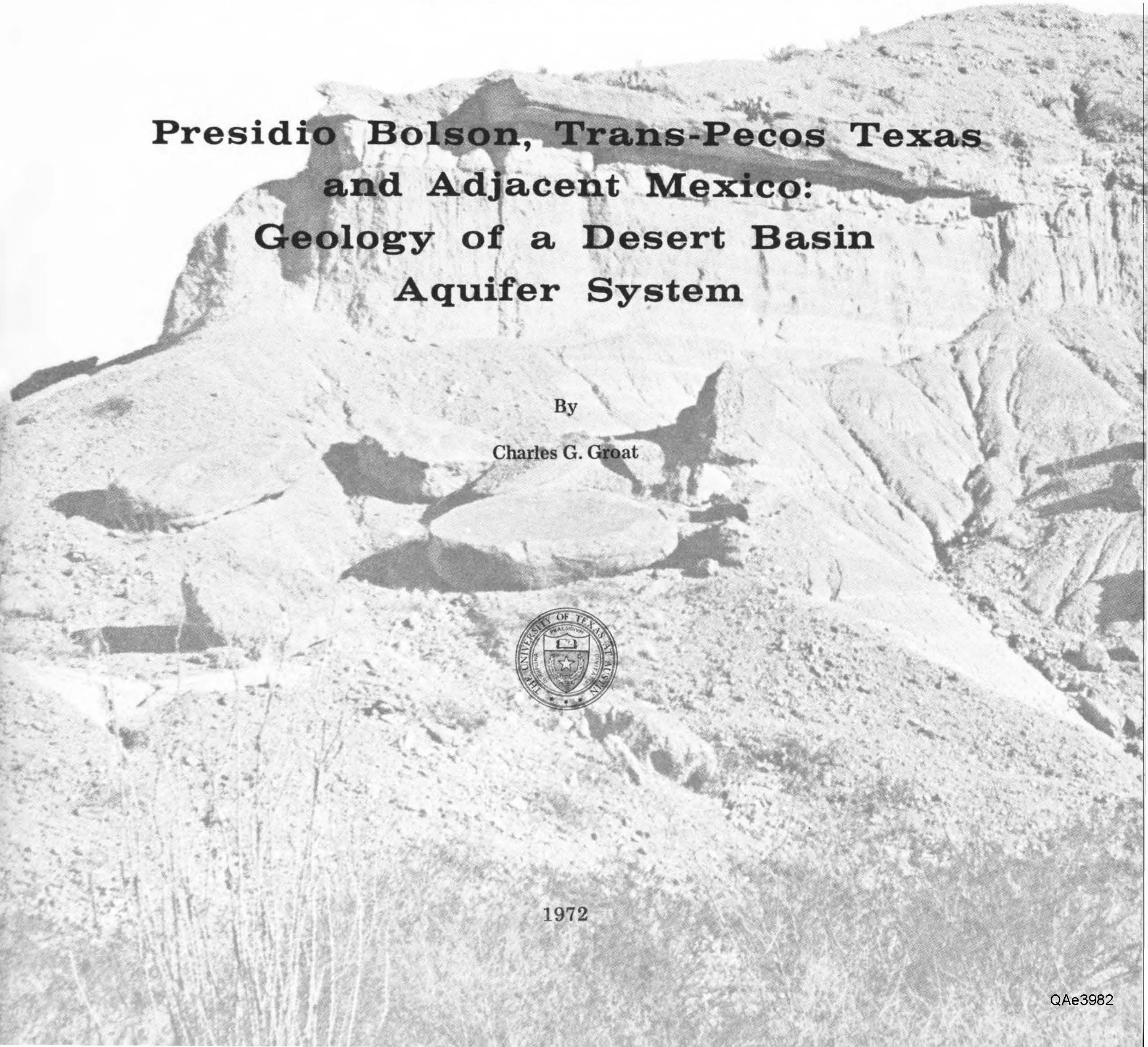
BUREAU OF ECONOMIC GEOLOGY
The University of Texas at Austin
Austin, Texas 78712

W. L. Fisher, Director

Report of Investigations—No. 76



Presidio Bolson, Trans-Pecos Texas and Adjacent Mexico: Geology of a Desert Basin Aquifer System

By

Charles G. Groat

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ILLUSTRATIONS

PRESIDIO BOLSON, TRANS-PECOS TEXAS AND ADJACENT MEXICO: GEOLOGY OF A DESERT BASIN AQUIFER SYSTEM

CHARLES G. GROAT

ABSTRACT

Mountain-bounded basins or bolsons are the most important aquifer systems throughout most of southwestern and western United States and northern Mexico. The dissection of the Presidio Bolson by the Rio Grande and its tributaries has afforded an ideal situation for detailed study of the stratigraphy of one of these important aquifer systems. The results of this investigation provide a framework for understanding the relationships between the types and distribution of bolson-fill sediments and the occurrence of ground water in desert basins in the United States and Mexico.

The Presidio Bolson formed by middle Tertiary normal faulting; the basin was filled with detritus shed from the surrounding mountains. Poorly sorted conglomerate and interbedded sandstone deposited on alluvial fans characterize the basin-margin facies; gypsiferous mudstone and fine sandstone of the basin-center facies, the greatest volume of deposits, were deposited on the toes of alluvial fans, in ephemeral playa lakes, and in relatively permanent lakes.

Excavation of the bolson fill began, probably during the Pleistocene, when the bolson was integrated into a regional, degradational drainage system with the Rio Grande as a master stream. Tributaries or sidestreams have been the dominant elements in dissection of the bolson fill; spectacular steplike abandoned erosion surfaces, cut by these streams by lateral planation, are the most striking features in the modern landscape. The high, prominent surfaces were cut by large sidestreams, transporting gravel, that head outside the bolson in the surrounding mountains; the gravel forms a cap that protects the surfaces from further dissection. Low, irregular, discontinuous surface remnants characterize areas drained by numerous smaller streams that head in fine-grained bolson fill.

The steplike arrangement of the surface remnants is at least in part caused by the interaction of side-stream processes with lateral migration of the Rio Grande channel-floodplain complex and by commonly occurring sidestream captures. The Rio Grande swings laterally, trimming back side-stream valley floors and creating sidestream terraces; the heights of these terraces above the Rio Grande are determined by the sidestream valley-floor gradients and the distance the main-stream swings. Capture of high-gradient, gravel-carrying, large sidestreams by lower-gradient streams heading in the fine-grained bolson fill produces abandoned, gravel-floored valleys that become high erosion-surface remnants. The role of pauses in downcutting, related to Pleistocene climatic changes, in producing the stepped surface remnants is not clear. Probably it was not great.

Ground water is the most valuable resource in the basin. The most reliable supplies are obtained from Rio Grande alluvium south of the juncture with the Rio Conchos. Sidestream alluvium yields small quantities of water in a few places. The bolson fill is potentially the most important aquifer, but the large plug of impermeable, gypsiferous mudstone results in small yields of poor-quality water over much of the bolson.

INTRODUCTION

GENERAL REMARKS

Mountain-bounded desert basins or bolsons, filled or partially filled with detritus shed from the flanking mountains, are common throughout the southwestern United States and northern Mexico. Bolson deposits and geomorphic features record the latest phase in the geologic history of the Basin and Range Province; they reflect tectonic and environmental conditions during much of Tertiary, Pleistocene, and Holocene times.

The Tertiary and Quaternary deposits that fill bolsons constitute the most important source of water throughout most of the western and south-western United States and northern Mexico. Ground water stored in bolson-fill sediments is, in fact, the only water supply available in much of this region. The amounts of ground water that can be extracted from alluvial aquifers and its quality are closely related to the types of sediments and their distribution in a basin. An understanding of these relationships requires, first of all, an appreciation

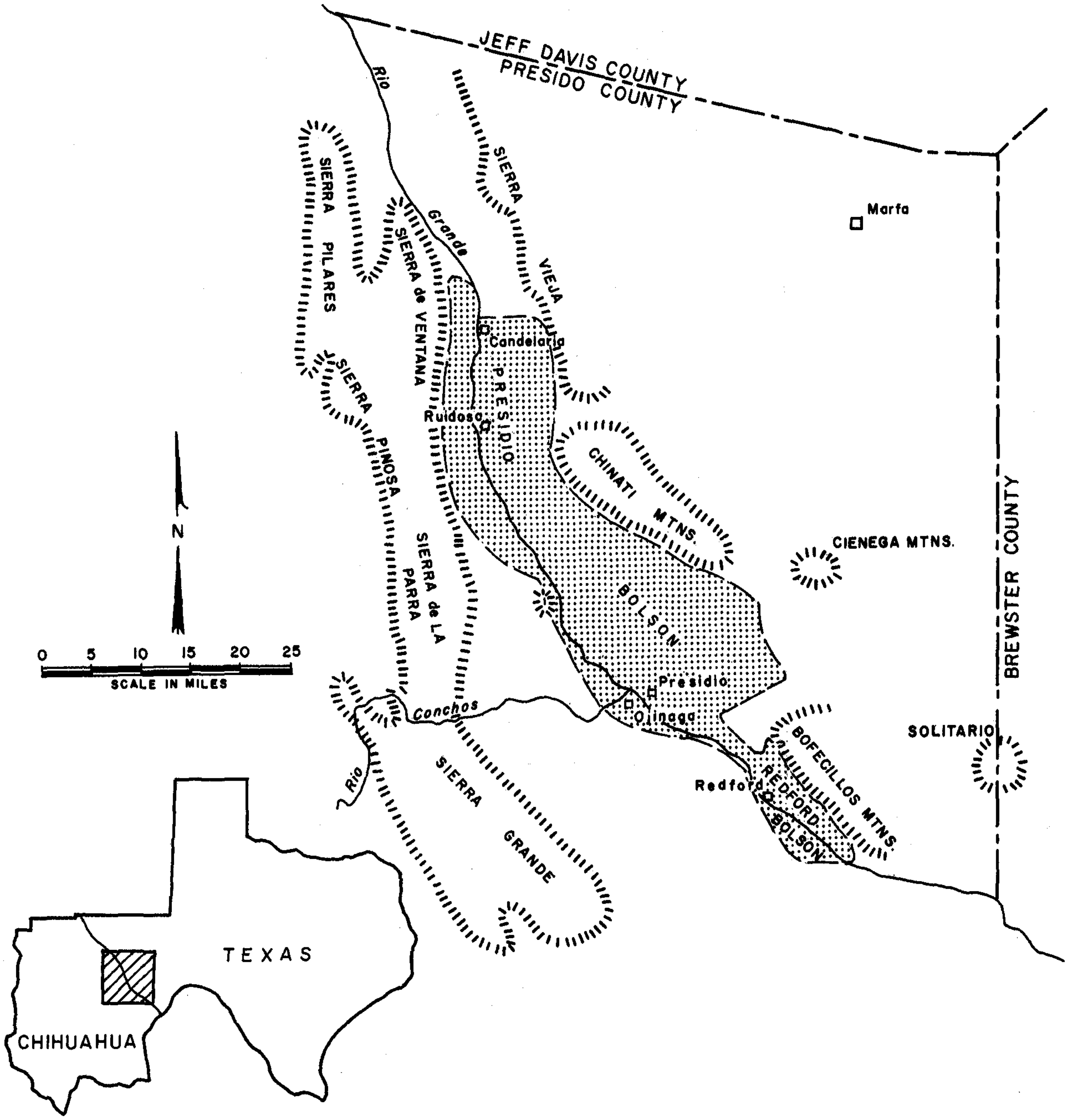

FIG. 1. Map showing location of Presidio Bolson and related features.

of the details of bolson-fill stratigraphy and composition; this is the first step in creating a model that can be used as a ground-water exploration tool in most bolsons. The stratigraphy of bolson deposits is not well known, however, because in most places only the most recently deposited sediments can be studied by direct observation. The dissection of the Presidio Bolson (fig. 1) by the Rio Grande and its tributaries has provided excellent exposures of the deposits that fill the bolson. This setting is opportune for study of the stratigraphy and depositional history of the bolson deposits. It also permits interpretation of the history of the Rio Grande in this area on the basis of the deposits and geomorphic features the river and its tributaries have left as they have excavated the basin.

The depositional and geomorphic environments in bolsons are directly influenced by the adjacent mountains; therefore, it is important that the geology of the mountain blocks be studied to provide data on source areas and tectonic relationships. The mountains flanking the Presidio Bolson either have been or are being mapped.

PREVIOUS WORK

Parry (1857) provided the earliest published descriptions of the geology along the Rio Grande, including observations on the pediment and terrace gravels. Baker's (1927) reconnaissance map of the Trans-Pecos and his discussion of the bolsons along the Rio Grande (pp. 37–40) made a significant contribution to an understanding of the area. DeFord (1964) gave a detailed account of the history of early geologic exploration of the Big Bend and Rio Grande areas.

The number of geologists that have studied in and around the Presidio Bolson during the last two decades is legion. Except for the area south of the Rio Conchos in Mexico, the bolson and bordering mountains have been mapped and described by graduate students and staff members of The University of Texas at Austin. With the exception of Dickerson (1966), who studied the bolson and terrace deposits in the Ruidosa—Hot Springs area, and Zinn (1953), who mapped and described a strip of the bolson deposits near Alamito Creek, those investigators whose areas have included parts of the Presidio Bolson have been primarily concerned with the bedrock geology of the adjacent mountains. Each has described the bolson deposits in general terms, but none has carried out detailed studies of them. General descriptions of bolson deposits are included in Amsbury (1957, 1958), Dietrich (1965, 1966), McKnight (1968, 1970), Haenggi (1966), Gries (1970), Lampert (1953), and the theses of several of R. K. DeFord's graduate students (Buongiorno et al., 1955). The Tertiary formations in the Rim Rock Country at the north end of the bolson have been described by DeFord (1958); volcanic rocks adjacent to the bolson in Mexico were mapped by Heiken (1966).

Studies of other bolsons along the Rio Grande have provided useful information concerning the history of basin filling in the Rio Grande depression and the history of the river itself. Notable among these are the work of Strain (1964) and Albritton and Smith (1965) in the Hueco Bolson south of El Paso; in New Mexico by Ruhe (1962, 1967) and Hawley and Gile (1966) in the Mesilla Bolson near Las Cruces, Wright (1946) in the Rio Puerco area, Denny (1940, 1941) in the Española Valley near Santa Fe and the San Acacia area, Lambert (1968) near Albuquerque, and Bryan (1938) along the Rio Grande depression in Colorado and New Mexico.

TERMS

Definitions of terms as used in this report are presented below. Other terminology is explained in appropriate sections of the report.

Bolson—basin or topographic depression surrounded by mountains. Drainage is toward the center (basinward), terminating either at a central depression or at a through-flowing stream that crosses the basin.

Bolson fill—materials deposited in a bolson during the aggradational phase of its history and before excavation is initiated by integration with a regional degradational drainage system. Aggradational deposits emplaced after drainage integration are not considered in this report as bolson fill.

Mainstream—a through-flowing, regional master stream. In this report, the Rio Grande.

Pediment—broad surface or plain of fluvial erosion; capped by deposits (pediment gravel) of the streams which cut the surface. Pediment is also used informally in this report to include both the erosion surface and the deposits that cap it.

Sidestream—a tributary to the mainstream; most commonly perpendicular to the mountain front and mainstream.

Terrace—relatively flat, narrow fluvial erosional or aggradational surface that approximately parallels the course of the stream that formed it.

ACKNOWLEDGMENTS

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W. L. Fisher read the manuscript and made helpful suggestions. Mrs. Elizabeth Moore typed and Miss Josephine Casey edited the manuscript. Illustrations were prepared by the Bureau cartographic staff under the supervision of James W. Macon.

PHYSIOGRAPHY

GEOLOGIC SETTING

The Presidio Bolson is one of several mountain-bounded basins in the Mexican Highlands section of the Basin and Range physiographic province. The mountain blocks and adjacent basins are the result of normal faulting that occurred in middle and late Tertiary time after most volcanic activity had ceased (McKnight, 1968, p. 126). These high-standing mountain blocks shed great quantities of detritus into the adjacent basins or bolsons, partially filling them and constructing the broad alluvial flats that surround the mountain ranges.

The Presidio Bolson is bordered on the west by the Sierra Pinosa and Sierra de la Parra; these rugged ranges are developed on structurally complex rocks of Cretaceous age (Haenggi, 1966; Gries, 1970). Tertiary volcanic rocks form a small cluster of hills, the Cerros Prietos, in the Sierra de la Parra (Heiken, 1966) and are common on the western margin of the Presidio and Redford Bolsons south of Ojinaga.

The mountains bordering the bolson on the east, in Texas, are massive fault blocks of Tertiary volcanic rocks and Cretaceous and Permian sedimentary rocks. Volcanic rocks occur east of the northern part of the bolson in the Sierra Vieja or Rim Rock Country (DeFord, 1958), in the Chinati Mountains (Rix, 1953; Amsbury, 1957), and the Bofecillos Mountains along the eastern margin of the southern Presidio and Redford Bolsons (McKnight, 1968; Dietrich, 1966). Cretaceous and Permian sedimentary rocks crop out in large areas in the Pinto Canyon area (Amsbury, 1957) and around Shafter (Dietrich, 1966; Rix, 1953).

The Cretaceous rocks were deposited along the eastern margin of and in the Chihuahua trough, a Mesozoic depositional basin. These clastic and carbonate rocks were intensely deformed during the Laramide orogeny (Haenggi, 1966, p. 137). The Tertiary block faulting that formed the basins was followed by basin filling and subsequent dissection by a regionally integrated drainage system; this post-block-faulting history is the subject of this report.

DRAINAGE

The Presidio Bolson is within a broad regional drainage system that has the Rio Grande as a master stream. From its headwaters in the San Juan Mountains of Colorado, the Rio Grande flows across a series of mountain blocks and desert basins before it enters the limestone plateaus and, finally, the Gulf Coastal Plain. A large part of the drainage system is in Mexico; in fact, perennial flow of the Rio Grande below Presidio is maintained by the Rio Conchos which heads in the Sierra Madre Occidental; above this confluence the Rio Grande is an intermittent stream.

The tributary pattern in the Presidio Bolson is similar to that in other basins crossed by the Rio Grande. Tributaries (sidestreams in this report) head in the bolson fill and in the bordering mountains; they join the Rio Grande at nearly right angles (Pl. I, in pocket). The larger sidestreams, such as Alamito, Cibolo, San Antonio, Pinto, Hot Springs, and Sandiguela Creeks, drain large areas in the adjacent mountains and surrounding areas outside the basin. These large sidestreams have produced the most striking landforms in the bolson; in fact, the sidestreams have been the dominant agents in excavating the bolson-fill sediments. The Rio Grande has cut terraces at various levels near the basin axis, but the main influence of the mainstream has been as a lowering base level for the sidestreams.

Except for flow from small springs, notably in Alamito, Hot Springs, and "Boundary" Creeks, flow in the sidestreams occurs only in direct response to rainfall. Runoff from the infrequent but intense storms is nearly instantaneous, and the resulting flow in the sidestreams is sudden and short-lived. Peak discharge occurs soon after the storm begins, and the streams are commonly only a trickle within an hour or two.

CLIMATE

Dietrich (1966, pp. 14–23) treated the climate of the Presidio area in some detail; the climatic data presented here are summarized from his report and are based on records covering 1931–1960.

Presidio has a hot desert climate (BWh in the Koeppen system). The mean annual temperature is 69.5° F., mean January temperature is 49.8° F., and mean July temperature is 86.5° F. A maximum of 117° F. has been reported, and temperatures in excess of 100° are very common from May through September. Winters are cool, but freezing temperatures are rare during the daylight hours.

The average annual rainfall is 8.31 inches; most precipitation occurs during the months May through October. Rainfall during the summer months occurs most often as brief, intense storms.

STRATIGRAPHY

GENERAL REMARKS

The rocks that crop out in the Presidio Bolson are separated into two groups on the basis of distinct differences in texture, geometry, and volume. The first group comprises the largest volume of rock in the basin; it consists of brown, orange-brown, and pink sedimentary rocks that grade from conglomerate near the bordering mountains to mudstone near the basin center. The second group of deposits unconformably overlies the first group and consists of sidestream-pediment, terrace, and alluvial-fan materials, interbedded in some places near the axis of the basin with Rio Grande gravels. They cap the broad surfaces that are so conspicuous throughout the Presidio Bolson.

The two groups record two genetically different phases in the history of the Presidio Bolson. Rocks of the first group, the bolson fill, accumulated as the structural basin filled with sediments shed from the surrounding mountains and probably in part with sediments transported into the basin from areas to the northwest. Deposits of the second group, the gravel sheets and fans, record the more recent erosional phase during which bolson fill has been planed, dissected, and in part removed by sidestreams graded to a through-flowing Rio Grande. These sediments are the excavation-phase deposits of this report.

BOLSON FILL

About 1,000 feet of bolson fill crops out; the most complete and easily accessible exposures occur along the banks of the numerous incised sidestreams. These cuts provide near-vertical faces that range from 3 feet to nearly 100 feet in height with 5- to 50-foot-high exposures most common. Although the bolson fill also crops out in badland areas and in scattered rounded hills, these exposures are not suitable for detailed study because rainwash and alternating wetting and drying have produced a 1- to 6-inch-thick structureless crust that masks stratigraphic detail. In addition, gravel washed from overlying pediment and terrace deposits mantles parts of the bolson fill in these areas; throughout most of the basin bolson deposits are covered by a lag gravel from a few inches to a few feet thick.

Although the total exposed thickness of bolson fill is approximately 1,000 feet, continuous vertical and horizontal sections are limited because exposures occur chiefly along sidestreams. The gradients of these sidestreams range from 60 to 150 feet per mile, and the slopes of the erosion-surface remnants standing 5 to 100 feet above the stream channels are similar or greater. Thus, in moving up a sidestream from near the Rio Grande toward the mountains, one moves steadily up section. Laterally equivalent rocks cannot be observed because they lie beneath the level of the stream bed in the direction of the mountains and have been eroded in the direction of the basin center. This makes detailed reconstruction of lateral, roughly time-equivalent facies tracts impossible. The facies boundaries on the geologic map (Pl. I) are drawn on the basis of observed changes in rock texture, and the rocks bounded by one map-boundary line are not laterally equivalent to those bounded by another map-boundary line.

The total thickness of the bolson fill is unknown; wells that have penetrated the fill are scarce, and the logs of those that have are so vague that it is impossible to pick the base of the fill. The most reliable information on thickness was reported by Davis and Leggat (1965, p. U82); they mentioned a well near Presidio that penetrated clay from 68 to 1,320 feet, where sand was encountered. This, at least, gives a minimum thickness of the fill at that locality, but unfortunately the well did not continue to the base of the fill.

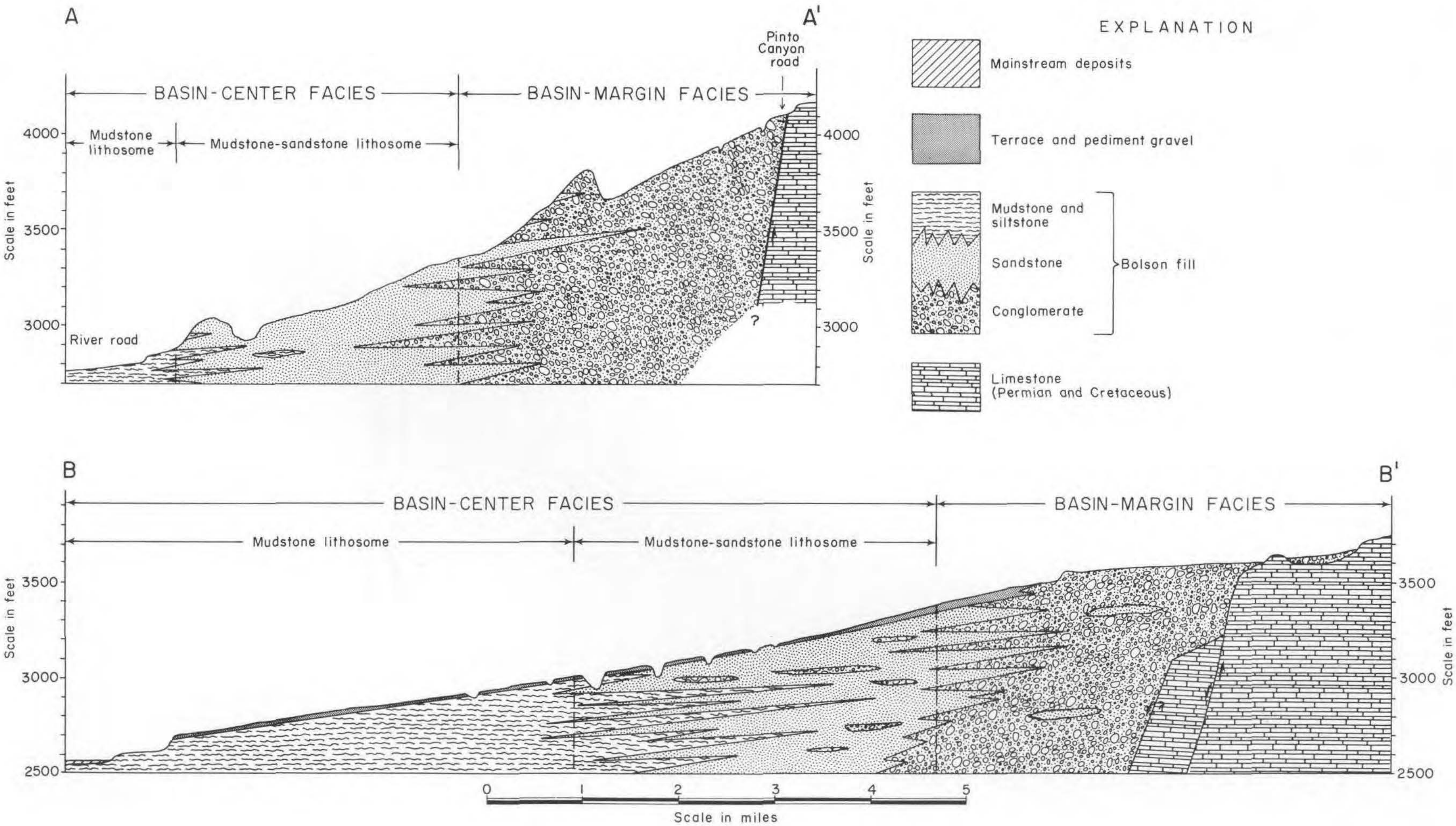


FIG. 2. Cross sections through the Presidio Bolson. Faults not shown. *See* Plate I for section locations.

FACIES DESIGNATIONS

Previous workers in the Presidio Bolson have recognized the gradation of rock types in the bolson fill from conglomerate near the mountains to mudstone near the basin center. Zinn (1953, p. 26) observed the lateral gradation of sediment types and applied the term "facies" to different lithologic units in the southern part of the Presidio Bolson. Amsbury (1957, p. 102) and Dietrich (1965, p. 152) recognized the variations but did not map them. Haenggi (1966, p. 125), working in Mexico near the northern end of the bolson, mapped a gravel-conglomerate facies and a sandstone-siltstone-claystone facies that grade into each other laterally and vertically. Dickerson (1966, pp. 18, 19), working in the Hot Springs area, described three facies—clay, sandstone, and conglomerate—separated by transition zones where the facies interfinger. McKnight (1968, p. 111) described the bolson fill in the Redford Bolson but did not map separate facies.

Although the pattern of conglomerate nearest the mountains grading through sandstone into claystone near the basin center is persistent, the zones in which these rock types interfinger are commonly broad, and with the exception of the claystone or mudstone, no rock type is exclusively present in any large area. Thus, it is not possible simply to designate facies, such as "sandstone facies" or "conglomerate facies," and map areas containing only sandstone or conglomerate because these rock types are not exclusively present over significant areas.

Facies boundaries are drawn on the basis of features observable at the outcrop. The boundaries are valid only for the exposed part of the bolson fill because available subsurface information is far too sparse to permit interpolation; thus, the boundaries and interpretations based on facies distributions are subject to the limitations posed by outcrop distribution. Figure 2 illustrates common stratigraphic relationships in the bolson and the application of the terminology used in this report.

The facies and lithosomes are defined on the basis of quantitative and semiquantitative field studies of nearly all available areas of outcrop. Each outcrop visited was described and either the section was measured or an estimation was made of the percent of each rock type present. Five textural groups were defined that reflect the most common and widespread lithologic associations. The five textural groups or lithosomes were combined into two facies, each of which was given an informal name reflecting the position in the basin where it crops out most extensively: basin-margin facies and basin-center facies.

BASIN-MARGIN FACIES

DEFINITION AND OCCURRENCE

The basin-margin facies is that part of the bolson fill consisting chiefly of interbedded conglomerate and sandstone, where conglomerate is more than 10 percent and mudstone less than 10 percent of the exposed rock. The sandstone-conglomerate lithosome is the only lithosome in the basin-margin facies, hence the two names are used interchangeably.

Rocks of this facies crop out along the flanks of the bordering mountains and extend into the basin from less than 1 mile to nearly 3 miles. There are excellent exposures near the mountains in the canyons of the major sidestreams, notably Alamito, Cibolo, Spencer, Pinto, Hot Springs, and Sandiguela Creeks (Pl. I). The road to the Gonzalez ranch and the Pinto Canyon road (Pl. I) afford easy access to exposures of the basin-margin facies. There are also good exposures in Mexico west of the river road in the area north of San Antonio.

There are areas in the relatively narrow Redford Bolson where the basin-margin facies occupies the entire width of the bolson. There are also places in the Redford Bolson and in Mexico where this facies is not present adjacent to the mountains; in these places the basin-center facies extends from the axis of the basin up to the mountains.

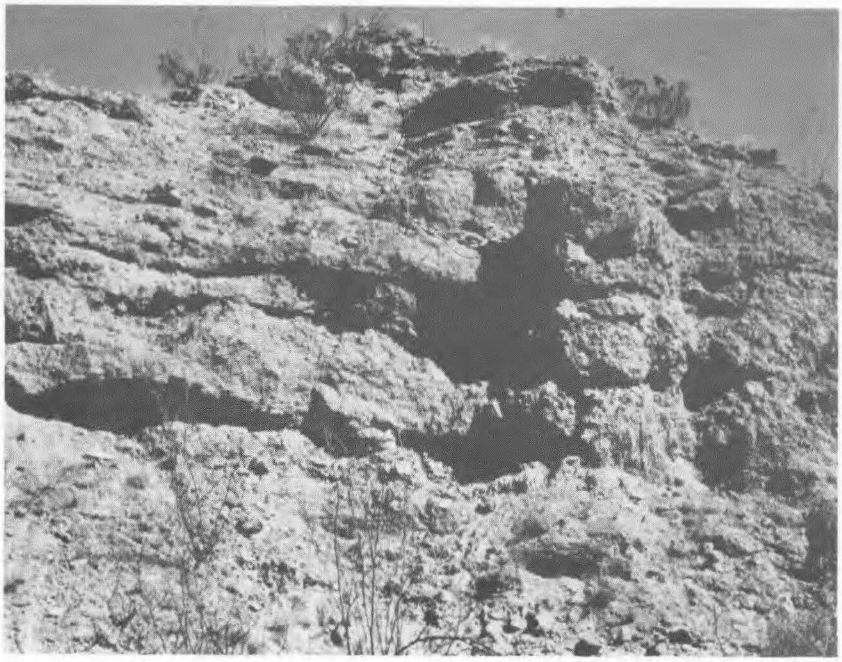
DESCRIPTION

The general makeup of rock types in the basin-margin facies is sandy conglomerate, with subordinate amounts of conglomeratic sandstone, nearest the mountain front, grading to sandstone and slightly pebbly sandstone with minor interbedded small- and medium-pebble conglomerate toward the basin center (figs. 3 and 4). Variations are present, but the conglomerate and sandstone are characterized by:

(1) Gradation and irregular variation in texture between conglomerate and sandstone, especially near the bordering mountains.

(2) Lack of distinct bedding and sedimentary structures near the basin margin.

(3) Poor sorting in general and within each of the textural classes (gravel, sand, mud).



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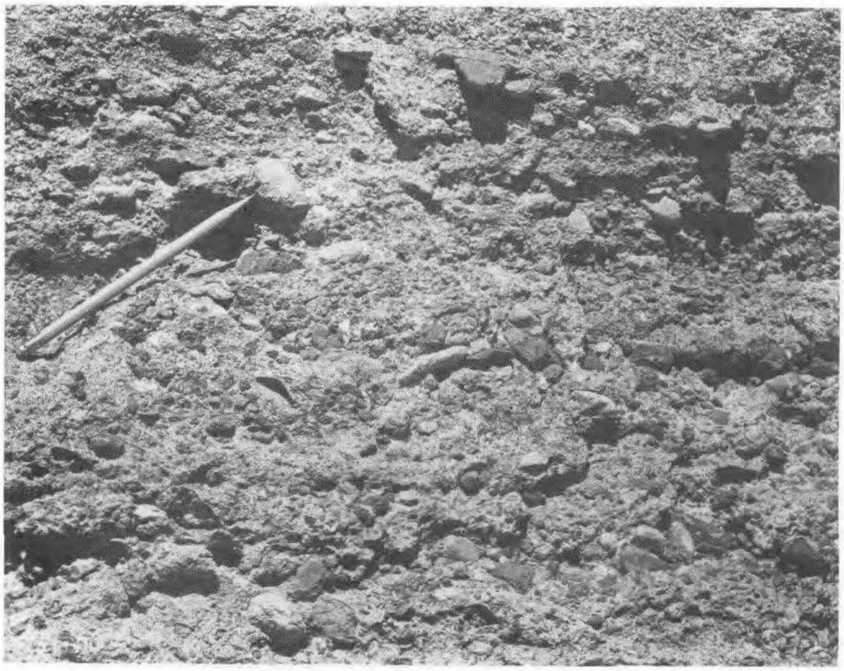

B

FIG. 3. Basin-margin conglomerate and sandstone near the edge of the Redford Bolson along Bofecillos Creek. A, Typical outcrop. B, Closeup of the conglomerate.

(4) Dominance of a small- to medium-pebble mode in the conglomerate, even near the mountains, with a general decrease in mean and largest grain size toward the basin center.

(5) Gravel clasts of local origin: The gravel clasts are all derived from rocks that crop out in

the adjacent mountains and are lithologically the same as gravel being transported from these mountains by modern streams (fig. 5).

(6) Pink color when viewed from a distance and various shades of pink, brown, orange brown, and gray in hand specimen.

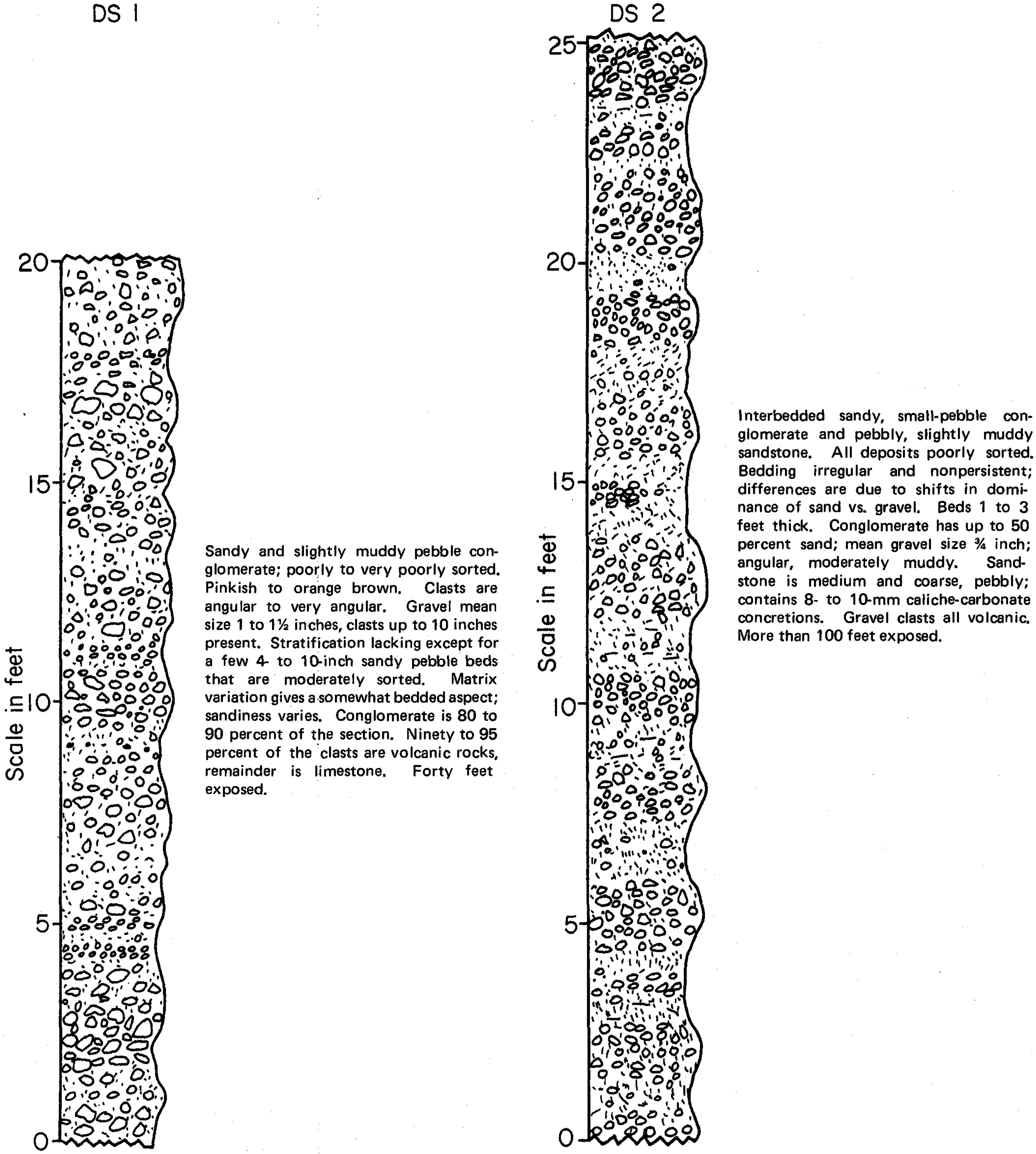

FIG. 4. Representative columnar sections of basin-margin deposits. DS 1 is characteristic of deposits near the mountains where conglomerate dominates the section. DS 2 is typical of most of the basinward two-thirds of the basin-margin facies where sandstone comprises as much as 50 percent of the section. *See* figure 5 for location of sections.

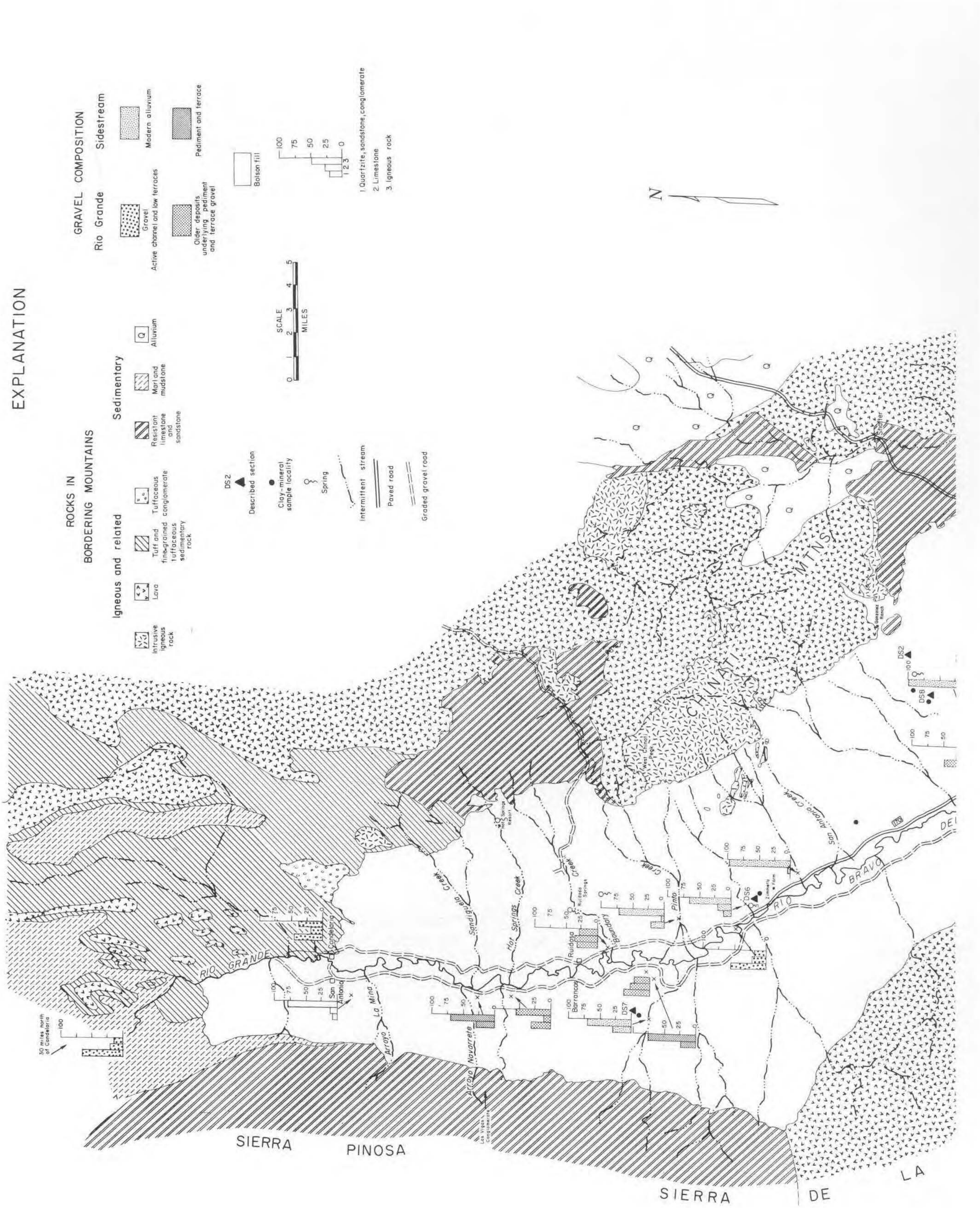
EXPLANATION
ROCKS IN BORDERING MOUNTAINS
Igneous and related
Intrusive igneous rock
Lava
Tuff and fine-grained tuffaceous sedimentary rock
Tuffaceous conglomerate
Sedimentary
Resistant limestone and sandstone
Marl and mudstone
Q Alluvium
GRAVEL COMPOSITION
Rio Grande
Gravel Active channel and low terraces
Older deposits underlying pediment and terrace gravel
Sidestream
Modern alluvium
Pediment and terrace
Bolson fill
1. Quartzite, sandstone, conglomerate
2. Limestone
3. Igneous rock
DS2 Described section
Clay-mineral sample locality
Spring
Intermittent stream
Paved road
Graded gravel road
SCALE
MILES
N
RIO GRANDE
RIO BRAVO DEL
SIERRA PINOSA
SIERRA DE LA
CHINATI MTNS
Candelaria
San Antonio
Ruidosa
Barrancos
Shafter
Arroyo La Mina
Arroyo Navarrete
Sandiguela Creek
Hot Springs Creek
Boundary Creek
Pinto Creek
San Antonio Creek
DS6
DS7
DS8
DS2
30 miles north of Candelaria

FIG. 5. Pebble counts, sample and section locations, and springs in the Presidio Bolson. Geology of the mountain areas generalized from Amsbury (1958), Buongiorno et al. (1955), Dietrich (1966), Gries (1970), Haenggi (1966), McKnight (1970), and Rix (1953).

(7) A rolling, hilly topography with a coarse drainage texture.

The conglomerate of the basin-margin facies is without exception sandy, and the sandstone, especially near the bordering mountains, is nearly all at least slightly conglomeratic; both conglomerate and sandstone commonly contain 2 to 30 percent mud. The sorting of the whole rock is necessarily poor, therefore, and the sorting within each of the textural classes is likewise poor. Better sorted, more texturally mature conglomerate is present but is much less abundant than the very sandy, commonly muddy conglomerates.

Near the basin margins, textural boundaries between sandstone and conglomerate are gradational and irregular; they can best be described in terms of gradational modal shifts rather than as the interbedding of distinct textural types. In addition to gradational relationships, most sandstone beds contain lenses and stringers of more conglomeratic material and vice versa. The lack of distinct bedding in these areas is due to gradational rather than sharp boundaries between textural types.

Bedding, obscure or absent near the basin margin, becomes more distinct toward the basin center as pebbles decrease and some mudstone is interbedded with sandy pebble conglomerate. The "cleaner" sandstone in these areas contains some trough and foreset cross-stratification, although sedimentary structures are not common in any part of the basin-margin facies. The only sedimentary structures noted are crude trough and foreset crossbeds associated with channels.

The most abundant gravel clasts in the basin-margin conglomerate, even near the bordering mountains, are small, medium, and large pebbles. Cobbles and small boulders are present in some parts of the fill adjacent to the mountains, but the mode and median gravel size are in the pebble-size class. Away from the mountains toward the basin center, the amount and size of material coarser than small to medium pebbles decrease and sandiness increases. The thickness and distinctiveness of the interbedded sandstone also increase as the median size of gravel clasts decreases.

Pebble lithologies were noted at more than 50 localities in the conglomerate and conglomeratic sandstone of the basin-margin facies, and all rock types were from the bordering mountains (fig. 5). The generalized groupings of rock types presented on figure 5 show the relation of gravel-clast lithology to source area, but it is best demonstrated where distinctive rock types are present. The riebeckite rhyolite in the bolson-fill, terrace, and modern gravels in and along Alamito Creek is from the outcrop of this rock in the Cienega Mountains (fig. 1). The same relationship is present near Pinto Creek where the distinctive Brite Ignimbrite is a constituent of bolson conglomerate and modern sidestream gravel.

An overall pinkish hue is characteristic of the bolson fill as a whole; individual beds, however, exhibit a range of colors including green, gold, brown, orange, tan, gray, and various shades and combinations of these. The conglomerate and sandstone are likewise characterized by a pink hue with orange brown, pink, and gray dominant. The pink and orange-brown color is directly related to the presence of mud in the matrix; when mud is less than about 1 percent of the rock the rock color is generally gray. The pink or orange-brown color is associated with very fine silt and clay grains and aggregates of these, or as hematite (?) coatings on these grains. The hematite (?) dissolves in cold, dilute hydrochloric acid; HC1 also breaks down aggregates of the grains, suggesting that some hematite (?) is associated with the calcium carbonate cement.

Most conglomerate and sandstone are well indurated; muddy sand matrix and calcite, in varying proportions, are the binding agents. Conglomerate beds are more resistant than interbedded sandstone, especially in areas where mud, rather than calcite, is the binder. Calcite cement is most common in all rock types in the Hot Springs and Pinto Canyon areas where deep, narrow canyons have been cut into the resistant conglomerate and sandstone. Calcite cement is also more common where limestone clasts are present in the conglomerate.

Most first-cycle gravel clasts in the bolson fill are subangular to angular, especially those in the modal pebble class. Exceptions are scattered subround to round tuff and limestone pebbles and small cobbles. The proximity of most bolson-fill conglomerate to the mountain blocks from which it was derived, dictates a short transport distance which precludes rounding of any but the least resistant of clasts.

The conglomerate and sandstone of the basin-margin facies lap onto the bedrock of the adjacent mountains; in places they are in fault contact. The contact is not exposed over large areas except along Bofecillos Creek in the Redford Bolson. Where both types of contact are present in one area, faulting contemporaneous with deposition of the fill is indicated.

The bolson fill adjacent to the bordering mountains is not everywhere conglomerate. Where the large unnamed wash enters the Redford Bolson from the Bofecillos Mountains about 1.2 miles south of Buzzard Creek (Pl. I), sandstone, mudstone, and minor sandy small-pebble conglomerate are in fault contact with volcanic rock. Mudstone, or mudstone interbedded with sandstone adjacent to the bordering mountain blocks, is not widespread, but it has been reported by Strain (1964, p. 28) in the Hueco Bolson. In tectonically active areas of modern bolsons, such as Death Valley and Panamint Valley, California, muds are being deposited against mountain blocks. As faulting occurs along one side of a valley or graben, the raised borderland sheds increased amounts of detritus, forcing the locus of deposition of fine-grained sediments against the opposite valley side.

ENVIRONMENT OF DEPOSITION

The following characteristics of the conglomerate and sandstone of the basin-margin facies indicate that they are alluvial-fan deposits:

(1) Location along the basin margin adjacent to mountain blocks.

(2) Gravel clasts derived from the adjacent mountains.

(3) Dominance of sandy conglomerate and conglomeratic sandstone, poor sorting, indistinct and irregular bedding, irregular and rapid textural changes, crude scours, and lack of any sedimentary structures except scattered trough cross-beds and crude foresets.

These characteristics are shared by sand and gravel on modern alluvial fans throughout the Mojave Desert of California. Denny (1940, p. 687) described similar deposits in the Santa Fe Formation in the Española Valley, New Mexico; he ascribed them to alluvial-fan origin for many of the same reasons outlined above. Alluvial-fan deposits described by Blissenbach (1954) and Bull (1963), among others, are also similar to the conglomerate and sandstone of the basin-margin facies. Lawson (1913) designated similar deposits he observed on active alluvial fans "fanglomerates," a term applicable to the conglomerate of the bolson fill.

BASIN-CENTER FACIES

DEFINITION AND OCCURRENCE

The conglomerate and sandstone of the basin-margin facies grade laterally into interbedded sandstone and mudstone, and in some areas to mudstone, toward the basin center. This comparatively fine-grained part of the bolson fill is the basin-center facies; the boundary is drawn where conglomerate is less than 10 percent of the section. The basin-center facies is subdivided into a mudstone-sandstone lithosome and a mudstone lithosome. The mudstone lithosome includes all basin-fill deposits in which conglomerate plus sandstone is less than 10 percent.

Rocks of the basin-center facies crop out over a much larger area than rocks of the basin-margin facies (Pl. I). Exposures are numerous along the many washes tributary to the Rio Grande; there are also many badland areas where exposure is widespread, but detail is obscured by slopewash and a mud-cracked crust. The "pinkish" deposits clearly visible north of Farm Road 170 between Cibolo Creek and Pinto Creek, and west of the Rio Grande in Mexico between Vado de Piedra and Barrancos, are mudstone, with some interbedded sandstone, of the basin-center facies.

MUDSTONE-SANDSTONE LITHOSOME

The zone of lateral gradation between conglomerate and sandstone of the basin-margin facies and interbedded mudstone and sandstone of the basin-center facies is a few hundred yards to nearly a mile wide (fig. 6). In this zone conglomerate decreases in abundance, becoming very sandy and thin bedded; it is succeeded by small pebbly and granular sandstone in the marginal areas of the basin-center facies. Farther toward the basin center, mudstone beds are more common, and sandstone beds are gravel-free, better sorted, and finer grained. Except for some areas in the Redford Bolson, the mudstone-sandstone lithosome does not contain interbedded conglomerate on the basin-center side of the transition zone.

Brown to dark orange-brown mudstone and light brown to buff siltstone are the dominant rock types throughout this lithosome; sandstone generally makes up only about 20 to 40 percent of the section except near the northern end of the bolson where it is 40 to 70 percent of the basin-center facies. There is no consistent texture or pattern of textural variation in the mudstone, siltstone, and sandstone units. They range from massive, slightly sandy, poorly sorted mudstone to thin-bedded interbeds of moderately well-sorted silt, mud, and fine sand. The siltstone most commonly displays horizontal laminae and ripple cross laminae, but structureless beds are present. Mudstone and siltstone beds

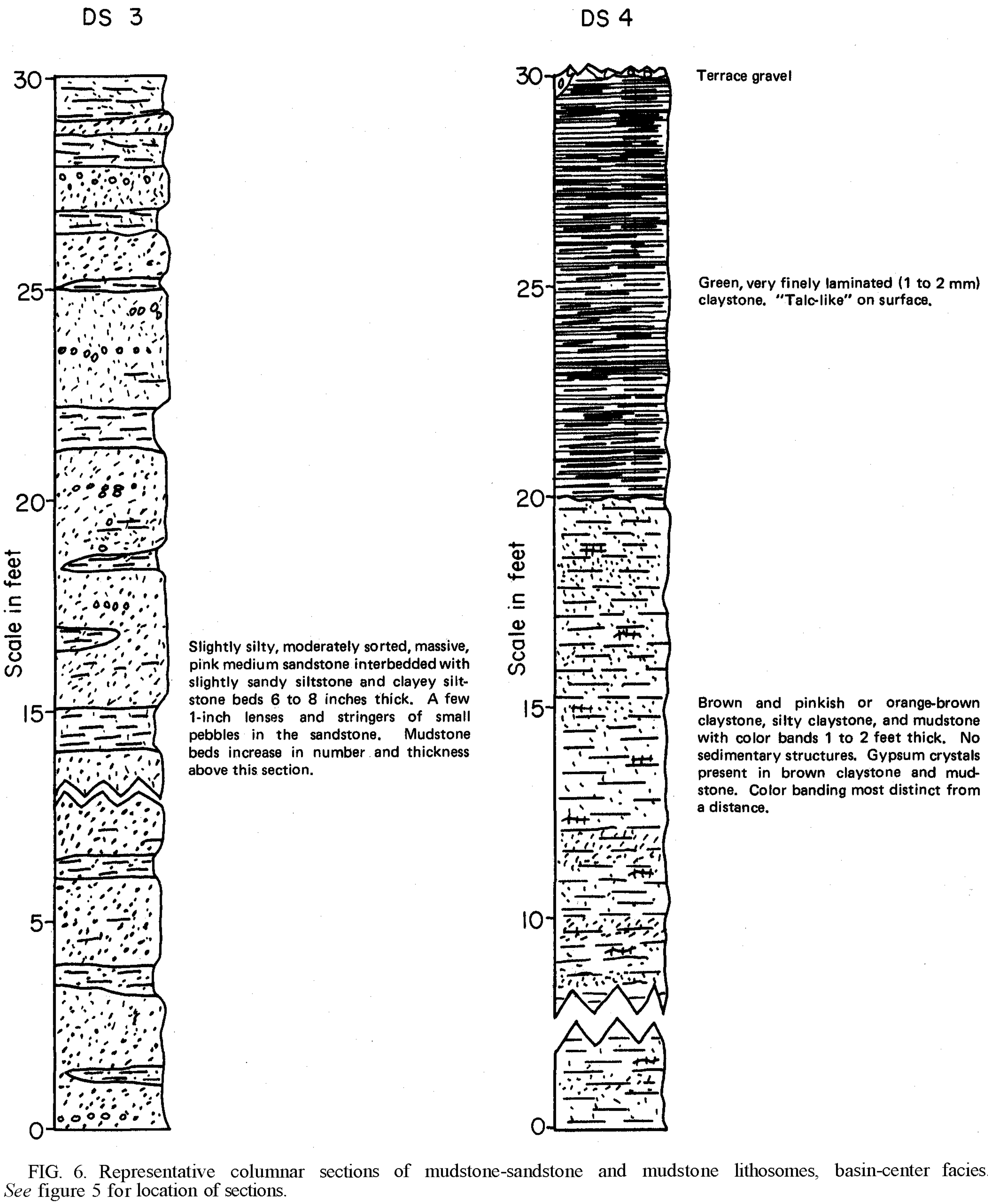

FIG. 6. Representative columnar sections of mudstone-sandstone and mudstone lithosomes, basin-center facies. *See* figure 5 for location of sections.

FIG. 7. Rocks of mudstone-sandstone lithosome. Section exposed west of river road along Sandiguela Creek.

range from a few inches to nearly 15 feet thick; many of the more massive beds are texturally complex, containing thin, irregular interbeds of claystone, mudstone, and siltstone, whereas some are structureless orange-brown mudstone. The lateral continuity of individual beds is highly variable; some can be traced only a few feet whereas others can be followed for several hundred yards.

The interbedded sandstone of the mudstone-sandstone lithosome is lighter colored, generally tan to buff, than the mudstone. Sandstone beds are 1 inch to 4 feet thick and are distinct because they are more resistant to erosion than the mudstone. Most beds, as with the mudstone and siltstone, are a few inches to a foot or two thick. Near the boundary between this lithosome and the basin-margin facies, sandstone is medium to coarse, granular, and muddy; however, toward the basin center it is fine and moderately well sorted. The beds are commonly broad lenses with horizontal laminae, trough and foreset cross-stratification, and ripples. The stratification types and sequences of types indicate small-scale braids with shallow channel-fills and thin barlike units in the sandstone and much of the siltstone, interbedded with the more blanket-like structureless or laminated mudstones (fig. 7). This pattern is similar to that in deposits at the nearly flat toes of modern alluvial fans where they merge with mud-floored playas or barrials.

Gypsum is common in the mudstone as disseminated crystals, thin beds and lenses of crystals, and as veins. Gypsum also cements some of the sandstone beds, although others are carbonate cemented and many are friable. Calcium carbonate is present in some of the mudstone and sandstone as irregular nodules. The occurrence of gypsum and calcium carbonate is discussed in detail in separate following sections.

Northern sections.—In the southern two-thirds of the bolson the mudstone-sandstone lithosome is a poorly developed, comparatively imprecise map unit. In the northern third of the bolson, however, the lithosome is well developed and makes up the best exposures in the bolson fill (fig. 8).

In the northeastern part of the bolson, from near Pinto Creek northward to the vicinity of Sandiguela Creek, the outcrop characteristic of the interbedded mudstone and sandstone changes. In other areas, pediments and terraces developed on the poorly indurated mudstone and sandstone dominate the landscape, and bolson fill is exposed only in valley walls. In the northern part of the bolson, cementation of the siltstone and sandstone is more complete and a bench and slope topography is developed. The cementation and resulting more delicate differential weathering have emphasized stratigraphic detail and show that sandstone, siltstone, and mudstone are complexly interbedded and contain ripple cross

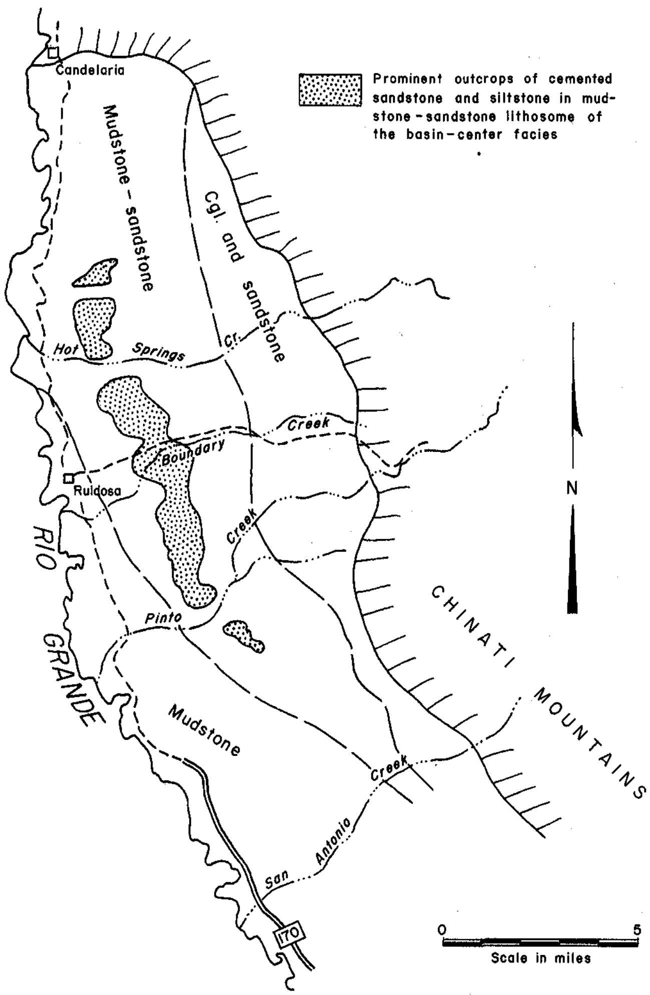

FIG. 8. Map of northern part of Presidio Bolson where mudstone-sandstone lithosome is well developed and sandstone is abundant. Well-cemented portions contain limestone and/or tufa.

laminae and horizontal laminae. Whether the pattern of textural variation and structures is a unique characteristic of this area or whether it is present in other parts of the mudstone-sandstone lithosome, but obscured by weathering and lack of cementation, is not known.

Horizontal laminae and small-scale ripple cross laminae are common throughout this area. The laminae are delicate and relatively persistent. Except for a few very thin granular medium and coarse sand lenses, the sand is fine and moderately well to well sorted; siltstones are similarly well sorted. Mudstone is present, but commonly the textural end members, silt and clay, have been deposited as distinct beds and laminae. These textural properties and sedimentary structures indicate that most of the sediments in this well-cemented part of the mudstone-sandstone lithosome were deposited from suspension in standing water and by gentle currents.

Two lithologic types not found elsewhere in the bolson are present in this area—beds of white, massive chalcedony 10 to 18 inches thick and very light gray, laminated, sandy limestone (fig. 9). Many seeps in the area are presently depositing calcareous and siliceous material on rock surfaces. The springs coincide (1) with the zone of interfingering of the basin-margin facies with rocks of the mudstone-sandstone lithosome and (2) with a series of faults. Thus, it is difficult to determine if the chalcedony and limestone were deposited as part of the original sequence or formed as secondary mineralization. If the mineralized ground water was not introduced along post-depositional faults, then the water was present in the subsurface or at the surface during deposition of the mud and sand; if post-depositional faulting brought mineralized water to the area, the interbeds and cement of siliceous and calcareous material are epigenetic. The intricate and fine horizontal laminations in the mudstone and algaelike strands in the limestone suggest that a body of water was probably present; ground-water discharge is a possible mechanism for maintaining it. The dominance of calcareous material and the presence of floating sand grains in many of the limestone beds further suggest that the carbonate is primary. Thus, this area may have contained a permanent or semipermanent shallow lake located at the margin of the broad basin floor; if spring-fed, this lake could have existed at the same time that another part of the basin was occupied by ephemeral or playa lakes.

Near the northern margin of the bolson, in Texas and in Mexico, sandstone and siltstone are more abundant than mudstone; broad, shallow sand and silt-filled channels covered by more extensive mudstone units are characteristic (fig. 7). This sandy portion of the basin-margin facies is well exposed in the bluffs along both sides of the Rio Grande north of Hot Springs Creek. Sandiness increases to the north, and conglomerate of the basin-margin facies borders much of the bolson in Mexico, where gravel-producing limestone and sandstone crop out in the bordering mountains (fig. 5). The northern margin of the bolson in Texas is bordered by less resistant tuffaceous volcanic rocks, and sandstone, with some interbedded conglomerate, persists nearly to the basin edge.

The abundance of sand and silt in the northern part of the bolson may reflect a major influx of

FIG. 9. Limestone interbedded with siltstone and sandstone near Ruidosa Springs.

sediments from the broad areas of weak Tertiary tuff and tuffaceous sedimentary rocks that crop out over much of the Rim Rock Country north of the bolson (Pl. I). There is no evidence that an ancestral stream of the size and extent of the modern Rio Grande entered the bolson in this northern area. Channel gravels and clasts of rock types derived from areas beyond the bordering mountains are present only in deposits that can be definitely related to the more recent excavational phase of bolson history. It is possible, however, that a relatively large drainage system, heading in the Rim Rock Country, introduced much of the mudstone and sandstone in this northern area. Directional features in the bolson fill are not consistent but do indicate a generally south, southeast, and southwest direction of transport.

In this northern area and in other parts of the bolson, sandstone beds decrease in number and thickness toward the basin center. The sand becomes finer until, over large areas, siltstone is the coarsest material present in the fill.

MUDSTONE LITHOSOME

The mudstone lithosome includes all bolson-fill sedimentary rock that contains less than 10 percent sandstone plus conglomerate; it crops out basinward of and is gradational to the mudstone and sandstone lithosome (Pl. I). The mudstone, claystone, and siltstone of this lithosome are moderately well exposed in steep banks along streams and poorly exposed beneath the gravel lag covering low, rounded hills near the bolson axis (figs. 10 and 11).

All textural variations and combinations of clay and silt, including sandy mud, were grouped together as mudstone in designating the lithosome. Most sediment in the mudstone lithosome is texturally a mudstone as Folk (1964, p. 27) used the term, but much is siltstone and some is claystone. These textural types are all interbedded throughout the section along with minor amounts of fine to very fine sandstone.

From a distance, outcrops of mudstone display an overall brown to orange-brown color with banding of various shades of these colors and, in places, green. These bands reflect bedding or textural variations that commonly become less distinct closeup. Green mudstone and claystone constitute a conspicuous, although volumetrically minor, part of the section. The green color bands are commonly traceable over considerable distance, nearly a mile in one area. These persistent bands seem to follow a particular bed, but it is extremely difficult to keep exact track of a particular bed over more than a few hundred feet due to intervening encrusted and covered intervals. In other places, the green coloration is mottled with brown within a unit in a "marble cake" fashion or is present as lenses.

Beds range in thickness from less than 1 inch to

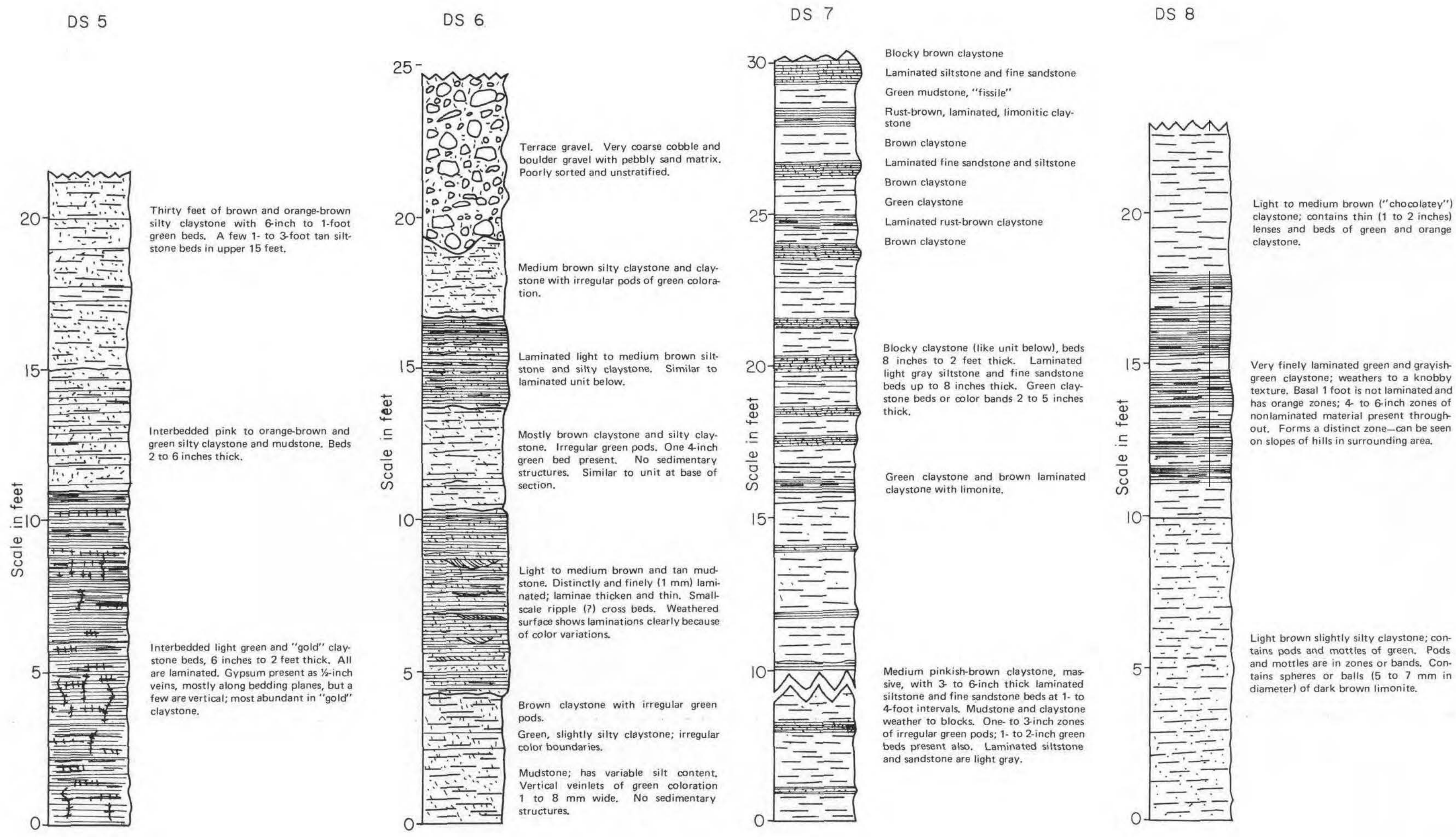

FIG. 10. Representative columnar sections of mudstone lithosome, basin-center facies. *See* figure 5 for location of sections.

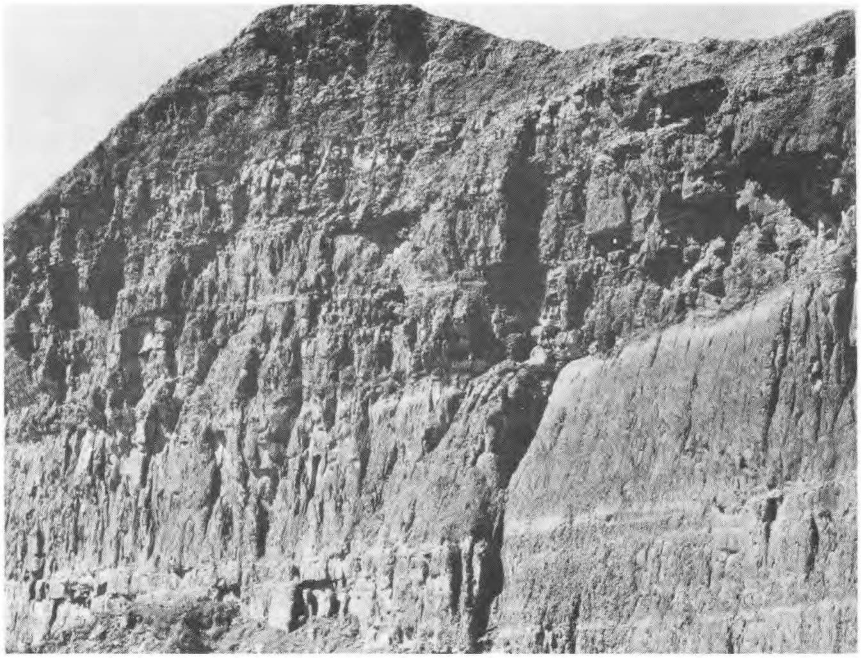

FIG. 11. Mudstone and siltstone of mudstone lithosome, basin-center facies; 14 feet exposed. Located in Mexico, 5 miles southeast of Barrancos.

nearly 5 feet. The more massive beds are generally mudstone that varies in texture and lacks sedimentary structures. Claystone and siltstone beds are most commonly 1 inch to 3 feet thick. These rocks, especially the siltstone, display the most distinctive colors; most siltstone is tan or buff whereas the claystone is medium brown or "chocolate brown." The various shadings of brown, orange brown, and pink are most characteristic of the mudstone beds. Lateral persistence of individual beds is highly variable, but in general it ranges from a few to a few hundred feet.

Ostracods, the only fossil material collected from the bolson fill, were found in green mudstone. The valves are of the plain, unornamented "jellybean" type. Positive identification was not made, but P. U. Rodda (personal communication, 1968) suggested that they resemble modern species that are very common in standing-water bodies ranging in size from puddles to lakes.

Gypsum occurs throughout the basin-center facies but is most common in the mudstone lithosome. It occurs in several forms or modes and is discussed in a separate section. Calcium carbonate nodules and powder, similar to that in the mudstone-sandstone lithosome, are present in some mudstone and sandy mudstone beds.

SEDIMENTARY STRUCTURES

Sedimentary structures are common in rocks of the basin-center facies; however, they are not easily discerned in all exposures. Horizontal laminae are most common in mudstone, siltstone, and fine sandstone; ripple cross laminations are present in much siltstone and fine sandstone. The scale of these structures is small; laminae range in thickness from less than 1 mm to 5 mm and ripple cross laminae are most commonly less than 1 inch thick. Where interbedded mudstone and siltstone comprise the section, as throughout most of the basin-center facies, the mudstones are either structureless or laminated and the siltstones contain horizontal laminae and ripple cross laminae.

In the northern portion of the basin-center facies where fine to medium sandstone dominates the section, the generally larger scale structures include trough cross-stratification and foreset cross-stratification as well as horizontal laminae. Good exposures of these occur along the lowermost reaches of Sandiguela Creek in Texas and in the high vertical bluffs just across the river in Mexico (Pl. I). Figure 7 shows the relationships. Troughs range from 2 to 6 inches in depth and are from 1 to 2.5 feet wide. Braided channel sequences are indicated by trough cross-stratification and by foreset cross-stratification associated with channel bars. Foreset cross strata, present in medium sandstone, dip gently and are up to 8 inches thick. Horizontal laminae are 1 mm to 1 inch thick and consist of interlaminated silt and fine sand. Ripple cross strata up to 1½ inches thick are present in the muddy siltstone. Mudstone beds comprise up to 25 percent of the section at the Sandiguela Creek locality; they are 2 to 18 inches thick, commonly delicately laminated, and can be traced up to 60 feet along the outcrop. Deformed or convolute bedding is present in slump sections up to 3 feet thick; smaller scale deformation of laminae is common throughout the basin-center facies wherever mud and silt or sand are interbedded.

Thick sequences of mudstone contain beds up to 3 to 4 feet thick that are structureless as well as thinner beds that are commonly very delicately laminated on a small scale. The structureless mudstone is generally brown to red brown whereas many of the finely laminated beds are very clayey and greenish. Laminated and rippled siltstone beds are present in some of these sequences.

The delicate, small-scale ripples and laminae in the finer grained parts of the basin-center facies reflect "gentle" currents and deposition from suspension. As silt and sand beds increase in number, ripples, troughs, and foresets become more common and the scale increases; interbedded mudstone shows little change in scale or types of structures. This pattern is established laterally from the thick mudstone sequences near the basin center through increasing sand content toward the basin margin. This change in type of structures and scale reflects the change from deposition in standing water by currents and suspension, to deposition by small-scale braided streams near the water-body margins and on the toes of alluvial fans. The interbedding of mud with silt and sand is a result of fluctuation in the loci of these types and sites of deposition. The patterns of sedimentary structures reinforce and supplement the lithologic data upon which the interpretation of the basin-center depositional environment is made.

MINERALOGY, TEXTURE, COLOR

More than 80 samples of bolson fill were collected and described utilizing a binocular microscope for identification of clast lithologies and rock texture and for counts and estimates of clast types. In addition, 15 samples of mudstone were collected from near the center of the bolson along its southeast-northwest axis for analysis, by x-ray diffraction, of the clay fraction. Most samples described here were collected from the basin-center facies; however, the sand and mud fractions from sandstone and conglomerate of the basin-margin facies are also included.

Sand and silt composition.—Feldspar and quartz are the most abundant constituents of bolson-fill sandstone and siltstone. These minerals account for 60 to 95 percent of the sand and silt grains in the bolson fill; rock fragments (2 to 30 percent), heavy minerals (1 to 5 percent), and, in a few places, calcite grains (0 to 2 percent) comprise the remaining fraction.

Quartz and feldspar vary in relative percentages, but neither is less than 20 percent in any sediment. Feldspar is most abundant (up to 60 percent) in sands derived from the West Chinati stock and from volcanic outcrops, whereas quartz is more common in deposits derived from sedimentary rocks. Much of the feldspar is orthoclase that shows little evidence of alteration. Both clear and smoky quartz are present; some clear grains are subhedral and exhibit crystal faces on some sides.

Rock fragments are common in the medium and coarse sand fractions. Most are aphanitic volcanic rock, some are tuff fragments, and a few are granular intrusive rock. Calcite grains and small calcareous rock fragments are present in some samples.

Fine and very fine sand-sized aggregates of 0.003 to 0.01 mm silt grains are present in many of the rocks, especially muddy sandstone and siltstone. These fine silt grains are bound together by calcite containing hematite and by an amorphous orange substance that dissolves in hydrochloric acid. The aggregates may be fragments of cemented silt that is massive in less weathered parts of the fill.

Opaque heavy minerals comprise 1 to 5 percent of the coarse silt and sand fractions of nearly all rocks; concentrations of 1 to 3 percent are most common. Magnetite and ilmenite are most common with varying amounts of hornblende and pyroxene. They are concentrated in the 3 to 4.5 phi fractions of most rocks. The heavy minerals are of the same composition and degree of freshness as those in the floors of modern streams near the bordering mountains. They are most common in the bolson fill in front of the West Chinati stock and in stream-bottom and terrace deposits of modern streams draining the West Chinati stock.

Clay mineralogy.—Clay (smaller than 2 microns) fractions from 15 samples, including claystone, mudstone, and muddy fine sandstone, were analyzed by x-ray diffraction of oriented slides to determine the clay mineralogy. The samples were selected to obtain data from (1) different points along the axis of the bolson (fig. 5), (2) clays of different color within a single area, and (3) clays that are a constituent of different rock textural types. This approach was used to maximize the possibility of finding variations, thereby providing a starting point to see if differences in clay mineralogy might reflect anomalies significant to this study in terms of source-area variation or environment of deposition.

Variations in clay mineralogy are minor. The only variation is in the amount of kaolinite present, and this is not great nor can it be related to any particular location or texture. The most abundant clay mineral in all samples, based on relative diffraction peaks, is montmorillonite; illite is next in abundance, and kaolinite either equals or is less than illite. Traces of chlorite are indicated in a few samples, but substantiating data obtained from heating the samples are inconclusive.

The abundance of montmorillonite is readily explained by the abundance of tuffaceous volcanic rocks along the basin margins; likewise illite, and perhaps kaolinite, was probably derived from limestone and shale adjacent to the bolson. Diagenesis of bolson sediments may have been a factor in determining the kinds of clay minerals present; evaluation of this factor requires a more detailed study.

Texture.—Textural parameters—sorting, grain size, roundness—are highly variable in the basin-center facies, but a few generalizations can be made. Better sorted sediments, especially sandstone and siltstone, are present and are more common than in the basin-margin facies. The range in grain size is smaller than in the basin-margin facies where conglomerate and muddy sandstone are common. This is somewhat controlled by the definition of basin-center facies used here, but a uniformity of textural features is present in the finer deposits of the basin center that is lacking near the margins of the bolson.

Most sandstone is medium to fine and is moderately well sorted. Moderately to moderately-well sorted siltstone and very fine sandstone are also common. The most abundant textural type present is mudstone; true claystone is minor.

Grain roundness variation reflects both first-cycle clasts derived from igneous rocks and multicycle grains derived from Permian and Cretaceous sedimentary rocks. Rock fragments, common in the coarse sand fractions, are generally subround. Feldspar grains, derived chiefly from intrusive rocks, are subangular to angular with some subround grains. Quartz grains show the greatest variety of roundness types; subangular and angular grains are most common, but samples from deposits down the depositional dip from outcrops of Permian and Cretaceous sedimentary rocks also contain subround, round, and well-rounded quartz grains. These comprise less than 10 percent of all quartz grains.

Color.—Bolson-fill deposits are brown, tan, green, yellow, orange, red brown, and pink, and although all these varieties are present the overall aspect can be characterized as reddish brown or pink. Several factors are responsible for the colors and the variations. There is a definite association of reddish-brown, pink, and orange coloration with the presence of mud. Some sands with less than 1 percent mud have a reddish color related to hematite stain or grain coatings, but most nonmuddy sediments are gray or light tan. This relationship is illustrated best in the basin-margin facies, where gray mud-free conglomerates are present among pink muddy conglomerate beds, and in parts of the basin-center facies, where nonmuddy gray and light tan sandstone is interbedded with orange-brown muddy sandstone.

Mottled brown and green mudstone is common in the basin-center facies as are discontinuous green beds and lenses. Study in the field and in the laboratory showed no consistent relationship of color to texture or bedding. Boundaries between brown and green sediment are gradational, sharp, planar, wavy and irregular, horizontal, vertical; color boundaries correspond to textural boundaries in some places and intersect them in others. Clay mineralogy does not vary across color boundaries nor do light- or heavy-mineral compositions. Some mottling may be related to organic material, but this commonly cited cause for localized reducing conditions cannot be demonstrated in these deposits.

All samples, regardless of color, with silt- and sand-sized grains contain at least 1 to 3 percent unaltered heavy mineral grains, chiefly magnetite, ilmenite, and some hornblende. There are a few "grains" or patches of soft, limonitic material in a few samples as well as 2 to 4 mm by 10 to 20 mm laths or seams of similar material in some muddy sediments. The origin of these grains and seams is unknown; some of the grains may be heavy minerals transported to the depositional site in an altered state.

Much of the orange-brown or pink coloration is associated with orange clay or colloidal-sized particles in the material that binds the fine silt aggregates described above. There are also a few scattered authigenic brick-red crystalline grains of fine to very fine silt size in some of the more orange mudstones. The presence or absence of gypsum is not a factor; gypsiferous sediments are both orange brown and green.

The abundance and widespread occurrence of apparently unaltered heavy minerals indicate that complete diagenetic breakdown of heavy minerals is not a significant factor in determining rock color in the bolson fill, although some iron may have been derived from solution at the surfaces of the grains. The association of pink and brown coloration with muddy sediments suggests the iron compounds were derived from weathering in the source area and transported, perhaps as colloids or ions adsorbed to clay particles, to the depositional site. Oxidation may have occurred in the source area, during diagenesis, or both. The association of pinkish coloration with muddy sediments may be more subtle; varying ionic, redox, or other chemical conditions within the ground-water saturated zone, and at least in part related to the clays and the substances they contained, may have been responsible for the array of colors present in bolson sediments. This aspect of diagenetic processes in the ground-water saturated zone is little understood and generally not considered; it deserves further study.

GYPSUM

Gypsum is common in the basin-center deposits; it is present in mudstone, siltstone, and fine sandstone as:

(1) Disseminated crystals and subhedral grains; most are small (0.5 to 3.5 mm), but larger (to 10 cm) clear selenite crystals are also present.

(2) Lenses and thin (1- to 8-inch beds) of subhedral crystals in a clay and mud matrix. The amount of matrix ranges from 10 to 50 percent.

(3) Distinct beds and large lenses of fine-grained, massive, white, pure gypsum and translucent, honey-colored gypsum. Beds and lenses are ½ inch to 2 feet thick.

(4) One-fourth to 1-inch-wide veins.

(5) Cement in moderately to well-sorted, relatively mud-free sandstone.

Gypsum occurs most commonly as disseminated crystals and, in some places, beds and pods of crystals. It is most common in mudstone; most mudstone that contains gypsum is brown or orange brown, but it is not uncommon to find gypsum associated with green or yellow mudstone. Mudstones containing gypsum typically lack sedimentary structures and vary texturally within a given bed from claystone to sandy mudstone; some of this textural heterogeneity and lack of structures may be due to disturbance of the sediment as the gypsum crystals grew. Gypsum crystals are concentrated in some interbedded mudstone and sandstone sequences into pods, lenses, and beds ½ inch to 8 inches thick. The crystals are randomly oriented in a brown or green mud matrix.

Bedded, massive gypsum was observed at only one locality (fig. 12). The claystone and mudstone with interbedded gypsum are faulted out basinward of this outcrop making it impossible to determine the geometry of the gypsum deposit beyond the 200 yards of continuous exposure at this locality. The massive gypsum here is clear and colorless to snow white and finely crystalline. This thick (2½ feet) bed of gypsum grades eastward, toward the mountains, into finely interlaminated gypsum and clay; rocks of this type are present in the mudstone lithosome from this area north to at least Pinto Creek. The thin-bedded gypsum that is interbedded with laminated green and orange claystone is fibrous in some places, honey-colored and translucent in others. The bedded gypsum is in the mudstone lithosome and is overlain and underlain by brown and orange-brown mudstone typical of this lithosome. The total amount and lateral extent of gypsum exposed at this locality are not impressive, but they do indicate that ponded, highly mineralized water was present, in at least this part of the bolson, during the deposition of part of the basin-center facies.

Veins of translucent, honey-colored gypsum are common throughout the mudstone lithosome and basinward parts of the mudstone-sandstone lithosome. Some veins are clearly filled fractures associated with faults; others may be filled desiccation cracks similar to those developed in playa muds in bolsons in the Mojave Desert of California.

Gypsum-cemented sandstone is moderately common in the basinward margins of the mudstone-sandstone lithosome. These sandstones are moderately well sorted and mud-free. Veins of gypsum are commonly associated with the mudstone-sandstone sequences and the mudstones contain gypsum crystals. Some sandstone contains pods of crystalline gypsum that are probably filled voids or vugs.

Gypsum occurs in Mojave Desert playa sequences

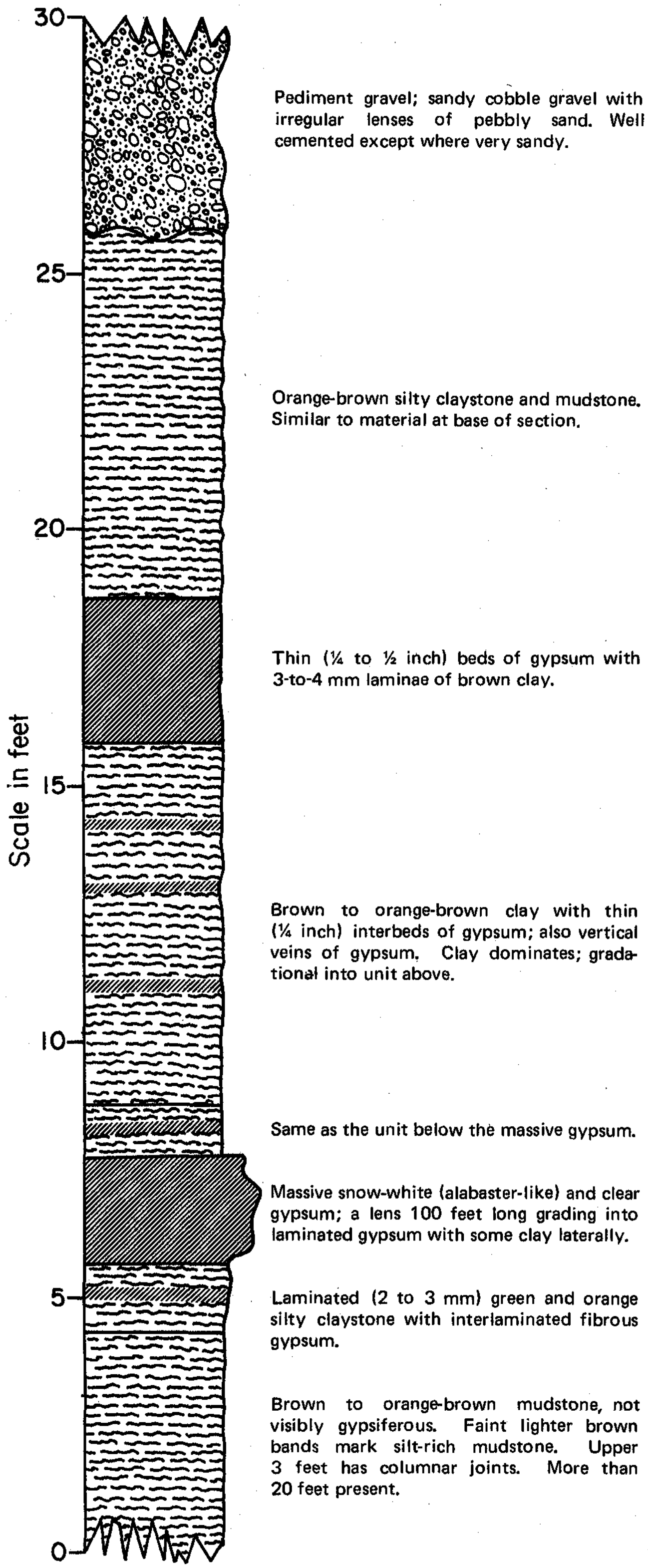

FIG. 12. Stratigraphic section at outcrop of massive gypsum in the mudstone lithosome of the basin-center facies. Located 2 miles east of the Zimmerly Experimental Farm.

in the same forms as in the Presidio Bolson (Thompson, 1929; Bassett et al., 1959). Associated sediments are also similar, both in type and distribution, suggesting that the Presidio Bolson clastics and gypsum accumulated in environments similar to those in which Mojave Desert playa and permanent-lake deposits were deposited during the Pleistocene and Holocene.

CALCIUM CARBONATE

Irregular, knobby, white to light gray calcium carbonate nodules are present in sandstone, sandy mudstone, and pebbly sandstone at various places in the bolson fill. Most are an inch or less long and ¼ to ½ inch in diameter; irregular nodules of this type are common in siltstone north of Burro Creek in the Redford Bolson. The slopes below the siltstone are littered with nodules. They are accompanied in some places by streaks of powdery carbonate material. Similar nodules occur in sidestream-fill deposits which are associated with dissection of the bolson fill by the Rio Grande and its tributaries. These nodules strongly resemble ones in lower alluvial-fan and playa-margin deposits in the Mojave Desert of California and in terrace and pediment deposits in the Mesilla Bolson in southern New Mexico. Hawley and Gile (1966, pp. 28, 29) have described the carbonate nodules in the Mesilla Bolson; they have clearly demonstrated that the carbonate nodules are a step in the sequence of caliche development in nongravelly materials.

Tubelike calcite forms a delicate network in muddy sandstone in parts of the fill in the Redford Bolson along the large sidestream south of Buzzard Creek. The tubes are commonly less than 3 mm in diameter; they stand out clearly on weathered surfaces. They do not resemble pedologic carbonate and may be roots or other parts of plants. Longer pieces of sticklike carbonate, ½ inch in diameter and up to 3 inches long, with a woody surface texture, are present with the smaller tubes. Similar material from the Santa Fe Group in southern New Mexico has been described by LeMone and Johnson (1969, pp. 86, 87) as the stems of succulent (?) plants.

The extensive tufa and limestone deposits in the northeastern part of the bolson fill have been described in a previous section.

ENVIRONMENT OF DEPOSITION

Rocks of the basin-center facies were deposited at the toes of alluvial fans that extended toward the basin center from the surrounding mountains, in ephemeral playa lakes, and in more permanent lakes that contained water for long periods of time. This interpretation is based on the types of rocks present—their geometry, distribution, and relationships with basin-margin deposits—and on analogy to well-documented modern and ancient basin deposits. There is no question concerning the general environmental reconstruction as a basin center surrounded by alluvial fans extending from adjacent mountain blocks; this is a fact of geography and physiography. The principal matter for interpretation is the conditions of deposition and the source of the sediments.

Modern desert basins in the Basin and Range Province are analogous to the Presidio Bolson in physical setting. Alluvial fans from nearby mountain blocks extend toward the basin center, interfingering there with thick sequences of mud and interbedded silt and sand that underlie dry lakes or playas. Many modern basins were the sites of permanent lakes during Pleistocene pluvial periods; some were fed by extensive drainage systems originating far from the basin, others were not. The stratigraphy of several of these basins has been well detailed; some of the more enlightening works include studies of the Lake Bonneville basins by Hunt et al. (1953) and Feth (1955), of the Great Salt Lake by Eardley (1938, 1966), of the Salton Sea by Arnal (1961), and of Lake Lahontan by Morrison (1964). Core logs from several basins in the Mojave Desert (U. S. Geological Survey, 1960) and playa studies at the University of Massachusetts (Motts and Carpenter, 1968) have also contributed to the understanding of desert-basin sedimentation and stratigraphy. Deposits elsewhere in the Rio Grande depression similar to these and to the Presidio Bolson fill have been described by Wright (1964) for the Rio Puerco area, by Strain (1964) for the Hueco Bolson, and by others. The similarity of Presidio Bolson basin-center deposits to those described from similar basins is pronounced and predictable.

Much mud and sand in modern desert basins were deposited at the toes of alluvial fans and near the margins of ephemeral playa lakes. The small-scale foresets and troughs in sandstone beds, and the filling of local lows by muds, are characteristic of the shallow-braid channels and local depressions present near the toes of modern alluvial fans and on the adjacent desert flats. The fluctuation of this zone, as the locus of playa deposition shifted, is represented in the mudstone and sandstone lithosome by thicker, more persistent brown, generally structureless, mudstone beds representing playa-lake deposits. Much or most of the mudstone-sandstone lithosome was deposited on the nearly flat toes of alluvial fans adjacent to playa and more permanent lakes. This is further indicated by the caliche carbonate nodules found in modern basin deposits in the toes of fans and in the mudstone-sandstone lithosome of the Presidio Bolson fill.

The mudstone lithosome, characterized by brown structureless muds interbedded with laminated siltstone, mottled brown and green clay, and delicately laminated claystone, is made up of sediments deposited in lakes of varying permanence. Most common are the broad lenses of brown mud characteristic of modern playa-lake deposition (Motts and Carpenter, 1968; Groat, 1967). The laminated or varied silts and green mudstones are similar to those deposited in permanent lakes as described from Pleistocene Lake Bonneville (Alpine Formation) by Feth (1955), from Lake Manix in the Mojave Desert by Blackwelder and Ellsworth (1936), and from the Green River Formation by Bradley (1964). The interbedded laminated silts, clays, and algal limestones in the Ruidosa Springs area are clearly lacustrine, perhaps deposited in a localized water body maintained by springs issuing from the fault zone as they do today. The intertonguing of the permanent-lake-type deposits with playalike mudstones and the interfingering of all the basin-center sequences with alluvial-fan deposits indicate not only that the type of lake varied but also that the locus of deposition of fine-grained sediments was not static.

The common occurrence of gypsum indicates a hydrologically closed basin during at least some stage of deposition, but the lack of great thicknesses of evaporites argues against a persistent end-of-the-drainage-line type of lake maintained in a highly saline condition with alternate freshenings. In fact, the dominance of playa-lake-type deposits suggests that the bolson was the site of a dry lake throughout much of its history, perhaps with a more permanent spring-fed body of water existing in the Ruidosa area.

It is not clear whether or not a drainage system of large regional extent ever terminated in the Presidio Bolson. Physical barriers, such as the mountain blocks surrounding the basin, limit the access of an aggrading stream from several areas. If a larger stream did feed the Presidio Bolson, the most likely entry point would be near the north end of the basin where the Rio Grande presently enters the bolson. The abundance of sandstone in the fill at this end of the basin may be an indication of a major sediment source in that area. The extent of any such stream beyond the Rim Rock Country cannot be inferred because deposits are not preserved that might provide evidence. Gravels at the north end of the basin do not contain clasts that require a distant source.

In the Hueco Bolson (Strain, 1964) and in the Red Light Bolson (Akerston, 1967), the finer grained basin-center deposits are mantled by basin-margin-like gravels interpreted by these workers as the response to integration of basin drainage by a through-flowing regional stream as described by Wright (1946, p. 399). Unless the Rio Grande gravels that underlay the surface mapped as Qg4 by Dickerson (1966) and Haenggi (1966) represent the first entry of a regional mainstream into the basin, this encroachment of coarse detritus over basin-center deposits is not present or not preserved. If this "Ruidosa Conglomerate" of Dickerson (1966) is the earliest axial mainstream gravel deposit, then the associated pediment gravel represents the sidestreams' response to drainage integration. Unfortunately, the evidence is inconclusive.

AGE

The analogy of the Presidio Bolson fill to the Santa Fe Formation in the Rio Grande depression in New Mexico (Wright, 1946; Hawley et al., 1969) and to deposits described by Strain (1964) (Fort Hancock Formation) and Albritton and Smith (1965) (older basin deposits) in the Hueco Bolson, is strict in terms of genesis and probably they are in part equivalent in age. Strain (1964, p. 50) concluded that his Hudspeth local fauna, derived in part from the upper playa deposits that constitute the Fort Hancock Formation, probably lived during the Aftonian Age of the Pleistocene. The Santa Fe Formation has long been considered late Miocene and Pliocene on the basis of vertebrate fossils (Denny, 1940, p. 94); Wright (1946, p. 413) found vertebrate remains that indicated a late Tertiary age for the Santa Fe in the Rio Puerco area. Thus, the bolson fills in the bolsons along the Rio Grande in New Mexico and Texas were deposited in basins formed by middle Tertiary (Miocene ?) faulting; the ages of the deposits, from Miocene through early Pleistocene, indicate the general period of filling. Because no evidence was found in the Presidio Bolson for dating the deposits, it can only be stated with certainty that the bolson fill is post-middle Tertiary block-faulting and probably approximately the same age as the fills in other bolsons along the Rio Grande.

FIG. 13. Closeup photograph of well-rounded Rio Grande gravel. Knife rests on distinctive Yucca or Las Vigas chert and quartz-pebble conglomerate clast. Terrace near Fort Leaton.

EXCAVATION-PHASE DEPOSITS

GENERAL REMARKS

Except for possible overflow of lake waters, no mechanism for transport of sediment out of the basin existed until the drainage of the Presidio Bolson became integrated with that of lower basins by a through-flowing axial mainstream. At this point the aggradational phase of bolson history ended, and the excavation phase began as the axial stream and its tributaries within the basin began eroding the bolson fill. The excavated sediment was transported out of the basin either into a lower basin to the south or directly to the Gulf of Mexico.

As excavation proceeded, the sidestreams and mainstream left generally thin veneers of sediment over terrace and pediment erosional surfaces, parts of which were subsequently abandoned and stand as remnants above modern streams. These terrace and pediment gravels crop out over the greatest surface area of the bolson. At various times and places the erosional process was interrupted by local, perhaps even basin-wide, accumulations of sidestream alluvium deposited on the mainstream valley floor as alluvial fans and in sidestream valleys as valley fill. This complex of excavation-phase deposits, beginning in each case with modern examples where possible, is described in this section.

MAINSTREAM

MODERN RIO GRANDE

Deposits of the modern axial mainstream, the Rio Grande, consist of channel gravels and floodplain sand, silt, and mud; floodplain deposits are exposed over a much larger area than are the channel gravels (Pl. I). Together these deposits constitute the channel-floodplain complex.

Channel deposits of the modern Rio Grande are exposed in the active channel and on bars located downstream from the juncture of Alamito Creek. Rio Grande gravel ranges in modal size from granules to large cobbles, but most clasts are pebbles and cobbles. The gravel is moderately well sorted, sandy, and most clasts are moderately well to well rounded. This rounded characteristic of Rio Grande gravel is distinctive (fig. 13); sidestream gravels are mostly angular to subangular with a few moderately rounded clasts.

Another distinctive property of the mainstream gravel is its lithology. Several pebble counts made on bars and on mainstream terraces standing adjacent to the modern Rio Grande demonstrate a persistent quartzite-limestone-volcanic rock assemblage (figs. 5 and 14). The influence of local contributions by nearby sidestreams is apparent, but the persistence of the well-rounded quartzite-limestone-volcanic rock suite throughout the length of the Rio Grande in this basin is striking.

Mainstream gravels also contain clasts foreign to the mountains enclosing the Presidio Bolson. The most distinctive of these is a sandy chert-pebble conglomerate derived from the Las Vigas or Yucca Formation which crops out north of most of the Presidio Bolson (fig. 15). These clasts are easily recognized and are present only in mainstream or

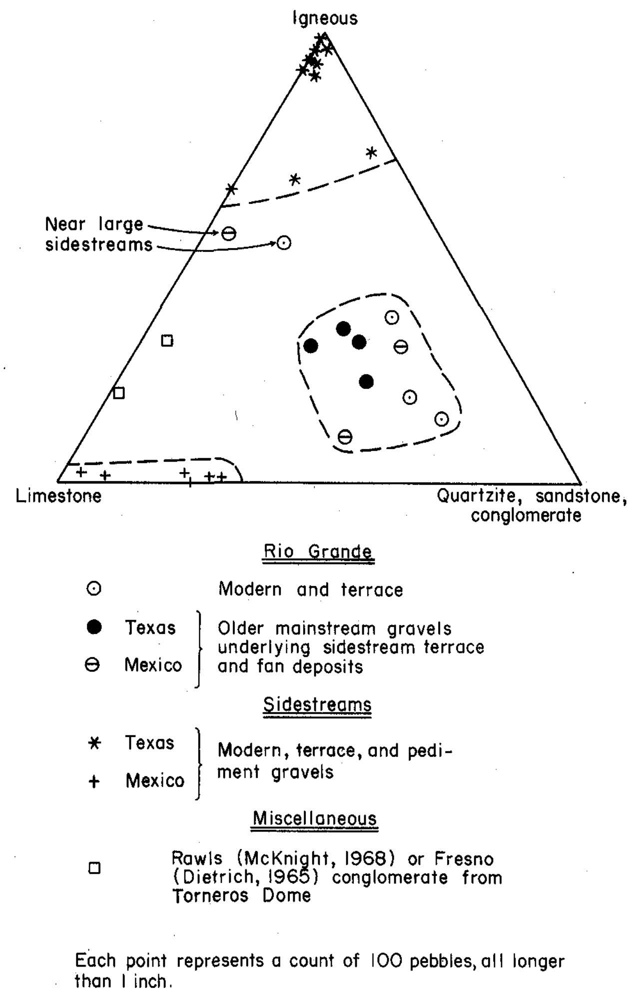

FIG. 14. Pebble-count data for Rio Grande and sidestream gravels.

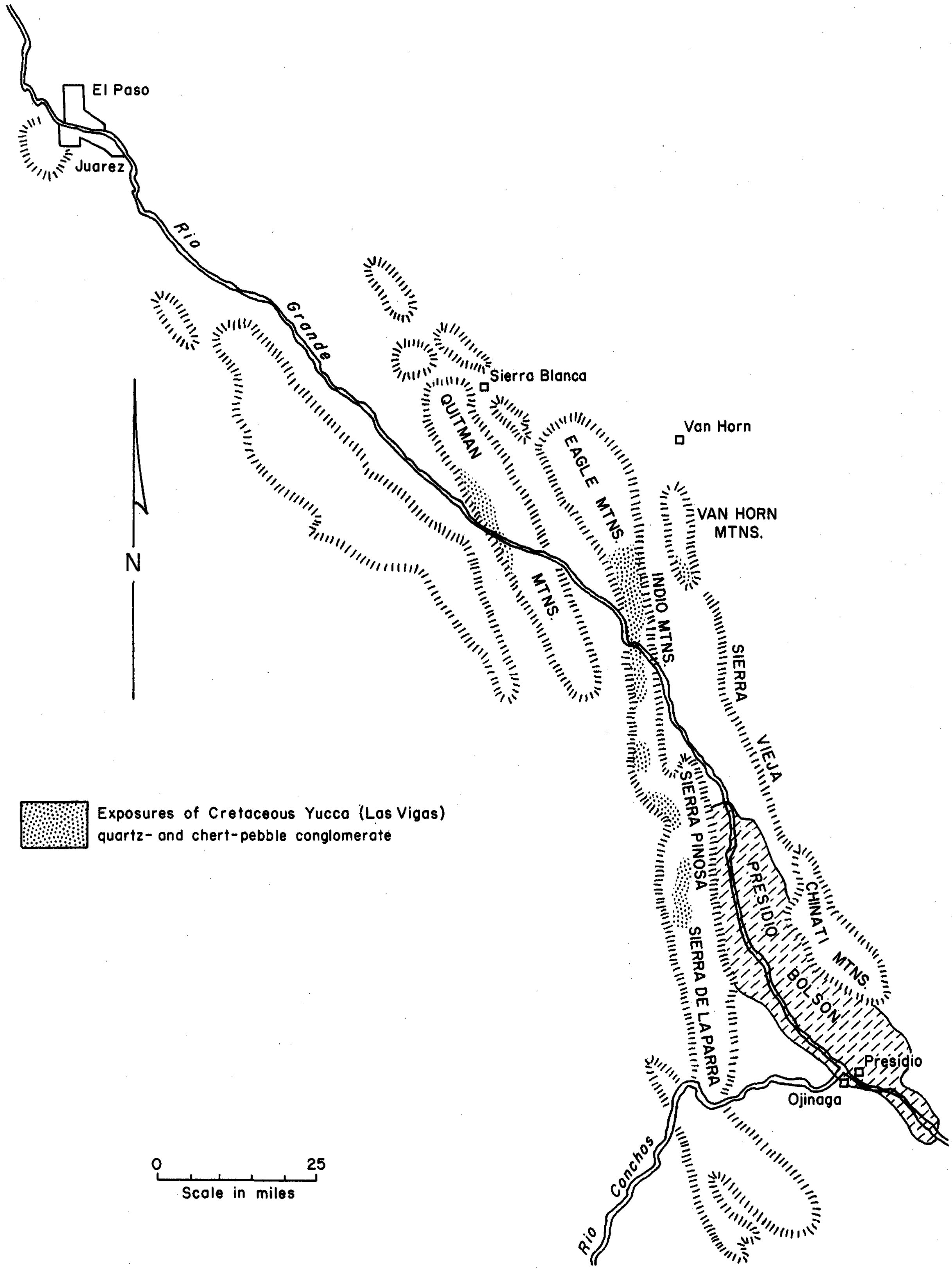

FIG. 15. Source areas for distinctive quartz- and chert-pebble conglomerate clasts present in modern and older Rio Grande gravel throughout the Presidio Bolson.

reworked mainstream gravels. These "foreign" clasts, the quartzite-limestone-volcanic rock suite, and the well-rounded clasts give mainstream gravels an aspect distinctly different from the more angular sidestream gravels characterized by clasts that can be traced directly to outcrops in the headwater areas of each stream.

The other mainstream in the area, the Rio Conchos, drains a vast area in Mexico ranging from the sedimentary rock terrain of most ranges in the Mexican Highlands section of the Basin and Range Province, to the volcanic highland of the Sierra Madre Occidental. The lithology of Rio Conchos gravel in the bolson area reflects chiefly the limestone and sandstone outcrop areas, although a few volcanic-rock clasts are present.

Rio Grande floodplain deposits were not studied in detail. Observations were made in shallow cuts in cultivated areas and on terraces where sidestream influences were not great. Floodplain fine and medium sand, silt, and mud are generally 1 or 2 feet to as much as 5 feet thick. Fine sand with small-scale (1 to 4 inches thick) trough cross-stratification overlain by a thin layer of rippled and horizontally laminated mud is common; however, details of the sedimentary structures have been destroyed by roots in many places. Thin stringers of gravel, both mainstream and sidestream, are present.

The map relations of the mainstream channel-floodplain complex to sidestream and bolson-fill deposits are shown on Plate I. The modern floodplain extends laterally toward areas influenced by sidestreams, where it abuts against low scarps cut by meander swinging or merges with sidestream-fan deposits which are interbedded with and built out over the Rio Grande floodplain deposits. The cross-sectional relationships are best displayed in older, higher deposits that have been dissected.

OLDER MAINSTREAM

Older mainstream gravels resemble modern Rio Grande gravel in lithology, roundness, and the presence of "foreign" clasts. As with modern Rio Grande gravel, the well-rounded quartzite-limestone-volcanic rock suite is persistent and distinct (fig. 14). Figure 5 includes pebble counts of these older mainstream deposits. These gravels were deposited by a large through-flowing mainstream similar and ancestral to the modern Rio Grande.

Gravels deposited by the ancestral mainstream are exposed in many places in the axial area of the bolson (Pl. I). They occur at various heights above the modern Rio Grande on terraces and in erosional remnants capped by sidestream pediment and terrace gravels. Mainstream gravels are well preserved in the toes of pediments on both sides of the Rio Grande north of Ruidosa. Many low sidestream terraces and pediment remnants between Ruidosa and Alamito Creek are developed on Rio Grande deposits; not all these were mapped individually, but the lateral extent of mainstream gravels throughout the bolson was determined (Pl. I). Mainstream terraces, with little or no alteration by sidestream activity, are preserved from south of Ojinaga north to Cerro Alto in Mexico.

The mode of occurrence of the older mainstream gravel is similar in all areas (fig. 16). Channel gravels are 6 to 12 feet thick; thicker mainstream deposits are not common. Near the end of the pavement

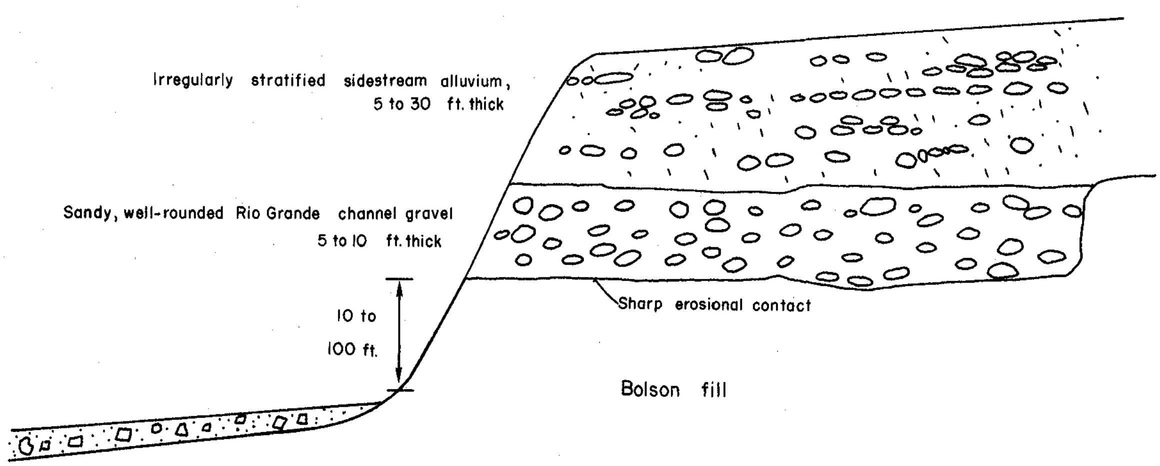

FIG. 16. Mainstream gravel, bolson-fill, and sidestream relationships in pediment remnants bordering the Rio Grande floodplain.

west of Farm Road 170, adjacent to the Rio Grande, 30 feet or more of mainstream gravel crops out in a steep bluff. The constriction of the Rio Grande is pronounced in this area, probably because large sidestreams enter the valley here. The gravel was thus stacked in a narrow band as the river cut down with limited lateral movement.

The gravel is sandy (medium to very coarse sand) and moderately to moderately-well sorted. Most is medium-pebble to medium-cobble gravel, overlain in a few places by mud and fine sand interpreted as floodplain deposits but in most places by sidestream gravel. Stratification of the channel gravel is not well defined; crude parallel beds and trough cross-stratification are recognizable at some places.

The mainstream gravels are in erosional contact with underlying bolson fill at all places the contact was observed; at no locality does bolson fill overlie mainstream gravel. In most places older mainstream gravel is overlain by 5 to 25 feet of sidestream sand and gravel. Figure 16 illustrates these relationships which can be observed at many localities along the basin axis, for example, near Fort Leaton 3 miles southeast of Presidio, in many stream cuts between Adobes and the Zimmerly Experimental Farm, and along the bluffs on both sides of the Rio Grande near Ruidosa. Older mainstream gravel without significant sidestream-gravel caps is present on the Mexican side of the Rio Grande from Ojinaga north to Cerro Alto. These terraces lack a sidestream gravel mantle only because there are no gravel-producing mountain blocks near enough to the river area to supply the detritus.

Mainstream deposits were spread laterally as the ancestral Rio Grande swung across the valley floor. As it moved away from one side of the valley toward the other, the sidestreams on the recently occupied side of the valley spread sand and gravel over the mainstream deposits as fans of varying thickness.

SIDESTREAMS

MODERN DEPOSITS

Ephemeral streams transport detritus eroded from the bolson deposits and from the surrounding mountains toward the Rio Grande. Over most of the bolson these streams are eroding by lateral and vertical cutting. During the process of removing the bolson fill the streams leave a sandy gravel veneer over the beveled bolson fill: (1) in distinct channels of varying width in areas where one or a few vigorous streams dominate the drainage system, as along Alamito, Cibolo, and Hot Springs Creeks; some of these channels broaden into fan-shaped surfaces near the Rio Grande where lateral corrasion by the sidestream is most pronounced; or (2) as a broad, thin surficial mantle where many small streams have carved an irregular broad surface of low relief, such as the broad plain east of Ochoa and northeast of Adobes. These sidestream deposits are absent in the upper and middle reaches of many streams, where bolson fill is exposed in the wash floors, and at least 8 feet thick near the Rio Grande where streams are slightly incised into sidestream alluvium. Bolson fill is not exposed in stream bottoms near the basin center.

Several large sidestreams are eroding bolson fill along their upper and middle reaches while building alluvial fans out onto the valley floor near the Rio Grande; Pinto and San Antonio Creeks are good examples of sidestreams that are definitely aggradational in their lower reaches. The thickness of these fan deposits is unknown; relief between fan surfaces and the surfaces the fans are built onto suggests at least 30 feet of sidestream alluvium. Several triggering mechanisms and causes for fan deposition are possible, but most commonly either capture or swinging away of the Rio Grande is responsible.

The composition and texture of sidestream deposits are extremely variable; they are influenced strongly by the lithology of the bedrock and/or bolson deposits drained by each stream. Streams draining resistant limestone, sandstone, or lava outcrops transport much gravel. The lithology of these gravels, as determined by pebble counts (figs. 5 and 14), reflects the rock type exposed in the headwaters areas. Streams draining West Chinati Peak, a syenite intrusive body, transport much sand but very little gravel. Sidestreams heading in the tuffaceous volcanic rocks east of Ochoa likewise transport little gravel but much mud and sand; gravel-sized clasts are not produced during weathering of the tuffaceous rocks or of the syenite. Many sidestreams crossing mudstone and claystone of the bolson fill carry armored mudballs.

The thinnest, least gravelly sidestream deposits are those deposited by the numerous smaller sidestreams that head in the bolson fill, especially those originating in the basin-center facies. Much of the beveled bolson fill in Texas from Pinto Creek to south of Ochoa is mantled by thin, sandy alluvium spread by the numerous small streams that head in the fine bolson-center rocks that dominate the area

(Pl. I). Some streams are reworking older pediment and terrace deposits and thus carry some gravel, but the amounts are small. The valley border surface, the area between the edge of the Rio Grande floodplain and the ends of the pediment spurs, is strewn with reworked pediment gravel and reworked bolson-fill deposits laid down by these abundant smaller, local streams, some of which carry sediment out onto the Rio Grande floodplain.

PEDIMENT AND TERRACE DEPOSITS

Pediment and terrace remnants stand at various heights above modern stream channels. The deposits mantling these surfaces were left by the streams that cut the surfaces, streams analogous in morphology and source areas to modern sidestreams but which were graded to higher elevation of the Rio Grande during earlier phases of excavation of the bolson fill. The origin and history of development of these surfaces have been discussed in detail elsewhere (Groat, 1970a, b).

Old terrace and pediment deposits are chiefly sandy gravel, for only surfaces mantled by gravel are resistant to erosion and therefore preserved; erosional remnants capped by sidestream deposits are scarce in areas where the sidestreams head in nongravel-producing bedrock or within the bolson. The coarsest, most gravelly pediment and terrace deposits are those that cap the prominent erosion surfaces adjacent to the major sidestreams, such as Alamito, Cibolo, and Hot Springs Creeks. The lithology of gravel clasts in these older sidestream deposits is similar to that in adjacent modern streams and reflects bedrock lithology in the adjacent mountains.

The thickness of the older terrace and pediment deposits is variable and bears no consistent relation to the height or age of the surface beneath the deposits. In most places terrace and pediment gravels are 5 to 15 feet thick, but as much as 40 feet is present in some areas. In some places the deposits are thickest near the mountains and thin toward the basin axis; in others there is an appreciable increase in thickness toward the basin center. Thick deposits, up to 50 feet, near the mountains probably represent local fan and slopewash deposits. They are poorly sorted, locally derived, and "bedding" is inclined at angles that approximate the slope of the land surface at the base of the mountains. The increase in thickness of some terrace and pediment deposits toward the basin center reflects transition from channel gravels deposited as sidestreams eroded the bolson fill, to fans these streams built onto the valley floor, and to valley fills. The preserved thickness of older sidestream deposits near the basin center is largely a function of how far the Rio Grande has swung laterally, that is, whether all, part, or none of the thicker sidestream-fan deposits, if ever present, have been removed by the mainstream.

The older sidestream terrace and pediment deposits are coarser than the bolson fill they overlie. Where sidestreams have built fans onto the valley floor there is more sand and mud than in the middle and upper reaches of the streams, but in terrace and pediment deposits the sandy gravel present in the upstream reaches is also present near the basin center. In the upstream reaches, the sidestream gravel is coarser than the bolson conglomerate it overlies there. This textural contrast between bolson deposits which grade from conglomerate near the basin margin to mudstone near the basin center, and overlying sidestream deposits which are sandy and gravelly from basin margin to center, is due to a fundamental genetic difference in the origin of the two kinds of deposits. The bolson fill was deposited in a closed basin by ungraded aggrading streams; these streams dumped the coarsest part of their load near the basin margin and carried only the finer sand and mud to the basin center. When the Presidio Bolson became integrated with other basins by a through-flowing axial mainstream and excavation of the bolson fill began, debris carried toward the basin center by sidestreams was transported out of the basin by the mainstream. The sidestreams became graded to the mainstream and all of their load, including gravel and sand, reached the basin center; channel deposits left on erosional surfaces by these streams reflect this difference.

Caliche.—Caliche is present in many higher and older terrace and pediment deposits capping the pediment remnants adjacent to or near the major sidestreams. Although the completeness of cementation of the gravels is variable, and is generally less complete on lower, younger surfaces, the sequence on each is similar: (1) The surface is armored with a one-pebble-thick armor, commonly varnished; (2) beneath the pebble layer are 1 to 3 inches of "honeycombed" or porous, slightly indurated silt and mud with patches of white calcium carbonate powder or crusts; then (3) 6 inches to 2 feet of light brown or buff silt with scattered pebbles or cobbles and containing disseminated white powdery, calcium carbonate; some of the gravel clasts are commonly partially coated with a white calcium carbonate crust that increases with depth; and, finally, (4) gravel that is partially or completely cemented by white calcium carbonate. The chief differences noted in several trenches dug in the highest to lowest surfaces near Cibolo Creek was in the degree of cementation of unit 4. Little or no difference was noted between the profiles on Dietrich's (1965) high Qg2 and slightly lower Qg3, but the gravels of the lowest or Qg4 surface are not cemented. These lower terrace deposits throughout the bolson lack the caliche cement common in the higher deposits.

Caliche development on the highest extensive surfaces has the complete sequence described above. The degree of caliche development on these surfaces does not approach the massive, complex profile of the high La Mesa surface described in an excellent account by Hawley and Gile (1966) of caliche formation on valley-border surfaces. Whether or not this is due to a younger age for the high surfaces in the Presidio Bolson is unknown.

SIDESTREAM FILLS

Relatively thick deposits of sidestream gravel and sand are exposed in the basinward edges of pediment remnants adjacent to several of the large sidestreams. These sediments were deposited in the zone of interplay between the mainstream valley and the mouths of sidestreams on alluvial fans and in ponds on the mainstream floodplain. The details of the relationships between sidestream and mainstream deposits are commonly complex. Thick sidestream fills occur near the mouths of Alamito, Cibolo, and Sandiguela Creeks; only the Sandiguela fill complex is described here.

Sandiguela Creek.—The most interesting, probably because it is the best exposed, sidestream-fill sequence crops out along the lower reach of Sandiguela Creek in the northern part of the bolson (fig. 17). The sequence postdates, by an unknown period of time, the formation of the Qg4 surface and the Rio Grande gravel ("Ruidosa Conglomerate") beneath this surface as mapped by Dickerson (1966).

At the eastern apex of the valley fill, the sediments are gravel and sand that were deposited in channels cut into the bolson-fill sandstone and mudstone. Toward the Rio Grande the gravel and sand are interbedded with volcanic ash and both of these are interbedded with thin-bedded sandstone and mudstone that contain nonmarine ostracods, reported by Dickerson (1966, p. 27) as *Deyocypris* sp., *Candona angulata* G. W. Muehller, and *Cypria* sp. (?). Terrace gravel caps the 20 to 35 feet of fill exposed along Sandiguela Creek. At the southern edge of the sequence, the ash directly overlies Rio Grande terrace deposits that are a few feet lower than the mainstream gravels underlying the Qg4 surface.

The thin-bedded, and in places laminated, muds and fine sands and the interbedded structureless ash were probably deposited in shallow, ponded water along the valley border fed by Sandiguela Creek or the Rio Grande. The clean ash is probably of air-fall origin, the fine sediment could be of either Sandiguela Creek or Rio Grande origin, and the gravel was deposited by Sandiguela Creek.

Strain (1964) reported volcanic ash from his Camp Rice Formation, which he believed is an aggradational unit deposited on the mainstream valley floor in the Hueco Bolson; he correlated the ash with the Pearlette. No correlation of the Sandiguela ash with ash deposits in similar stratigraphic position in the Hueco Bolson or with other ashes in the New Mexico part of the Rio Grande graben can yet be justified.

This fill unit is not especially thick, but the presence of the ash and its stratigraphic relationships make it an interesting one. The deposits are definitely post-bolson fill and postdate the entrenchment of the Rio Grande and the formation of the Qg4 surface of Dickerson (1966). Another ash deposit north of Spencer Creek (Pl. I), overlying Rio Grande gravels in a position similar to the mainstream gravels here, may be correlative with this deposit. If so, the relationship of some geomorphic surfaces in separate parts of the bolson can be inferred. The possible correlation of this ash with ashes in distant parts of the Rio Grande complex presents the only possibility of linking histories of the physically separated basins.

DISCUSSION

All deposits described in this section have one thing in common: They were deposited during the excavation phase of Presidio Bolson history—they postdate the initiation of a through-flowing axial mainstream. Most deposits—mainstream terrace gravels, sidestream pediment and terrace deposits, and modern alluvium—bear no unique relation to the history of excavation. They are essentially lag deposits left as erosion proceeded. The question to be considered here is, do the sidestream-fill deposits reflect special conditions such as pauses in downcutting or aggradation, or are they also the result of processes incident to excavation?

No unqualified interpretive statement regarding valley or sidestream fills is possible because they are geographically separated, and only one marker, the ash, might indicate the relation of one of these fills to deposits in other basins. It can be stated that sidestream processes active today could account for the sidestream fills in at least as suitable fashion as a period of aggradation by the mainstream, which is not documented in the Presidio Bolson. Fan building, capture, and shifts in the position of the mainstream, as described in the section on geomorphology, are all factors that are presently accumulating deposits that resemble some of the valley fills. Climatic differences during deposition of some of the fills, such as the lacustrinelike parts of the Alamito—Black Hills—Torneros and Sandiguela fills, could account for ponded water along the mainstream-valley margin. This is not to say that a general period of aggradation did not occur during the history of excavation, or that these valley fills are definitely not related to such a period; rather the point is that there is no evidence that general aggradation of the mainstream valley *must* be responsible for the separated fills. An understanding of the relationship of the valley-fill deposits of the Presidio Bolson to the Camp Rice Formation in the Hueco Bolson (Strain, 1964, p. 33) and to the "Mixed Rounded Gravels" in the Mesilla Bolson (Ruhe, 1962) awaits (1) the results of studies of the ash deposits in all of these areas or (2) another type of evidence for determining correlation.

REDFORD BOLSON

The Redford Bolson is a narrow, complex graben bordered on both the east and west sides by

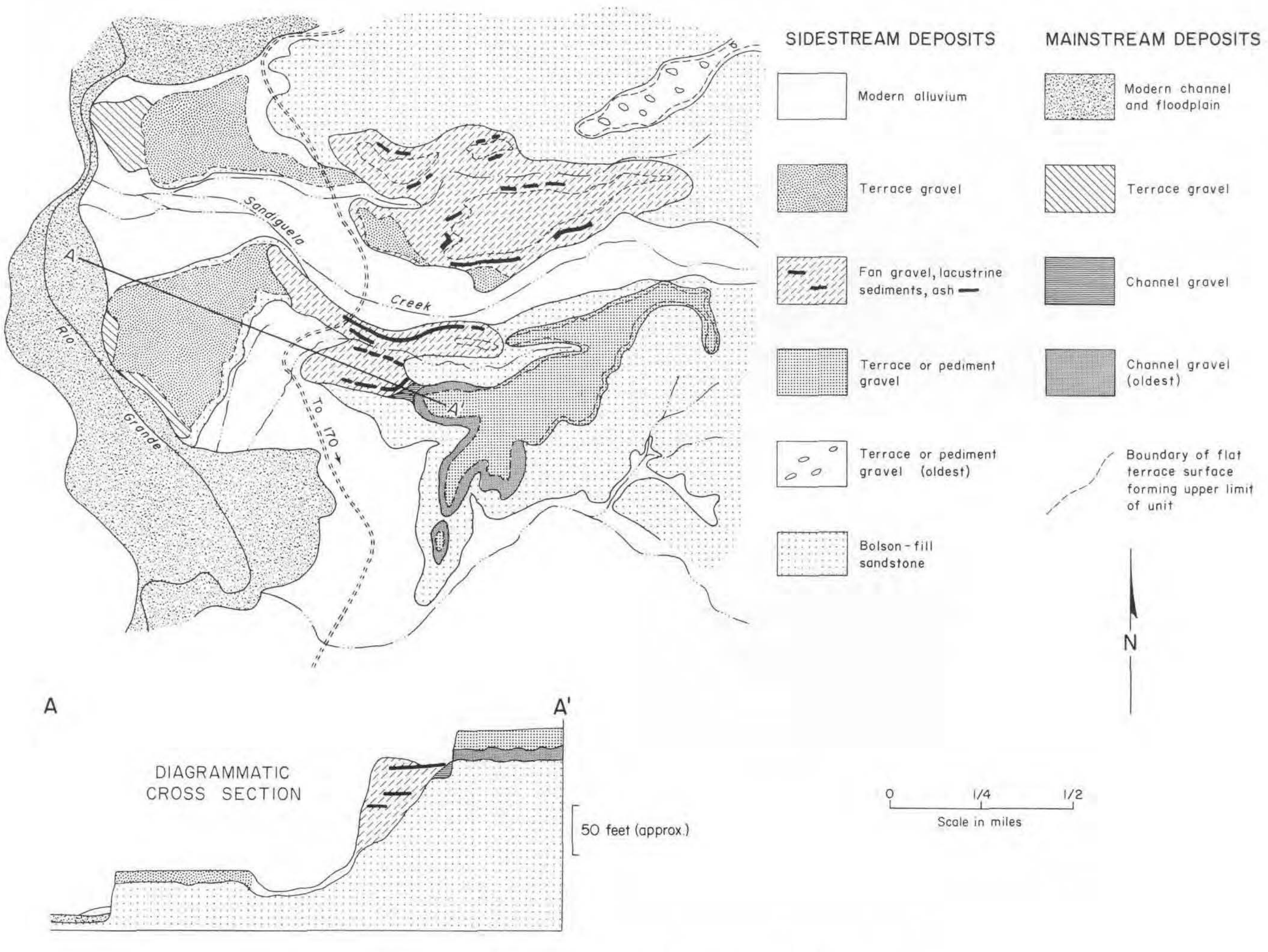

FIG. 17. Sandiguela Creek sidestream fill and ash.

volcanic highlands; it is the southeastward extension of the larger Presidio structural basin. The Redford Bolson is much smaller than the Presidio Bolson; it is only 6 miles wide at its broadest point and is 12 miles long. The depositional history of the Redford Bolson is similar to that of the Presidio Bolson and the sedimentary fills of the two are continuous.

Most of the Redford Bolson fill is interbedded, poorly sorted pebbly sandstone and sandy conglomerate; stratification is irregular and poorly defined. These deposits lap onto the adjacent fault-block complex from which they were derived. Sandstone and siltstone interfinger with the conglomerate near the basin center; they contain caliche nodules and the fine network of calcium carbonate "tubes" described in the section on calcium carbonate. Sandstone and mudstone occur adjacent to the bordering highland on the east, between the major gravel bodies which are located near the canyon mouths of modern streams. The shift of the locus of fine-grained sediment deposition toward the eastern mountain edge could have resulted from an increased supply of detritus from the west occasioned by faulting and uplift there. This is a relatively common phenomenon in bolsons of the Basin and Range Province.

Mudstone, claystone, and siltstone similar to sediments in the mudstone lithosome of the Presidio Bolson occupy a small area near the center of the basin. These mudrocks interfinger with sandstone and conglomeratic sandstone characteristic of most of the deposits. The fines are poorly and discontinuously exposed, hence details of their geometry are unknown. In one place, however, along the large unnamed creek between Buzzard and Burro Creeks, the lateral migration of mudrocks toward the north, over gravelly deposits, is seen in more or less continuous exposures.

The fine-grained bolson sediments of the two basins are separated by pebbly sandstone and conglomerate, indicating that an alluvial divide created a sub-basin in the Redford graben in which a separate playa existed. McKnight (1968, p. 113) believed that the muds in the Redford Bolson were derived from upstream, from the Presidio Bolson, but the presence of a wedge of coarser-grained deposits between the two areas does not support this interpretation.

Excavation-phase deposits are similar in kind and mode of occurrence to those in the Presidio Bolson. Sidestream-terrace deposits mantle distinct terrace remnants standing above and adjacent to the larger sidestreams, those that head in the bordering volcanic terrane. Older mainstream deposits underlie sidestream-terrace gravels near the axis of the basin and are restricted to a narrow belt in the axial area.

Exposures of bolson fill in the Mexican part of the Redford Bolson are limited to the few bluffs near the Rio Grande. Nearly the entire extent of the bolson, from the edge of the bordering highland to the Rio Grande, is a broad, washed plain of low, irregular terraces and sidestream fans. Large sidestreams are not common, hence gravel-capped pediment and terrace remnants are not common. Topographic maps are not available, but this erosional-depositional plain of low relief has a steep gradient, probably 200 feet per mile or greater. Faults are present in the fill along the river and in the volcanic rocks near the southern end of the basin in Mexico; the steep gradient may be directly related to a series of fault blocks that step sharply down toward the river.

STRUCTURAL GEOLOGY

BOUNDARY FAULTS

The regional structural patterns, including the large normal faults that bound the Presidio Bolson, have been mapped and discussed by the workers who have concentrated their studies in the surrounding mountain ranges. The discussion that follows is taken from the reports of Dietrich (1965), Amsbury (1957), Haenggi (1966), and McKnight (1968). The writer did not map any faults along the basin margins or in the bolson itself; those in the bolson mapped by others are not included.

The regional tectonic grain throughout most of Trans-Pecos Texas is southeast to northwest; most mountain blocks, bolsons, and the normal faults that bound them trend in this direction. The borders of the Paleozoic Diablo Platform and Mesozoic Chihuahua trough also trend northwest, and their edges in this area correspond approximately to the eastern margin of the Presidio Bolson.

The trend of the Presidio and Redford Bolsons parallels the trend of the major normal faults that bound the basins (Pl. I). The Redford Bolson and the southern half of the Presidio Bolson trend northwest, as do the Redford-Lajitas and West Chinati fault zones that border the bolsons on the east. The trend of the northern half of the Presidio Bolson swings gradually from northwest to north-northwest and finally to nearly due north at its northern end. Likewise, the border faults on the east—the Bienevides fault zone and the Candelaria fault—swing toward the north.

The border faults on the west side of the bolson, in Mexico, are somewhat more complex. The fault that borders the bolson on the west near and north of Ojinaga has the same north- to northwest-swinging to a north-south trend as does the Palo Pegado fault at the northern end of the bolson. The La Parra fault, which borders the bolson south of the Palo Pegado fault, has a northwest trend that is lost where it enters the bolson at an angle to the basin margin (Pl. I). The complexity of this fault has been documented by Haenggi (1966, p. 275) and Gries (1970); it has a normal down-to-the-east configuration where it borders the bolson.

The Tascotal fault zone trends approximately east-west; it separates the Bofecillos Mountains and Torneros Dome on the south from bolson fill on the north. The fault zone forms the southern boundary of the Presidio Bolson east of the Rio Grande. The history of the Tascotal fault zone and the La Parra fault, which intersect the trend of the bolson, is more complex than for most border faults, perhaps because the Presidio and Redford Bolsons are situated near the margin of the mobile, salt-floored Chihuahua trough and the edge of the more stable and rigid Diablo Platform to the east. The Tascotal fault zone marks the northern border of the Bofecillos Mountains volcanic highland; east of the bolson a broad stretch of country nearly 8 miles wide north of the fault zone and south of Alamito Creek is underlain by thick gravels and the thin edges of one or two lavas. These Tertiary conglomerates, Rawls unit 9 and the Perdiz Conglomerate (Dietrich, 1965), fill a depression of unknown depth that trends nearly perpendicular to the margin of the Presidio Bolson but parallels the Tascotal fault zone and perhaps the extension of the La Parra fault. This fill of conglomerate, and the Rawls unit 9 conglomerates exposed in the Torneros Dome immediately south of the Presidio Bolson, may have been deposited in a graben that persisted during at least the late stages of volcanism in the Bofecillos and Chinati Mountains area. It is possible that this trend may have been a continuation of the Presidio graben during the late stages of volcanism and early stages of basin filling; faulting that preceded most filling of the Presidio Bolson may have ended this period of basin coincidence and raised the Perdiz and Rawls deposits to a borderland-source-area position.

The border faulting is considered to have begun during the late stages of volcanism, but most of the movement probably occurred in post-volcanic time (McKnight, 1968, p. 126). The pattern and movement of the faults that bordered the bolsons during the filling of the bolsons is fairly straightforward. Steplike blocks, down to the basin, form the structural borders of the bolsons, and movement along them continued beyond the period of bolson-fill deposition.

FAULTING IN THE BOLSONS

Faults that parallel the margins of the Presidio Bolson have been mapped in the eastern part of the northern half of the bolson and at scattered localities elsewhere. Amsbury (1957) and Dickerson (1966) mapped several northwest- and north-northwest-trending normal faults of small displacement; Dietrich (1965) mapped faults of similar trend, but they are less common. Faults of this type also occur in the Redford Bolson, and like those in the Presidio Bolson, they are normal faults that are down toward the basin.

Faults are rare in the Mexican portion of the Presidio Bolson; Haenggi (1966, p. 230) noted that except for one small structure, the bolson deposits were not faulted. Gries (1970) made the same observations in his map area south of the El Cuervo area mapped by Haenggi (1966).

The beds in the bolson fill dip gently toward the bordering mountains in the northern half of the Presidio Bolson. Dickerson (1966) recorded dips of 2 to 3 degrees toward the east in the Hot Springs area, and Haenggi (1966, p. 229) described the fill as dipping gently (less than 5 degrees) westward in Mexico. Similar gentle dips toward the bordering mountains were noted in faulted parts of the Redford Bolson, but except near the basin margins, dips in the southern half of the Presidio Bolson are either a degree or two toward the basin axis or horizontal. This pattern is complicated by local faults but holds for most of the southern area. There are local faults of small displacement in the area of evaporite outcrop east of the Zimmerly Experimental Farm, along Spencer Creek, in the Redford Bolson, and in the area near the end of the pavement along Farm Road 170. In most places pediment and terrace gravels are not affected by the faulting, although Dietrich (1965, p. 216) reported faulted pediment gravel. Gravels are faulted along the middle reaches of Spencer Creek. In several areas, what on aerial photographs appeared to be faults, turned out to be the erosional edges of terraces.

Near the end of the pavement on Farm Road 170 the bolson fill is cut by a series of crescent-shaped slump faults that have dropped bolson-fill mudstone down toward the west and northwest. The floodplain of the Rio Grande is very narrow in this area, although it widens both upstream and downstream. River gravels are thick in the constricted area, but exposures are poor and mantled by slopewash. There are no evidences of bedrock near the surface nor any differences in bolson-fill lithology that would account for confinement of the river. The bolson does reach its widest extent in Mexico in this area, however, and large streams draining the bolson and adjacent mountains do join the Rio Grande from both Chihuahua and Texas near this point. The influx of detritus from both sides of the basin may have been a factor in restricting the lateral movement of the river; the significance of the faults is even less well understood.

The presence of faults within the bolsons indicates a continuance in some degree of the faulting that formed the graben system that comprises the bolson complex. The fact that faults have not been observed at the surface of bolson deposits in nearby bolsons away from the Rio Grande, such as the Marfa basin and Lobo Valley, may indicate a lack of continuing tectonic activity in these areas. It is also possible, however, that faults are present in these other basins and that surficial fluvial processes are sufficient to mask any expression of them.

GEOMORPHOLOGY

GENERAL REMARKS

Surfaces and landforms related to the excavation of the Presidio Bolson by the Rio Grande and its tributaries are evident throughout the bolson. The history of the formation of these geomorphic surfaces has been complex, influenced not only by Pleistocene climatic changes but also by the many factors that control the behavior of the Rio Grande and its tributaries regardless of the climate. Among these controls are the types and distribution of types of bolson deposits in the various tributary drainage basins, the lateral migration of the Rio Grande channel-floodplain complex, and, perhaps most important, sidestream capture.

GEOMORPHIC SURFACES

MAINSTREAM

The modern Rio Grande channel-floodplain complex occupies a belt 0.25 mile to 2 miles wide; the average width is 1½ miles. Numerous abandoned meander loops and scars demonstrate that the channel has meandered across the entire breadth of the modern floodplain. The floodplain margins are generally scarps, a few feet high, cut into infringing tributary fan deposits by the meandering mainstream. In some places, for example at San Antonio Creek, sidestream alluvial fans have been built onto the Rio Grande floodplain.

Rio Grande terraces are extensive only where sidestreams are small or weak; this condition is present on the west side of the river near Ojinaga and extending northward for approximately 12 miles (Pl. I). The lateral extent of Rio Grande gravels and terraces is indicated on Plate I. The presence of mainstream terrace gravels some distance from the present channel-floodplain complex and the absence of a paired terrace across the valley indicate that the Rio Grande channel-floodplain complex has shifted laterally during excavation of the bolson fill. The effects of this migration on the formation of the stepped sequence of sidestream erosion surfaces are shown in figure 18. It is clear from figure 18 that sidestream erosion surfaces influenced by this migration of the mainstream cannot be correlated on the basis of their relative heights above the Rio Grande because their gradients and the distance they have been trimmed by the mainstream control their height. Pauses in downcutting with increased lateral movement of the mainstream would accentuate the effects of trimming, resulting in a complex of surfaces at various heights rather than a single surface at a uniform height above the Rio Grande.

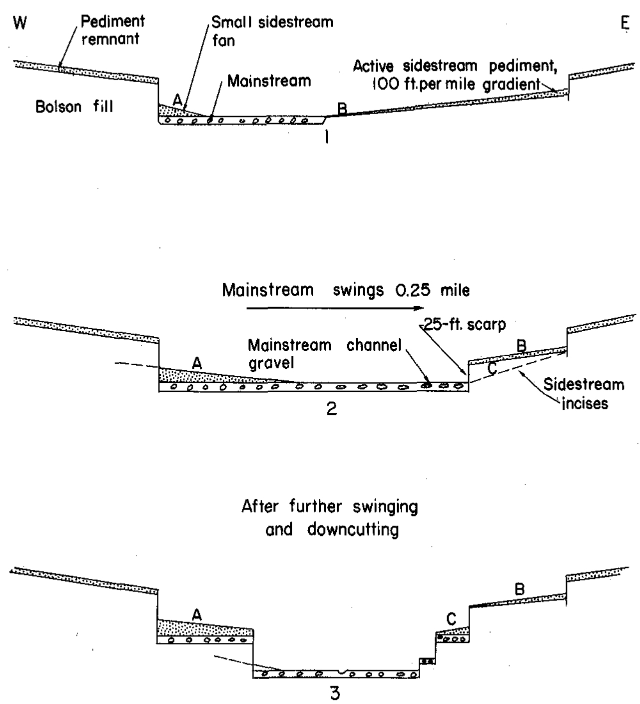

FIG. 18. Diagrammatic cross sections showing the effects of lateral migration of the mainstream on sidestream surfaces. The effect of lateral migration of the channel-floodplain complex is to produce a complex of sidestream surfaces at different levels without downcutting (sections 1 and 2). In section 2, surface B is equivalent in age to surface A but is 25 feet higher. In section 3, surfaces A and C are at approximately the same height and in the same position to the mainstream, but they are not equivalent in age.

SIDESTREAMS

The small sidestreams heading in fine-grained bolson fill or in nongravel-producing bedrock have produced a very irregular surface complex of relatively low relief at or near a graded relationship with the modern Rio Grande. The lack of much gravel in these streams has prohibited the preservation of terraces by a protective cap and fostered continual dissection by numerous rills and small streams. The resulting landform is a complex of low, dissected

FIG. 19. Low, irregular, discontinuous surface complex typical of areas drained by numerous small sidestreams heading in fine-grained bolson fill. View is north from above a point approximately 4 miles east of Ochoa.

terrace remnants, stream channels, and sheetwash areas with generally less than 10 to 15 feet of relief. The area east of Ochoa typifies this type of erosion surface (fig. 19).

The larger, gravel-bearing sidestreams, such as Torneros-Black Hills, Alamito, Cibolo, Sandiguela, and Hot Springs Creeks, have gravel-floored modern valleys and have cut broad terraces and pediments by lateral corrasion of the weak bolson fill. Remnants of these surfaces stand at several levels above the streams that cut them, protected by gravel caps. These prominent high-standing erosion surfaces are the most distinctive elements of the present topography of the Presidio and Redford Bolsons (fig. 20).

Aggradational sidestream surfaces are present near the mouths of some of the larger tributaries where these streams have built fans onto the floodplain of the Rio Grande. Prominent modern fans are present at the mouths of San Antonio and Pinto Creeks. Dissected sidestream fan deposits, underlain by Rio Grande channel gravels, crop out at the distal edges of several of the high pediment remnants that border the large sidestreams, notably near Alamito and Cibolo Creeks.

EVOLUTION OF EXCAVATIONAL SURFACES

The formation of the steplike sequence of pediment and terrace remnants in the Presidio and Redford Bolsons has been attributed to alternating periods of downcutting and lateral planation related to Pleistocene climatic fluctuations (Strain, 1964; McKnight, 1968). The role of cyclical climatic changes is difficult to assess without clear evidence that certain processes, for example, lateral planation, are necessarily associated with certain climatic conditions. The fact of Pleistocene climatic fluctuations of some magnitude is well established; they undoubtedly influenced geomorphic processes, if only their rates, but the implications of climatic change for pediment and terrace formation have not been adequately described beyond the knee-jerk assumption that stepped surfaces resulted from them. They may have, but evidence afforded by surfaces and processes in the Presidio and Redford Bolsons suggest that other factors are also significant in the formation of stepped erosion surfaces (Groat, 1970a, b).

There are several processes active today that affect pediment and terrace formation; some of these processes can result in stepped remnants without cyclic downcutting or climatic change. The effect of lateral migration of the mainstream channel-floodplain complex has been discussed previously (fig. 18); that migration has occurred or the same effect as migration achieved by widening of the channel-floodplain complex is demonstrated by the presence of older mainstream gravels beyond the lateral extent of modern deposits (Pl. I).

Stream capture plays a significant role in the

FIG. 20. High-standing, gravel-capped pediment remnants typical of those adjacent to large sidestreams. View is southeast from over the Rio Grande at a point approximately 2 miles north of Ruidosa.

abandonment of stream valleys by the larger, gravel-bearing sidestreams. The smaller sidestreams, heading in fine-grained bolson fill, have lower gradients and are topographically lower than the higher-gradient large sidestreams which head in the gravel-producing bedrock of the adjacent mountains. Intersection of these larger streams by headward erosion by a smaller stream or by lateral cutting of the larger stream into the valley of a lower, smaller stream, diverts the larger, leaving the gravel-floored downstream segment as a potential surface remnant following continued erosion. This process of capture can be seen at various stages and scales throughout the Presidio Bolson. Pinto, "Boundary," and Cibolo Creeks show all the signs that capture has played a role in the formation of the splay of surface remnants that borders each of these streams (Groat, 1970a). Dickerson (1966) has described in detail the capture sequence in the Javelina-"Boundary" Creek area. Capture is in the process of occurring beyond the edge of the bolson in Mexico near Rancho Canterra (Pl. I); floodwaters are presently partially diverted into the capturing stream, and it is only a matter of time before the entire flow is diverted into this lower stream.

As downcutting of the Rio Grande progressed, the areas drained by numerous small, generally gravel-deficient sidestreams were lowered at approximately the same rate, since conditions favoring capture and subsequent preservation of abandoned surfaces did not exist. The resulting landform is a broad surface of low relief at or near grade to the modern mainstream. The large gravel-bearing sidestreams were subject to capture by smaller, lower-gradient sidestreams; as mainstream entrenchment progressed, capture occurred at random locations throughout the Presidio and Redford Bolsons. Combined with lateral migration of the mainstream channel-floodplain complex, capture played a significant role in the development of the prominent pediment and terrace remnants.

Because at least some of the surface formation in the Presidio and Redford Bolsons has been in response to random, noncyclical processes, it is inappropriate to correlate surface remnants associated with different large sidestreams on the basis of relative height above either the present mainstream or the adjacent sidestream, for this practice presupposes the absolute control of surface formation by cyclical phenomena. Temporal correlations must, therefore, be based on reliable criteria that are independent of assumptions about position or processes of surface formation. Volcanic ash, present in some of the excavation-phase deposits, affords the best hope for this kind of evidence, but the age and affinities of these ashes have not been determined.

The roles of cyclical downcutting and climatic change in pediment formation are obscure. Most interpretations of the effects of these processes have been intuitive rather than tied to models based on observed modern processes. There is evidence, outlined above, in the Presidio Bolson that could be used to produce a completely noncyclical interpretation for erosion-surface formation. This is not warranted in the face of evidence from throughout the world that details more or less cyclical climatic change and sea-level variations. The current trend in geomorphology is to become entrenched at either end of the cyclic-noncyclic spectrum when, in all probability, the answer lies in the much more difficult-to-decipher middle ground; this type of answer probably holds for the origin of the stepped erosion surfaces in the Presidio and Redford Bolsons.

AGE AND HISTORY OF THE RIO GRANDE

The age and development of the Rio Grande have been the subjects of much speculation. Early workers, including Bryan (1938), Smith (1938), and Denny (1940), concluded that the Santa Fe Formation, the bolson fill in the New Mexico basins, was deposited in part by the ancestral Rio Grande that flowed down the axes of these basins. These workers believed that the Rio Grande dated from Pliocene, and perhaps Miocene, time.

Other investigators, including Wright (1946), Strain (1964), and Albritton and Smith (1965), recognized that at least part of the basin fills predated the establishment of an integrated regional drainage system—that much of the fill was shed from the adjacent mountains into closed basins. These and other workers believed that the Rio Grande is probably no older than early to middle Pleistocene.

Another bone of contention regarding the history of the Rio Grande has been the mode of integration of the various basins into a regional drainage system and the ages of the various segments. Lee (1907), Kottlowski (1958), Reeves (1965), and Strain (1964) are among those that believed the segment of the Rio Grande above El Paso originally flowed southward into Mexico where it emptied into a lake or lakes in the area now occupied by Laguna Guzman and Laguna de Santa Maria. The segment above El Paso was captured, in middle Pleistocene time, by a stream working headward along what is now the course of the river below El Paso. Strain (1964) described the chronology and processes believed responsible for this capture.

No direct evidence for the age of the Rio Grande in the Presidio Bolson was found during the course of this study. The only link with older, higher Rio Grande deposits in other basins is afforded by the ash that directly overlies Rio Grande gravels at the two localities described previously. This ash is similar in occurrence and associated deposits to the ash in the Camp Rice Formation in the Hueco Bolson (Strain, 1964). Strain interpreted the Camp Rice Formation and ash as representing a mainstream valley fill associated with the diversion of the Rio Grande into the Hueco area from its course southward into Mexico; vertebrate fossils in the Camp Rice Formation indicate it to be Late Kansan or Aftonian.

If the Rio Grande below El Paso is younger than the segment above, and if it worked its way headward toward the El Paso area from the south, one might expect to find some differences in the number or ages of the erosion surfaces in the different basins. There might be more surfaces, for example, in the Presidio Bolson than in the Hueco Bolson if the river has been in the Presidio Bolson longer. There is a greater number of surfaces in the Presidio Bolson, but there is also a greater number of active sidestreams that derive gravel loads from the adjacent mountain blocks, hence at least one reason for the development of more sidestream surfaces has nothing to do with age of the Rio Grande.

An unknown quantity in the whole Rio Grande drainage system is the Rio Conchos; this river drains a large, well-watered portion of Mexico. It may have been the master stream for much of the area, with the section of the Rio Grande above Presidio merely a tributary that may or may not have worked headward to capture a southward-flowing Rio Grande near El Paso. High, older Rio Conchos deposits are lacking across the broad mountainous belt it crosses just before entering the Presidio Bolson; interpretation of the history of this river awaits detailed work in the more completely preserved record far upstream beyond Sierra de la Alsea.

The ash beds in the Presidio Bolson are associated with mainstream gravels that are a few tens of feet below the highest and oldest mainstream deposits in the Presidio Bolson, thus the ash does not date the earliest entry of the Rio Grande into the basin. The associated deposits in the Presidio Bolson are similar to those in the Hueco Bolson, and possibly the Hueco deposits are not the oldest mainstream remnants. It can be said with reasonable assurance that the ash beds in both bolsons are associated with deposits of similar genesis that were deposited during comparable stages of bolson dissection; it cannot be stated, however, that the ash beds are of the same age. The age of the Rio Grande in the Presidio Bolson thus remains an open question.

ECONOMIC GEOLOGY

GENERAL

Important resources are obtained from bolson deposits: minerals and elements valuable to industry, and ground water. Brines and layered evaporites from dry lakes in California bolsons, notably Searles, Bristol, and Owens Lakes, yield borates, sodium, potassium, lithium, bromine, gypsum, calcium chloride, sodium chloride, and sodium sulfate valued at millions of dollars annually. The Presidio Bolson does not contain significant quantities of any of these materials. Gypsum is present as disseminated crystals, beds of crystals, cement in sandstone, and massive beds, but none of these deposits are of sufficient volume or purity for economic development. Ground water is the most common and probably most valuable resource obtained from bolsons.

Manganese oxide coats gravel clasts and sand grains in the bolson fill and in pediment and terrace gravels in scattered localities throughout the Presidio Bolson. The area southeast of Ruidosa, where many small springs and seeps occur along faults in the mudstone-sandstone lithosome, contains the largest concentrations of manganese oxide. Here, the manganese is present in the bolson fill as coatings on sand grains and as relatively pure concretions or botryoidal concretions. Manganese oxide coats grains in the pediment and terrace gravels and is present in the calcite cement in some deposits. Ground water moving basinward from the area of the West Chinati stock probably deposited the manganese oxide. A locality 3 miles southeast of Ruidosa and within this general area was represented by promoters in 1968 as a large, rich manganese deposit, but no development has occurred nor is any likely. Concentrations are too small for economic consideration.

Large-volume, low-unit-value deposits of industrial rocks and minerals that might be economic were they in or near metropolitan areas are present in the Presidio Bolson. However, their distance from market in this remote area precludes development. Clay from the basin-center facies of the bolson might be used for ceramics, bricks, or lightweight aggregate. Evaluation of these deposits awaits testing. Gravel and sand, particularly modern and older Rio Grande channel deposits, are good aggregate materials and are used in small quantities by the State Highway Department. Gravel pits in Rio Grande gravel are located near Fort Leaton southeast of Presidio.

GROUND WATER

GENERAL REMARKS

Whereas the Presidio Bolson is ideally suited for a study of bolson-fill stratigraphy, it is not well suited for application of this stratigraphic information to the occurrence of ground water in the same basin. This is because the dissection that has exposed the fill deposits has also allowed drainage of much of the normally available ground water, and ground-water development in the bolson is limited. In addition, much of the land that is topographically suited for agricultural use is on the mudstone lithosome of the basin-center facies; these deposits have very low permeability and yield very gypsiferous water, thus wells are not common.

Work in similar, but undissected, desert basins (Groat, 1967) has shown a distinct zoning of ground-water yields and quality. Water pumped from the central parts of a basin is generally highest in dissolved solids and yields are lowest; this part of the basin corresponds to the fine-grained basin-center deposits exposed in the Presidio Bolson. Moving toward the basin margins, yields increase and quality becomes better as grain size increases and gypsum content decreases. Where the muds of the basin-center deposits interfinger with sands, ground water is commonly confined, thus under artesian conditions. Water yields in the coarser parts of the basin-margin or alluvial-fan deposits tend to be high, but because of the great relief differences between these areas and the basin center and the high permeability of the coarse sediments, depths to ground water are commonly great.

Application of the stratigraphic results of this investigation to undissected basins where numerous wells have been drilled and significant ground water is being extracted should provide a good test of the validity of using the stratigraphic framework of the Presidio Bolson as a model for similar basins. This work is in progress.

AVAILABILITY AND UTILIZATION

Ground water is the most valuable resource presently being extracted from the Presidio Bolson; it is obtained from three aquifers: (1) Rio Grande and sidestream alluvium, (2) bolson fill, and (3) bedrock underlying the bolson fill. The amounts pumped and the quality are highly variable; only the bedrock aquifers furnish reliable supplies of good-quality ground water.

Irrigation accounts for most of the water use in the bolson, and the majority of water used for this purpose is taken from surface flow of the Rio Grande below its confluence with the perennially flowing Rio Conchos about 4 miles above Presidio. Irrigated farming along the Rio Grande floodplain above this confluence depends on ground water because the flow of the Rio Grande is irregular and infrequent. Davis and Leggat (1965, p. U83) reported that about 24 wells in the Rio Grande alluvium were used to irrigate crops between Presidio and Ruidosa. These wells extracted about 5,400 acre-feet of ground water in 1960.

Presidio presently draws its municipal water supply from ground water in Cretaceous (?) limestone by means of a deep well drilled through the thick overlying bolson fill. Presidio formerly derived its water from a 64-foot well in Rio Grande alluvium that yielded an estimated 50 gpm (Davis and Leggat, 1965, p. U83). Several residences in and around Presidio maintain private shallow wells, withdrawing water from Rio Grande and Cibolo Creek alluvium. Domestic use of water between Presidio and Redford depends on ground water from Rio Grande and sidestream alluvium.

Ranchers in the bolson area depend on ground water for domestic use and for their stock. Many wells with windmills pump water from sidestream alluvium and from the bolson fill.

AQUIFERS

RIO GRANDE ALLUVIUM

Rio Grande alluvium, consisting of permeable channel gravels and floodplain silt and sand up to 65 feet thick, and intertonguing sidestream alluvium are the most important aquifers in the Presidio Bolson. Water is obtained at shallow depths along most of the Rio Grande floodplain, although the quality is commonly poor, especially above the confluence with the Rio Conchos. Davis and Leggat (1965, p. U85) reported that water from a well in Rio Grande alluvium above Presidio and the confluence had a dissolved-solids content of 2,850 ppm while a well below Presidio had 1,610 ppm. During drought periods the quantity and quality of ground water available from Rio Grande alluvium above the confluence with the Rio Conchos deteriorate and become unreliable, thus accounting for the marginal and intermittent nature of agricultural development there.

Rio Grande alluvium is recharged in three ways: (1) underflow from upstream, (2) infiltration from surface flow along the Rio Grande and its tributaries, and (3) underflow from adjacent sidestream alluvium and bolson deposits.

Underflow from upstream is maintained by recharge from bedrock and bolson areas along the river's course. How much water is actually transported by this mechanism is unknown, but the amounts are probably small. Surface flow in the Rio Grande and its tributaries contributes directly to ground water in storage in the alluvium by infiltration from the channel. The amounts involved are considerable below the Conchos where flow is perennial but less significant above this point.

Underflow from sidestream alluvium and from the bolson fill probably contributes most of the recharge to the Rio Grande alluvium. The presence of ground water in sidestream alluvium indicates that it moves down the channel deposits to the Rio Grande. This may not be a continuous process in all major sidestreams, but those that are fed by springs, such as Alamito, Hot Springs, and Spencer Creeks, probably contribute significant amounts. Recharge from Cibolo Creek alluvium is indicated by a well near Presidio that penetrated alluvium in what is probably a zone of interfingering of Rio Grande and Cibolo Creek gravels. This shallow well yielded water containing 524 ppm total dissolved solids while a well farther down the Rio Grande yielded water with 1,610 ppm. More data are obviously required before anything definitive can be said about this means of recharge.

McKnight (1968, pp. 140, 142) reported fresh water below clays that underlie Rio Grande alluvium near Redford. The water in the alluvium is alkaline and indicates that a discordance in quality exists, which probably reflects a lack of hydraulic connection between the fresher water in bolson sandstone and conglomerate and the poor-quality water in the Rio Grande alluvium. Impermeable clays may be preventing recharge even though favorable head relationships might exist.

Recharge from bolson deposits depends on the potentiometric surface of bolson ground water being above the base of Rio Grande alluvium and on the presence, in the bolson fill, of permeable beds to transmit the water. Near the margins of the Presidio Bolson, where the river enters and leaves the basin and crosses the coarse basin-margin facies, this may be a significant process. The great bulk of the bolson fill near the center of the basin is mudstone, however, and transmissibility through much of this part of the fill is very low. A well drilled near Presidio penetrated clay from 68 to 1,320 feet before it encountered water in a sand. The water was very saline and rose to within 110 feet of the surface (Davis and Leggat, 1965, p. U82). The location of this well is not known, but any well drilled near Presidio was probably within a few tens of feet, and probably less, of the Rio Grande floodplain; the 68 feet of sediment above the clay may, in fact, have been Rio Grande or sidestream alluvium. The fact that water was not encountered until 1,320 feet and that it rose only to 110 feet beneath the surface, well below the base of Rio Grande alluvium, indicates that recharge from rocks of the very fine-grained mudstone lithosome of the basin-center facies is probably minimal.

To summarize these somewhat speculative statements about recharge to Rio Grande alluvium, it seems most likely that intermittent recharge occurs from surface and subsurface flow of the Rio Grande and its tributaries, and that bolson deposits yield ground water to the alluvium near the basin margins. Springs along sidestreams may contribute significant amounts of water to Rio Grande alluvium via sidestream channel alluvium; this alluvium may also transmit water obtained from adjacent basins where the stream has cut headward into the fill of that basin. This may be true for Alamito Creek which heads in the Marfa basin; contours on the water table drawn by Davis (1961, p. 17) indicate a movement of water from that basin toward the Alamito Creek valley.

SIDESTREAM ALLUVIUM

Dietrich (1965, p. 242) reported that wells drilled in the floodplains of the larger tributaries to the Rio Grande get adequate supplies of water at less than 50 feet, and commonly less than 10 feet. This is especially true along Cibolo and Alamito Creeks where windmills pump water for stock from shallow wells. These wells and dug wells near abandoned residences in the Cibolo Creek valley penetrate the entire thickness of alluvium and bottom in the bolson fill. Water is obtained from the lower few feet of the alluvium just above the bolson fill. Some of these wells go dry at times; two of the dug wells observed in July 1967 did not contain water, and the fact that crumbled, abandoned dwellings stood nearby may indicate that the supply of water was not dependable. It may be that these wells did not penetrate the alluvium at its thickest point and that flow is in fact continuous in the deepest part of the channel.

Recharge to sidestream alluvium is by direct infiltration during periods of flow, by inflow from springs, and probably to some degree by subsurface flow from rocks of the adjacent mountain blocks. None of these has been measured or estimated, nor is it likely that accurate estimates are possible. It is probable that only the largest sidestreams have sufficient surface flow during storms and contain a sufficient thickness of alluvium to provide significant ground water to wells or to the Rio Grande alluvium. Dr. Zimmerly, who maintains an experimental farm near the Chinati Mountain Store (Pl. I), dug a well to the base of sandy sidestream alluvium not far from an area of seeps. The well entered bolson-fill claystone at 35 feet but did not encounter water, although the lower alluvial sands and claystone below were moist. Thus, sidestream alluvium, based on the experience of previous attempts, should not be considered as a dependable source of ground water in exploration projects in the Presidio Bolson.

BOLSON FILL

Bolsons and related alluvium-filled structural basins supply much of the ground water used for irrigation, watering stock, municipal supplies, and domestic supplies in Trans-Pecos Texas. Wells deriving ground water from bolson deposits are numerous and productive in the Marfa basin, Lobo Valley, Salt Basin, Toyah basin, and Hueco Bolson. The most productive aquifers are the gravel and sand of the alluvial-fan complexes bordering the valley and sands interbedded with muds nearer the basin centers. The water is under water-table conditions, it is unconfined near the basin margins, but as interbedded muds increase in number and thickness toward the basin center, much ground water is under artesian head.

Because the Presidio Bolson is structurally and stratigraphically similar to these other basins in having permeable coarse-grained deposits lapping onto the bordering mountains where rainfall is concentrated, it can be assumed that ground water should be present in the bolson-fill sediments. Two factors complicate the picture, however, and while they do not negate the presence of ground water in the Presidio Bolson, they do exert a strong influence on its mode of occurrence. First, the bolson deposits have been dissected by the Rio Grande and its tributaries, and, secondly, a large part of the basin fill consists of relatively impermeable mudstones.

Dissection of the basin has resulted in over 1,000 feet of relief between the upper edges of the basin-margin deposits near the adjacent mountains and the surface of the Rio Grande floodplain. The water table in permeable sediments is commonly flat, and its elevation is controlled to a large extent by the elevation of the point of discharge down the potentiometric gradient. If some discharge is assumed into the Rio Grande alluvium, the depth to ground water in the marginal parts of the basin would be great, perhaps as much as 300 to 600 feet. This would discourage the drilling of wells that rely on windmills to pump the water, and the high costs of drilling such a well would be complemented by the low productivity of the bolson in terms of grazing.

The wide lateral extent (Pl. I) and great thickness of the relatively impermeable and highly mineralized basin-center facies restrict both the quantity and quality of ground water available over much of the basin. Low specific yields and the poor quality of water in these gypsiferous sediments make what water might be available from wells in the basin-center facies unusable for most purposes.

A few windmill-pumped wells do extract ground water from the bolson fill. A few are located near the basin margins where the thickness of fill over bedrock is not great, and water entering the bolson deposits from the mountain blocks can be tapped at reasonable depths. Wells of this type are located (1) along Torneros Creek in the Redford and Presidio Bolsons and near the base of the West Chinati Peak intrusive mass on the Gonzalez and Mesquite ranches and (2) in the Pinto Canyon area. Other successful wells have been drilled in the area corresponding to the zone of interfingering of bolson-fill sandstone and mudstone in the sandstone-mudstone lithosome. Depths to water in these areas are not known but are probably not over 200 feet. Most of the gypsiferous sediments are basinward of this zone and water is not too highly mineralized. A well of this type is located north of San Antonio Creek in the sandstone-mudstone lithosome.

SPRINGS

Several springs, associated with faults and facies changes, steadily discharge ground water from the bolson fill (fig. 5). Only those observed are described here; there may be more. Several of the springs and seeps are utilized on a small scale for watering stock or as a source of domestic supply, but other than at Hot Springs, no development has occurred in their immediate vicinities.

The best known springs, Hot Springs, are those located northeast of Ruidosa along Hot Springs Creek. Hot mineralized water issues from conglomerate and sandstone of the basin-margin facies, probably from a fault zone. The springs have been developed into a small resort area, and people come from all over West Texas to relieve aches, pains, old age, and various diseases with a bath in the warm water.

There are seeps at various places in the zone of interfingering of basin-margin conglomerates with sandstone and mudstone of the basin-center facies. Most are associated with faults of small displacement and yield very small quantities of water. A line of seeps and springs occurs along a series of faults in the sandstone and mudstone facies west and southwest of Ruidosa. Ruidosa Springs, located along "Boundary" Creek about 3 miles west of Ruidosa just south of the Pinto Canyon road, discharge several gallons a minute through a pipe placed into the seep area by local residents. Several families haul this water to their homes in Ruidosa and Barrancos. The line of seeps and springs that extends southwestward from this area has deposited calcium carbonate over much of the surface. The area of manganese deposits described in a previous section occurs along the series of small arroyos that head along this line of seeps. This is also the area in which the bolson fill contains limestone, lenses of chalcedony, and carbonate-cemented sandstone.

A small spring, or springs, discharges a few gallons per minute along the bank of the arroyo located near the end of the pavement along Farm Road 170. The reason for the presence of springs in this area is not entirely clear; the bolson fill is interbedded sandstone and mudstone with no facies changes evident. There is a series of slumplike faults in the area, however, and the springs may be related to these or to deeper-seated faults that produced the slumps. Small, intermittent seeps occur in similar deposits near the Zimmerly Experimental Farm and may be related to faults obscured by the thick sidestream alluvial cover derived from West Chinati Peak.

Springs discharging several gallons per minute occur on the Gonzalez ranch along Spencer Creek (fig. 5). The springs are located along the edge of an outlier of igneous rock in the zone of facies change from interbedded sandstone and mudstone to dominantly mudstone. The water runs a few hundred yards down a stream bed before infiltration into the sandy alluvium saps all flow.

A series of seeps and springs occurs along Alamito Creek a few hundred yards above the highway bridge and along the bluffs at the margin of the Rio Grande floodplain north of Alamito Creek. This is an area of faults and close proximity of volcanic rocks, exposed at various places along the road (Dietrich, 1965, Pl. 1); thus, the presence of springs is probably not directly related to facies changes in the bolson fill or to the fill itself. The Tertiary rocks in this area contain numerous conglomerate beds; ground water from these may be brought to the surface along one of the several faults in the area. It is possible, however, that the water is derived from the bolson fill where it has been faulted against, or deposited against, impermeable volcanic rocks.

FUTURE DEVELOPMENT

The extent and availability of ground-water resources in the Presidio Bolson are largely unknown. Few wells have been successful in drawing water of usable quality from the fill, but this may be because only a few have been attempted. If attempts to drill wells have been limited, and there is no information as to the extent of exploration in the bolson, it may be because the land in the bolson possesses little to encourage development. The soil is not arable and the grazing conditions are poor. The only land valuable for crops is that along the Rio Grande floodplain, and ground water from the bolson fill in this area of predominantly mudstone is in very small quantity and of very poor quality.

If a reason should develop for further exploration for ground water, based probably on increases in the tourist or retirement-living industry, the best sources of water from the bolson fill would be in the zone of interfingering of basin-margin and basin-center rocks. Depths to water are likely to be reasonable in this zone, and the chances for water of sufficient quantity and quality are best. In this zone, the best localities are probably in the area west of West Chinati Peak where the fill contains numerous beds of sandstone shed from the intrusive rock of West Chinati Peak. The presence of ground water in the bolson fill in this area is indicated by the presence of springs and seeps.

Ground water from rocks of the bolson fill near the axis of the basin is not suitable, for reasons mentioned above. Yields from sidestream alluvium are unreliable and those from alluvium of the Rio Grande are of variable quantity and quality. On the other hand, costs of shallow wells are not great and exploration might be justified.

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