P12	61.7	-69.9	20
P13	79.1	-9.6	25

APPENDIX C

CLAST TYPES
USED IN PEBBLE COUNTS FOR LITHOLOGY

Type No.	Discription	Possible Source
1	Trachy basalt porphyry, abundant large lath like phenocryst of plagioclase feldspar.	Rawls Formation, member four
2	Trachyandesite, olive-green weathering with oriented feldspars which give the rock a micaceous luster.	Rawls Formation, member five
3	Ash Tuff, non-welded to welded victric crystal tuff with large pumice fragments which weather out leaving lensoidal pits.	Santana Formation
4	Tuff, green to blue, friable, sandy victric crystal tuff.	Rawls Formation member seven
5	Ash-flow tuff, welded, lithic tuff containing accidental fragments of latite and latite porphyry.	Fresno Formation
6	Basalt, black with faint white spotches.	Rawls Formation member 9b
7	Sandstone, quartzarenite	Shafter?, Presidio? Finley? or equivalents
8	Limestone, dark, grey, micrite or biomicrite	"
9	Tuff, well-indurated, victric-crystal tuff, grey to cream white, with chatoyant phenocrysts of sanidine and glassy quartz	Mitchel Mesa Frm.

Clast Types (continued)

10	Chert	Shafter?, Presidio? Finley? or equivalents
11	Riebeckite? Rhyolite. Blue-grey, dendritic crystals, sparce phenocrysts of sanidine	Intrusions in the B.M. area
12	Ash tuff, air fall tuff, cream to brown exhibiting well developed laminations	?
13	Tuff, lithic-crystal, coarse texture with abundant corroded potassium feldspar phenocrysts, color is generally light pink.	?
14	Tuff, welded, lithin-crystal, contains abundant rock fragments and oriented sanidine? phenocrysts, some streching of phenocryst	?
15	Micro-syenite, light white, abundant white pehnocryst (feldspar), commonly has corroded reddish minerals.	?
16	All others	?

APPENDIX D

THIN-SECTION MINERALOGY*

No.	Quartz	Plagioclase Feldspar	Potassium Feldspar	Rock Fragments	Heavy Minerals	Unidentified
S19	11	1	31	42	10	0
RI33	11	10	27	46	4	5
P1	2	0	15	80	1	0
P8	1	2	13	82	2	0
P2	3	10	1	85	1	0
S5	5	10	15	66	2	2
S17	30	8	32	47	4	7
S13	4	9	8	71	3	4
S27	8	9	13	50	3	4
R39	6	8	15	70	1	0

*in percent

APPENDIX E

Textural Data

Station	Texture			Clast Size	Roundness	Form		Facies
	gravel	sand	clay	mean (CM)	mean	mean	MPS	
S1	100	0	0	39.7	2.72	b	.57	p
S2	-	-	-	39.1	2.63	b	.59	p
S3	60	40	0	26.1	3.48	b	.56	m
S4	90	10	0	41.4	4.21	b	.57	p
S5	50	50	0	35.4	3.07	b	.55	m
S6	100	0	0	52.6	3.95	b	.54	p
S7	100	0	0	31.6	3.86	b	.60	p
S8	40	60	0	19.8	3.43	b	.57	m
S9	40	60	0	9.7	2.83	b	.54	m
S10	1	9	90	4.7	-	-	-	d
S11	30	70	0	7.7	2.56	b	.57	m
S12	30	70	0	6.0	3.19	b	.62	m
S13	3	97	0	3.1	-	-	-	d
S14	13	87	0	9.9	3.09	b	.68	m
S15	45	55	0	13.9	3.3	b	.51	m
S16	50	50	0	27.2	2.62	b	.55	m
S17	40	60	0	5.3	2.77	b	.61	m
S18	85	15	0	30.7	2.18	b	.60	m
S19	10	87	3	15.0	-	-	-	m
S20	3	90	7	4.3	-	-	-	m
S21	20	80	0	5.2	3.18	b	.68	m
S22	1	90	9	7.6	2.57	c-b	.71	d
S23	2	97	1	-	-	-	-	d

Textural Data (continued)

S24	5	15	80	7.8	3.01	b	.66	d
S25	98	2	0	26.5	2.60	b	.57	p
S26	-	-	-	-	-	-	-	-
S27	1	9	90	-	-	-	-	d
RI28	100	0	0	21.7	2.96	b-vb	.51	p
RI29	100	0	0	10.8	4.22	c-b	.71	p
RI30	100	0	0	10.7	4.66	c-b	.75	p
RI31	100	0	0	9.9	4.26	vb	.69	p
RI32	70	30	0	16.6	3.33	vb	.49	m
RI33	100	0	0	5.8	-	-	-	p
RI34	100	0	0	9.0	-	-	-	p
P1	89	11	0	38.9	2.55	c-b	.71	m
P2	85	15	0	35.2	2.16	b	.66	m
P3	85	15	0	35.8	2.55	b	.59	m
P4	-	-	-	-	-	-	-	-
P5	70	30	0	28.9	2.78	b	.62	m
P6	99	1	0	32.4	2.89	b	.62	p
P7	100	0	0	61.7	2.78	b	.63	p
P8	85	15	0	42.6	3.20	b	.67	m
P9	99	1	0	50.4	4.85	b	.62	p
P10	99	1	0	55.8	2.62	b	.62	p
P11	70	30	0	49.5	3.61	b	.69	m
P12	70	30	0	41.2	3.31	b	.61	m
P13	100	0	0	55.3	3.43	b	.62	p
Laj.	-	-	-	-	-	-	-	-
R39	100	0	0	34.5	2.38	b	.57	p
P14	100	0	0	25.8	4.30	c-b	.73	p

Textural Data (continued)

Symbols Used

b	bladed
c	compact
v	very
p	proximal
m	mid-fan
d	distal

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