

THE GEOMORPHOLOGY AND MORPHOMETRIC CHARACTERISTICS OF  
ALLUVIAL FANS, GUADALUPE MOUNTAINS NATIONAL PARK AND  
ADJACENT AREAS, WEST TEXAS AND NEW MEXICO

A Thesis

by

JEFFREY LYLE GIVEN

Submitted to the Office of Graduate Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Geography

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## ABSTRACT

The Geomorphology and Morphometric Characteristics of  
Alluvial Fans, Guadalupe Mountains National Park and Adjacent Areas, West Texas and  
New Mexico. (May 2004)

Jeffrey Lyle Given, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Vatche P. Tchakerian

This study qualitatively and quantitatively analyzes the geomorphology of alluvial fans in the Guadalupe Mountains Region (GMR) of west Texas and south-central New Mexico. Morphometric data for 31 alluvial fans and drainage basins have been derived. The data set was subdivided into Guadalupe and Brokeoff Mountain fans and was further subdivided on the basis of their location along the two mountain ranges. A conventional morphometric analysis was conducted relating alluvial fan area and slope to drainage basin area in order to understand if and to what extent the alluvial fans of the GMR are dependent on the physical environment, including characteristics and processes of the drainage basin and depositional site.

The results of the morphometric analysis indicate that the morphometric relationships that exist between the alluvial fans of the GMR and their contributory drainage basins are comparably to those of alluvial fans of the western United States. Morphologic and morphometric differences between the various groups primarily reflect geographic differences in the physiography and lithology of the contributory drainage basin, tectonics, and the various physical constraints imposed by the GMR.

To my parents, Dr. Randall L. Given and Patricia R. Given,

My brothers, Jonathan C. Given and Jason P. Given,

My grandmother, Leona Light,

And the memory of my grandparents, C. Wayne Modlin and Effie Modlin

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I would like to thank the members of my advisory committee for their patience, guidance, and mentorship: my committee chair, Dr. Vatche Tchakerian, who has been an invaluable friend and advisor to me for the last seven years and is largely responsible for my academic success; Dr. David Cairns, not only for his statistical and GIS expertise, but for his willingness to do whatever it took to help me finish and his continual patience and reassurance; and Dr. Rick Giardino, who taught me to look at geomorphology from a different perspective and provided me with valuable editorial and cartographic advice. Special thanks should be extended to Dr. Gordon Bell at Guadalupe Mountains National Park for his hospitality and support as well as his geomorphologic and geologic input.

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Finally, I would like to dedicate this thesis to my family. There is not a word in the English language that justly describes what you people mean to me. That is another thesis in and of itself. Thank you for helping me become the person I am today. Without you I am nothing...

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## CHAPTER I

### INTRODUCTION

Alluvial fans (Fig. 1) are prominent depositional landforms found in all global climatic regimes (Fig. 2) and serve as a transitional environment between a degrading upland area and adjacent lowland (Harvey, 1997). Alluvial fans have a morphology resembling a cone segment and can be found individually, radiating unobstructed in a 180° arc, or laterally coalescing with neighboring fans to form an alluvial apron or bajada (Blair and McPherson, 1994). Alluvial fans have constant or slightly concave slopes that typically range from less than 25 degrees at the head, or apex, of the fan to less than a degree at the terminus, or toe (Denny, 1965; Bull, 1977). At their distal margins, alluvial fans may be bordered by, or merge with, aeolian, fluvial, lacustrine, or marine environments.

The formation of an alluvial fan results from the accumulation of coarse-grained, poorly-sorted fluvial and/or mass-wasting sediments downslope from where abrupt changes in channel morphology and flow velocity reduce the carrying capacity of a transporting medium as it emerges from an upland drainage basin (Rachocki, 1981; Blair and McPherson, 1994). Although depositional episodes result in complex patterns of alluvial deposits on the fan surface (Mabutt, 1977), there tends to be a simple gradient where the sorting of sediments produces an exponential decrease in downslope particle size (Graf, 1988).

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This thesis conforms to the style and guidelines of the journal *Geomorphology*.

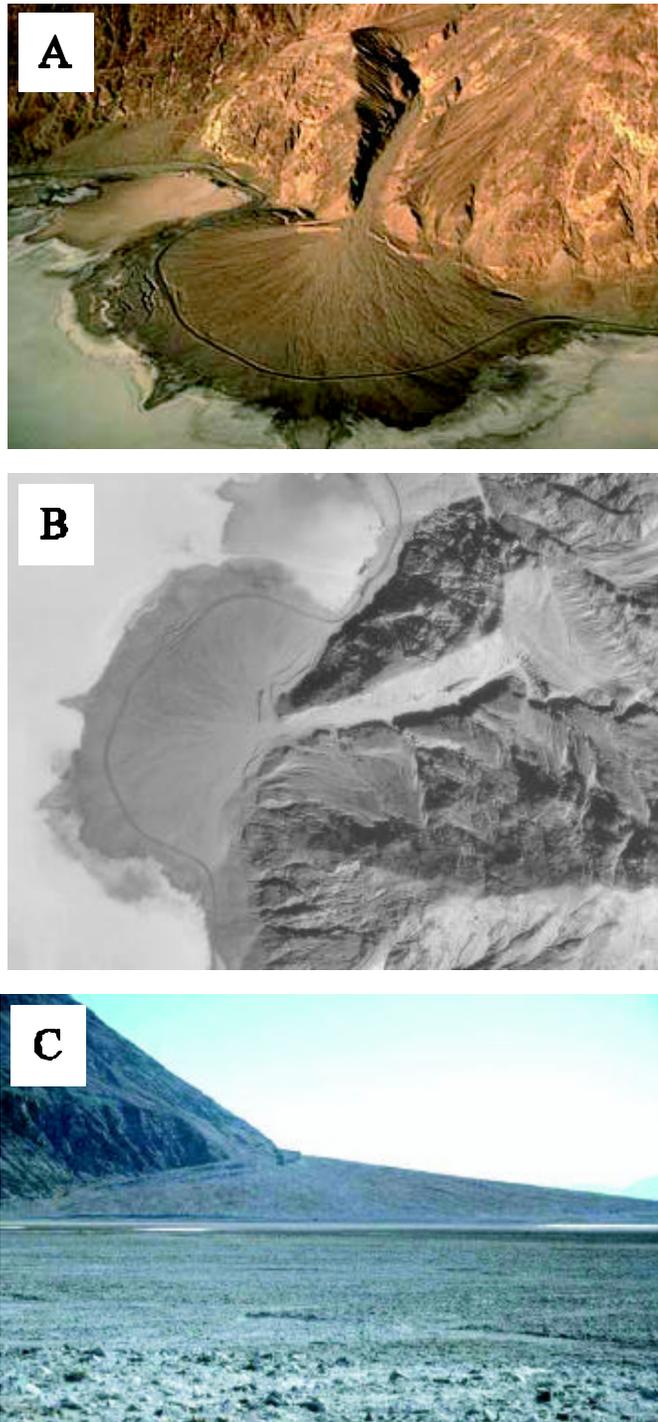


Fig. 1. Photographs of a typical alluvial fan. (A) An oblique aerial photograph (photo by M. Miller), (B) a modified 1997 Digital Orthophoto Quadrangle (obtained from California Spatial Information Library), and (C) a ground-level photograph (photo by M. Stokes) of the South Badwater alluvial fan in Death Valley, California.

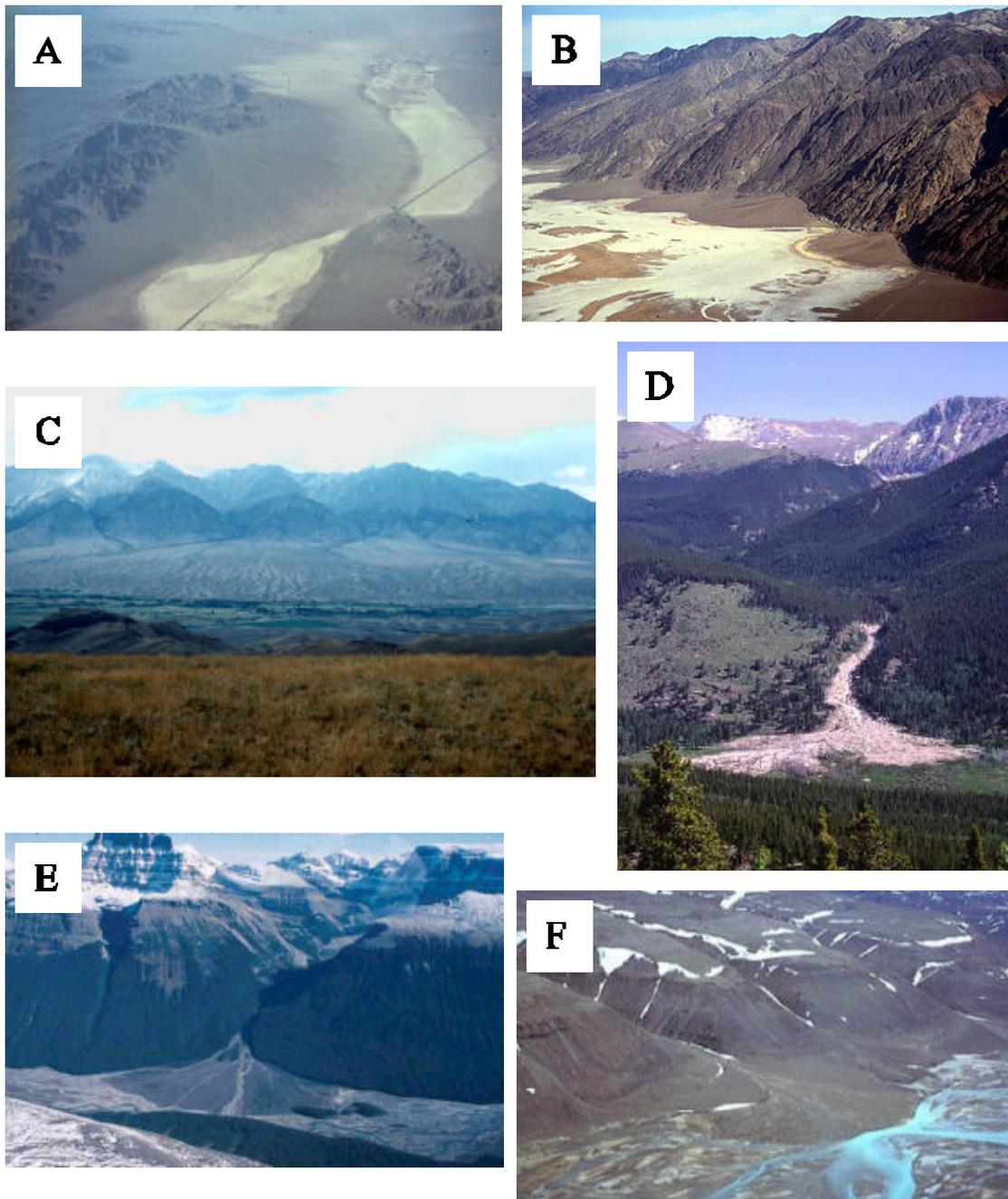


Fig. 2. Alluvial fans from various climatic regions. Arid alluvial fans from (A) Broadwell Lake, Mojave Desert, California (photo by V.P. Tchakerian) and (B) Black Mountains, Death Valley, California (photo by M. Miller). Semiarid alluvial fans from (C) Lost River Mountains, Idaho (photo by B. Railsback) and (D) Rocky Mountain National Park, Colorado (photo by T. Oguchi). Paraglacial alluvial fans from (E) Saskatchewan River, Alberta, Canada (photo by M. Stokes) and (F) British Columbia, Canada (photo by Geological Society of Canada).

### *1.1 Major morphologic features of an alluvial fan*

According to Blair and McPherson (1994), the typical alluvial fan system contains several major morphologic features: the drainage basin, feeder channel, fan apex, incised channel, distributary channels, intersection point, active depositional lobe, and headward-eroding gullies (Fig. 3). The drainage basin is the upland area from which sediment and a transporting mechanism is derived. Alluvial fan drainage basins in arid and semi-arid environments tend to have steep slopes and contain first, second, or up to fifth-order ephemeral streams. The highest order stream in the drainage basin that leads to the fan apex is the feeder channel. Usually a fan only has one prominent feeder channel, although some fans may have multiple feeder channels that are associated with subsidiary drainage basins. The fan apex is usually the highest part on the fan surface and represents the point at which the feeder channel emerges from the confines of the drainage basin. The incised channel is located on the alluvial fan and serves as the downslope extension of the feeder channel. The presence of a conspicuous incised channel is considered to be a sign of maturity. Although they typically occur on fans with longer radii, the presence of an incised channel, as well as its location, depth, and morphology, is dependent on a number of variables. Incised channels may extend down to the distal portions of the alluvial fan, but commonly terminate on the upper or medial part of the fan or divide into several distributary channels. When the incised channel merges with the slope of the fan, the transporting medium departs from the incised channel and begins to laterally expand. The point on the fan surface where this occurs is

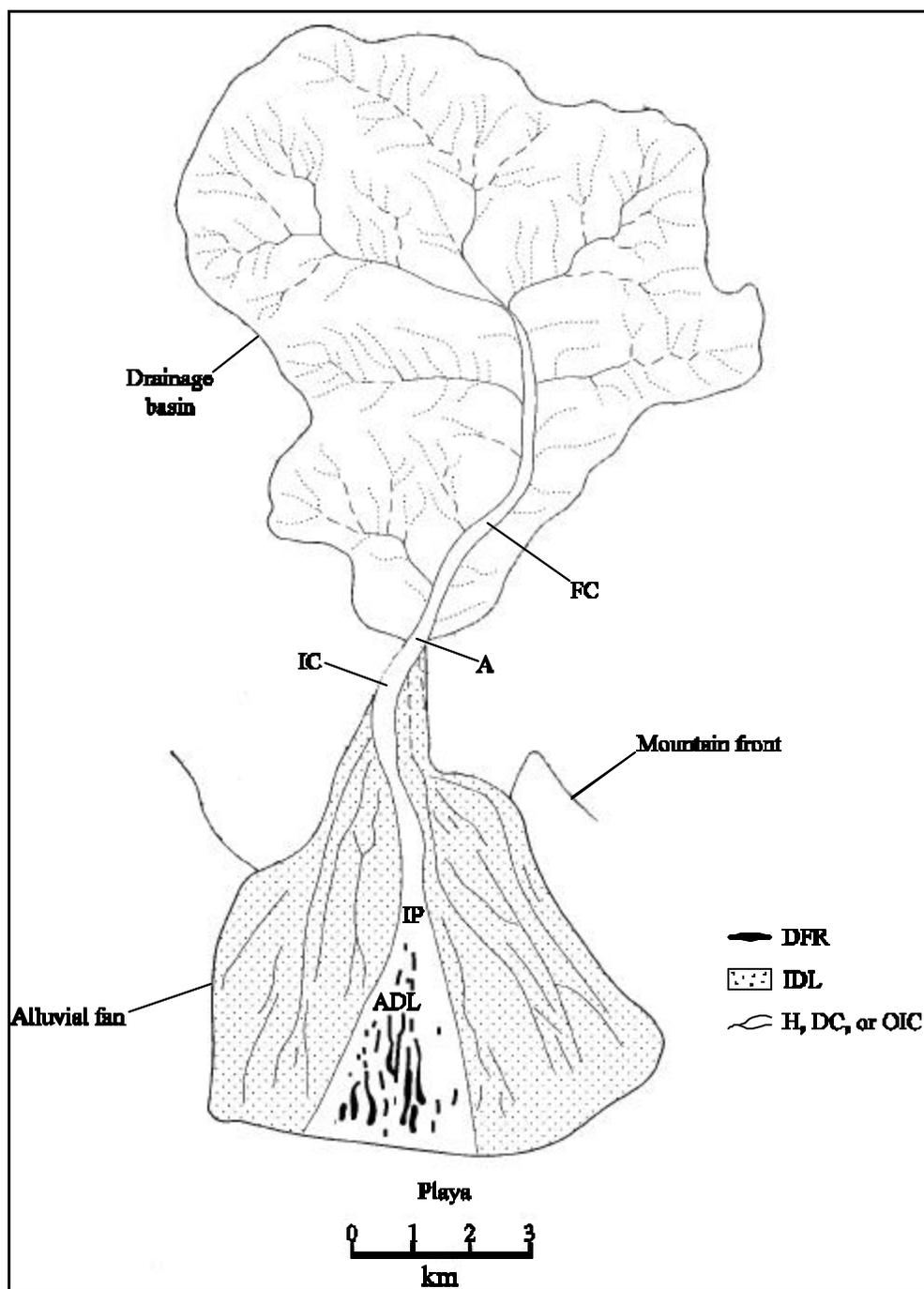


Fig. 3. Major morphologic features of an arid alluvial fan. Planview line sketch illustrating the location of the feeder channel (FC), fan apex (A), incised channel (IC), intersection point (IP), active depositional lobe (ADL), headward-eroding gullies (H), and distributary channels (DC). DFR, debris-flow remnants. IDL, "inactive" fan lobes. OIC, "old" incised channel (modified from Blair and McPherson, 1994).

termed the intersection point. The area directly downslope from the intersection point where sedimentation is taking place is termed the active depositional lobe. Headward-eroding gullies commonly form on the distal parts of the fan (Denny, 1967), particularly in older, temporarily inactive areas of the fan or in areas where the fan is composed of finer-grained sediments (Blair and McPherson, 1994). Headward erosion by these gullies progress in a proximal manner and may eventually alter the position of the active depositional lobe by merging with the incised channel (Denny, 1967; Blair and McPherson, 1994).

### *1.2 Alluvial fan development*

Three environmental factors are necessary for optimal alluvial fan development (Blair and McPherson, 1994). First, a topographic environment conducive to the development of alluvial fans must exist. In such a setting, a channel typically becomes unconfined as it emerges from an upland catchment onto a relatively level adjacent lowland. Prototypical settings may include tectonically uplifted mountain fronts, deglaciated or incised river valleys, or a bedrock escarpment or slope exposed to differential weathering and erosion (Blair and McPherson, 1994).

Sediment availability and production in the drainage basin, the second condition required for alluvial fan development, is highly dependent on the relief and lithology of the drainage basin (Blair and McPherson, 1994). The sediment yield in a drainage basin increases exponentially with an increase in relief due to the effects of gravity on slope

erosion and stability (Schumm 1963, 1977; Ahnert, 1970). The lithology of the drainage basin, and how it responds to various mechanical, chemical, and biological weathering agents, determines the rate and character of the sediment supply (Easterbrook, 1998). Weathering is greatly promoted within the drainage basins of alluvial fans that extend from tectonically controlled mountain fronts due to the preservation of relief and the efficiency of tectonic stresses and fracturing. Alluvial fans in non-tectonic settings, such as those located along paraglacial or incised river valleys (known as fan deltas), are typically composed of reworked glacial or fluvial sediment that was previously deposited in the contributing drainage basin (Blair and McPherson, 1994).

Third, a medium or mechanism is required for transporting sediment from the drainage basin to the site of fan construction. This is principally achieved by: (1) mass – wasting events or sediment-gravity flows and (2) high discharge fluvial events. The topography and shape of alluvial fan drainage basins in mountainous environments make them especially prone to generating high discharge events. Mountainous topography promotes orographic processes and quickly funnels precipitation into the feeder channel. Fan construction from drainage basin discharge events requires that the transporting medium loses some of its entraining capabilities upon exiting the drainage basin. This loss is due to decreasing flow depth and velocity resulting primarily from: (1) the lateral expansion of flows at the fan apex as the main feeder channel becomes unconfined or (2) a decrease in slope as the transporting medium reaches the fan apex (Blair and McPherson, 1994).

### *1.3 Problem statement*

Since the first published discussion of alluvial fans by Surell (1841), and the first use of the term by Drew (1873), alluvial fans have attracted substantial research interest. Because they are highly characteristic of arid and semi-arid mountainous areas, much of the classical research on alluvial fans has been conducted in the western United States (Eckis, 1928; Blackwelder, 1928; Blissenbach, 1954; Bull, 1962, 1964a, 1964b, 1964c; Beaty, 1963; Lustig, 1965; Melton, 1965; Denny, 1965, 1967; Hawley and Wilson, 1965; Hooke, 1968; Hooke and Rohrer, 1977; Lecce, 1988), with other notable studies based in Pakistan (Anstey, 1965), Iran (Beaumont, 1972), Australia (Wasson, 1974, 1977, 1979), Spain (Harvey, 1984, 1987, 1990; Silva et al., 1992), and throughout the Middle East (Bowman, 1978; Khalaf et al., 1982; Al-Sarawi, 1988; Maizels, 1990; Gerson et al., 1993; Freytet et al., 1993; Al-Sulaimi and Pitty, 1995; Al Farraj, 1996; Al Farraj and Harvey, 2000).

However, despite extensive research on the geology and geomorphology of the northern Chihuahuan Desert, the alluvial fans of the region have been largely ignored or received only passing mention. Consequently, the few publications (King, 1948; Jacka, 1974; McKnight, 1986; Hussain et al., 1988; Thuma, 1990) that mention the alluvial fans in this region tend to be descriptive and deal primarily with their location and appearance and, to a lesser extent, geology. Thus, the purpose of this study is to investigate the geomorphology of alluvial fans in the northern Chihuahuan Desert, specifically those located along the piedmont of the Guadalupe and Brokeoff Mountains

of west Texas and south-central New Mexico.

#### *1.4 Objectives*

The general objective of this study is to describe the morphology and analyze the morphometry of the alluvial fans of the Guadalupe and Brokeoff Mountains of west Texas and south-central New Mexico. More specifically, this thesis has 3 foci: (1) to describe the geologic and geomorphic characteristics of the Guadalupe Mountains Region (GMR), (2) to present a morphometric analysis of the alluvial fans of the Guadalupe and Brokeoff Mountains and compare the results to previously published morphometric studies from the western United States, and (3) to examine the factors influencing the morphology and morphometry of the alluvial fans of the Guadalupe and Brokeoff Mountains.

## CHAPTER II

### THE STUDY AREA

#### *2.1 Location and physiography*

The Guadalupe Mountains Region (GMR) is located in west Texas and south-central New Mexico and includes the Guadalupe Mountains, Brokeoff Mountains, Big Dog Canyon, and Salt Basin-Crow Flats (Fig. 4). The GMR is located about 180 km east of El Paso, Texas, and about 110 km southwest of Carlsbad, New Mexico, and includes federal lands managed by the National Park Service in Culberson and Hudspeth Counties, Texas, and the United States Bureau of Land Management in Eddy, Otero, and Chaves Counties, New Mexico (Fig. 5).

The GMR is positioned near the border of two major physiographic provinces: the southeastern margin of the Basin and Range and the southwestern edge of the Great Plains. The Basin and Range is centered in Nevada and lies to the west and south of the Colorado Plateau. It enters far west Texas from southern New Mexico and consists of block-faulted, subparallel or scattered, north-south trending mountain ranges separated by alluviated endoreic basins (Tchakerian, 1997) that were formed by high-angle extensional faulting (Dohrenwend, 1987). The Great Plains lie to the east of the Rocky Mountains and extend south from North Dakota and eastern Montana into northwest Texas. Structurally, the Great Plains is a broad, undisturbed syncline with a generally flat or gently undulating surface consisting of sedimentary rocks that dip slightly from

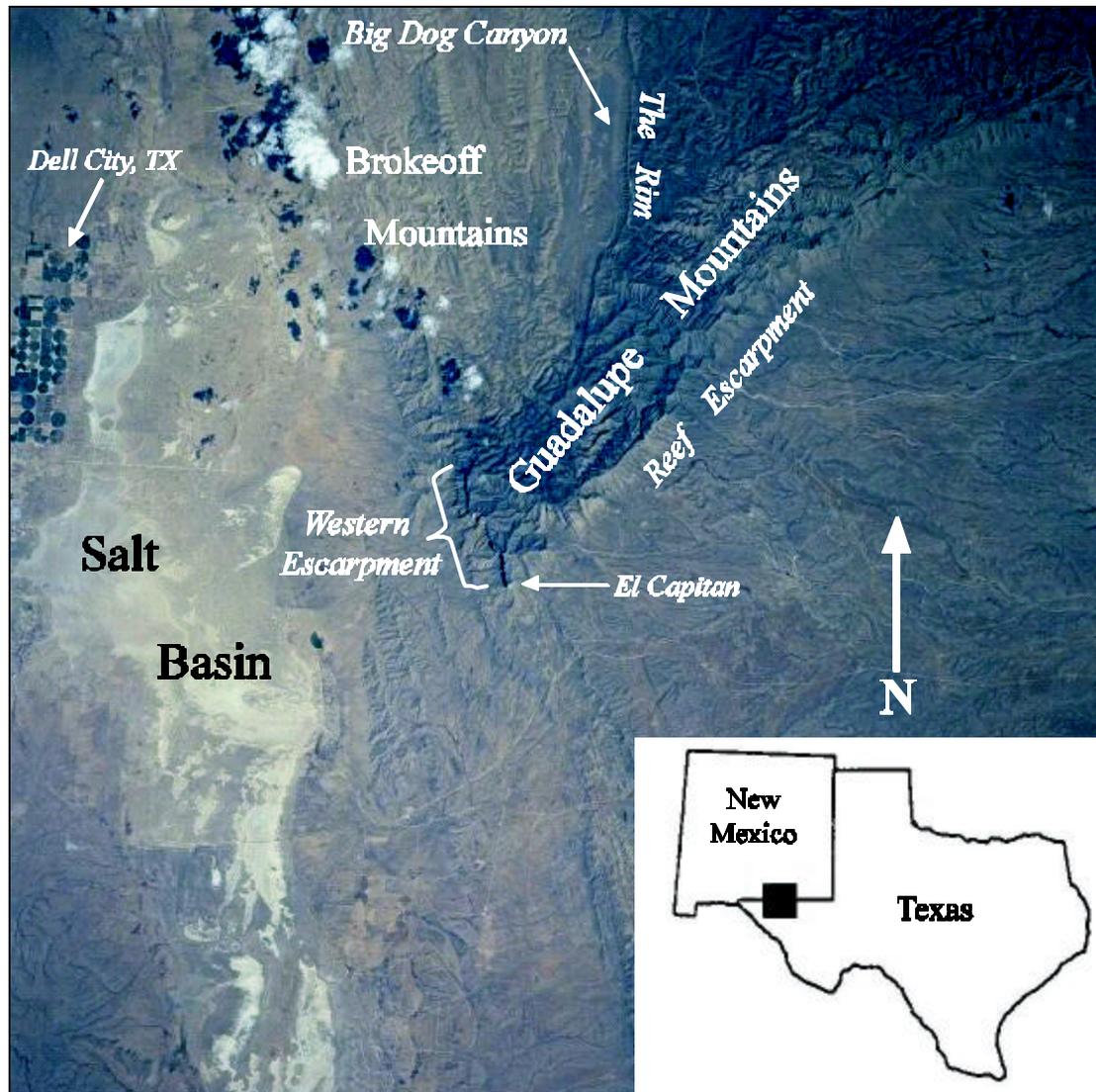


Fig. 4. Gross physiography of the Guadalupe Mountains Region (GMR). Undated NASA Space Shuttle photograph showing the gross physiography of the GMR. Inset shows location of the GMR within Texas and New Mexico (modified from McKnight, 1986).

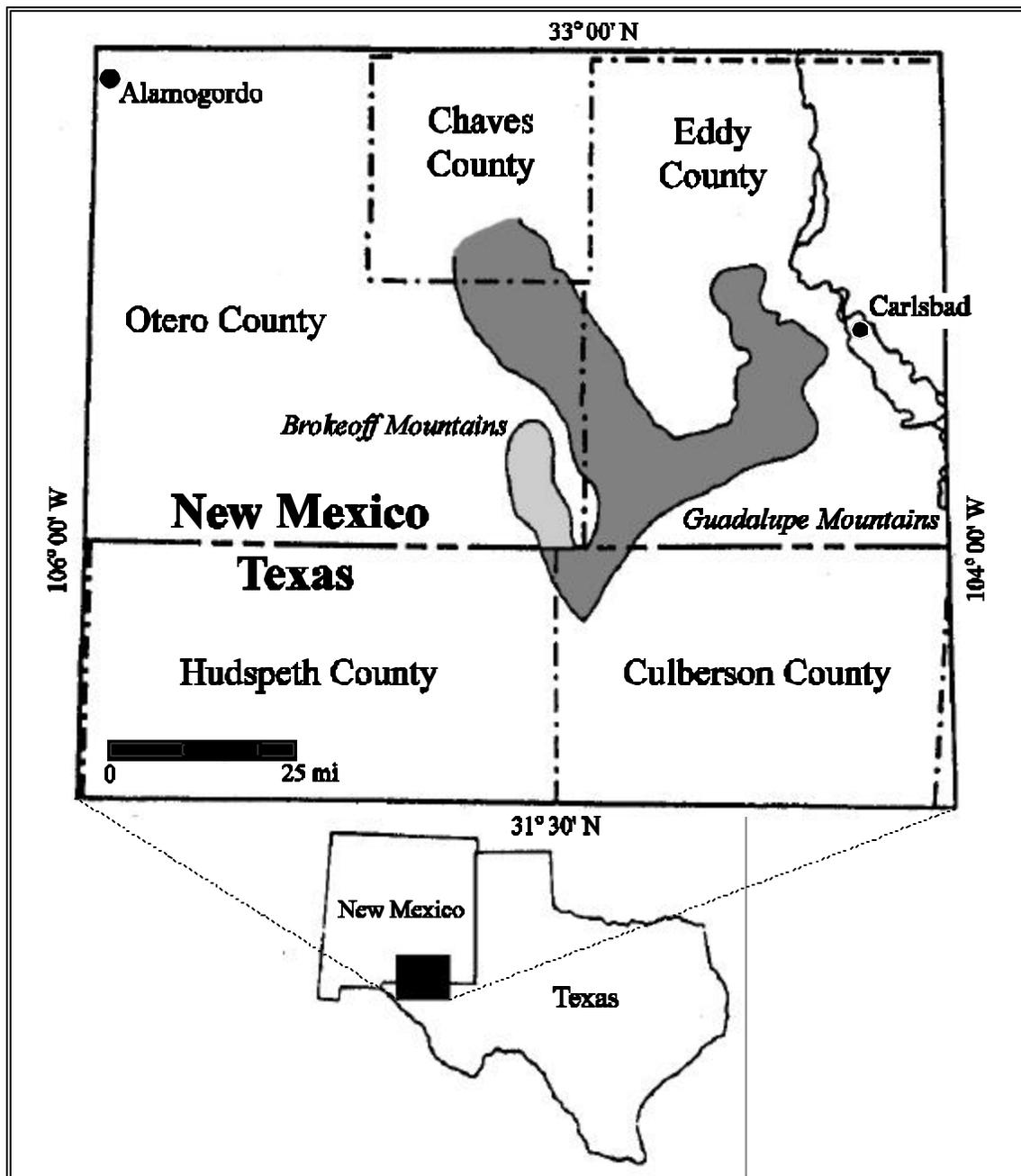


Fig. 5. Location map of the Guadalupe and Brokeoff Mountains within Texas and New Mexico (modified from McKnight, 1986).

west to east (Thuma, 1990; Mack, 1997).

The Guadalupe Mountains are a wedge or V-shaped, east-northeast-tilted fault block with the prominent El Capitan (elev. 2464 m) recognized as the southern-most point. The southeast-facing Reef Escarpment (King, 1942) of the Guadalupe Mountains extends to the northeast from El Capitan towards Carlsbad, New Mexico, and descends into the Pecos River drainage basin and then beneath the Great Plains. The western extension of the Guadalupe Mountains stretches roughly 120 kilometers to the north-northwest from El Capitan and features the fault escarpment known as “The Rim,” and the “western escarpment,” which is characterized by sheer cliff faces and a series of prominent peaks exceeding 2440 meters in height.

The Brokeoff Mountains are a range of smaller, anticlinal horsts trending north from the western escarpment slightly north of the New Mexico border. They are fractured by numerous north-south trending normal faults and dissected by ephemeral streams that flow into two basins, Big Dog Canyon to the east and Salt Basin-Crow Flats to the west (McKnight, 1986).

Big Dog Canyon is an alluviated, synclinal graben bounded on the west by the Brokeoff Mountains and on the east by The Rim. It originates near the prominent peaks of the Guadalupe Mountains and slopes north where it empties into the Crow Flats at the north end of the Brokeoff Mountains (McKnight, 1986). Salt Basin-Crow Flats is a 420-km-long half-graben that has an elevation of 1087 meters at its deepest point (Wilkins and Currey, 1997). It stretches from south of Van Horn, Texas, northwest into New Mexico, where it terminates between the Sacramento and Guadalupe Mountains (Mayer

and Sharp, 1998). The northern end of the basin in New Mexico is known as the Crow Flats, while the southern portion in Texas is called the Salt Basin (McKnight, 1986). The basin dips gently to the southwest and is bounded to the east by the Guadalupe, Brokeoff, and Delaware Mountains and to the west by the Sierra Diablo Mountains and Diablo Plateau. It is an endoreic hydrologic system where groundwater discharges into a chain of dry alkaline lakes, or playas. These playas collectively extend for roughly 95-km along the floor of the graben (Hussain et al., 1988).

## *2.2 Modern climate*

The semi-arid GMR lies on the northeastern margin of the Chihuahuan Desert, the largest (450,000 km<sup>2</sup>) and least studied of the North American deserts (Tchakerian, 1997). The Chihuahuan Desert is centered in the Mexican state of Chihuahua and is bordered on the west by the Sierra Madre Occidental, to the east by the Sierra Madre Oriental, to the south by the highlands of the Mexican Plateau, and to the north by the southern Rocky Mountains (Goudie, 2002). The modern climatic regime of the Chihuahuan Desert was established by 4000-5000 years before present (Leonard and Frye, 1975; Van Devender, 1990).

The weather station located at Guadalupe Mountains National Park headquarters, located in Pine Springs, Texas (elev. 1710m), reports approximately 442 mm of precipitation annually (16-year average, 1987-2002). Sixty-one percent of this annual total occurs from June to September in the form of orographic and localized

convectonal thunderstorms associated with the summer monsoon season of the American southwest. Compared to the summer rainy season, the winter months experience low intensity frontal precipitation, which may cover larger areas and take the form of snow at higher elevations. The mean annual temperature at Guadalupe Mountains National Park headquarters is approximately 14.8°C with mean monthly maximum and minimum temperatures occurring in July (23.5°C) and December (5.6°C), respectively (National Climate Data Center, 2002). However, Salt Flat, Texas, located near the floor of Salt Basin (elev. 1100m), receives only 280 mm annually (Tuan et al., 1973) and has mean monthly temperatures ranging from 27°C in July to 6°C in January (Griffiths and Bryan, 1987).

### *2.3 Geology and geomorphology of the study area*

The first publication describing the geography of the Guadalupe Mountains was that of Bartlett (1854), who traveled with the United States-Mexican Boundary Commission. The first geologic work was that of Shumard (1858) with Richardson (1904), Girty (1908), and Lloyd (1929) publishing subsequent notable studies. From a geomorphic perspective, the most significant studies on the GMR are those of King (1948) and Kelley (1971, 1972). King (1948) described and interpreted the stratigraphy and structure of the Guadalupe Mountains in great detail and provided the most comprehensive description of the geomorphic features of the region (McKnight, 1986). Kelley published detailed studies on the structure and stratigraphy of southeastern New

Mexico (1971) and the tectonic history of the Reef Escarpment (1972).

The geomorphic evolution of the GMR can be traced back to the Precambrian (Flawn, 1956; Kelley, 1971). During the late Precambrian, the GMR was divided into a gentle anticlinal western area, known as the Pederal Landmass, and a structurally low eastern area, the Tobosa Basin. During the early Paleozoic, the Pederal Landmass was tectonically erratic, at times buried by sediments eroded from surrounding highlands and at other times uplifted and denuded. During the early Pennsylvanian, the Pederal Landmass was uplifted and shed sediments into the Tobosa Basin, which at the time was beginning to subside along normal faults, marking the initiation of the Delaware Basin. During the late Pennsylvanian, the Delaware Basin received an abundance of sediment as a renewed uplift of the Pederal Landmass caused the overlying Paleozoic sedimentary rocks to erode (Kelley, 1971).

During the early Permian, the Delaware Basin continued to subside while the Pederal Landmass continued to be uplifted and eroded (Kelley, 1971). The early and middle Permian is characterized by the development of various barrier reef and related fore-reef and back-reef environments along the northwestern shelf of the deep Delaware Basin. These sediments are represented in the stratigraphic record by the various consolidated limestone, dolomite, and sandstone formations of the Guadalupe and Brokeoff Mountains (King, 1948). Evaporite deposits began to form in the Delaware Basin by the late Permian indicating a decrease in depth or inadequate circulation (Kelley, 1971).

During the Triassic and Jurassic, erosion dominated the GMR (Kelley, 1971).

After being buried by marine clastics and carbonates during the tectonically-stable early Cretaceous, the Laramide Orogeny (late Cretaceous to Eocene) caused extensive deformation and fracturing throughout the GMR (King, 1948; Kelley, 1971). During the Oligocene, the Trans-Pecos magmatic province became active (Barker, 1977). Some of the western portions of the GMR were uplifted and deformed as igneous intrusions were injected into the overlying Permian and Cretaceous rocks (Kelley, 1971).

During the early Miocene, the Cretaceous rocks covering the Guadalupe Mountains were eroded as the rise of the Rocky Mountains produced a gentle eastward tilt in the GMR (McKnight, 1986). The Rocky Mountains continued to rise, and consequently erode, from the late Miocene through the early Pliocene (Frye and Leonard, 1957), creating a huge bajada system (the Ogallala Formation) that possibly spread as far west as the present-day Guadalupe Mountains (King, 1948; McKnight, 1986). According to King (1948), the earliest phases in the formation of the Guadalupe Mountains were episodic and are poorly represented in the area. The initial uplift is thought to have occurred during the late Miocene or early Pliocene (King, 1948). As the Rio Grande Rift became active to the west (Ramberg et al., 1978; Mack, 1997), extensional forces split the region into several fault blocks and the Guadalupe and Brokeoff Mountains began to rise as an anticlinal arch along a series of normal faults (McKnight, 1986). During the uplift, erosion removed the Ogallala Formation from most of the GMR (McKnight, 1986). However, alluvial material washed from the mountains following this initial uplift serve as the oldest unconsolidated rocks deposited in the adjacent Salt Basin and are thought to be of Pliocene age (King, 1948).

By the late Pliocene or early Pleistocene, a second period of uplift had raised the Guadalupe and Brokeoff Mountains to their present height, causing the Big Dog Canyon and Salt Basin-Crow Flats grabens to subside (King, 1948; McKnight, 1986). During the Pleistocene, Salt Basin-Crow Flats and Big Dog Canyon continued to subside and were subsequently filled by as much as 500 meters (Veldhuis and Keller, 1980) of coarse-grained alluvium. This was, perhaps, the result of a fluctuation in climate but more likely was a response to the renewed uplift of the adjacent mountain ranges (King, 1948). It is during the late or middle-to-late Pleistocene, near the Last Glacial Maximum (LGM), that pluvial Lake King (to be discussed in section 2.6) occupied Salt Basin-Crow Flats (Wilkins and Currey, 1997). The late Pleistocene was characterized by a final period of minor uplift that displaced and dissected some of the previously deposited alluvial material (King, 1948).

Quaternary fault movements in the GMR are indicated by north- or northwest-trending scarps that are roughly parallel and proximal to mountain fronts or pre-existing structural trends and generally appear as lakeshore scarps, mid-fan breaks, or bedrock boundaries (Goetz, 1977; Muehlberger et al., 1978). Quaternary fault scarps are short and widely scattered along the eastern side of the Salt Basin-Crow Flats. The faults along the western margin are more numerous and continuous and exhibit progressively larger displacements southward, indicating greater modern subsidence on the western side of the basin (Muehlberger et al., 1978). Two small, conspicuous fault scarps in Quaternary alluvium trend north along the eastern margin of the Salt Basin-Crow Flats north of the Texas border (Muehlberger et al., 1978). The northernmost scarp, located

50 kilometers north of the Texas border, is a Holocene fan scarp that was mapped by Kelley (1971) near the northern end of the Guadalupe Mountains (Muehlberger et al., 1978). The second scarp is located 10 kilometers to the south and was mapped in the Crow Flats by Muehlberger et al. (1978). Near the Patterson Hills, concealed Quaternary fault scarps have contributed to stream dissection and the displacement of older fan conglomerates and gravels (King, 1948). The present structural configuration of the GMR is illustrated in Fig. 6.

#### *2.4 Geology and descriptive geomorphology of the alluvial fans of the study area*

##### *2.4.1 Guadalupe Mountains*

The Border Fault Zone (Fig. 7), which bounds the western escarpment of the Guadalupe Mountains on the west, consists of a series of branching, down-to-the-west normal faults that trend in varying directions (King, 1948; McKnight, 1986). The Border Fault Zone is mantled by Quaternary alluvial fans that have coalesced to form a three-to-six kilometer wide bajada that rises 150-450 meters from the floor of the Salt Basin to the base of the western escarpment (Fig. 8). These concave, elongated fans occur at the mouths of a series of V-shaped, steep-walled canyons that, according to King (1948: 135), “drain only a few square miles of area” (Fig. 9). The canyons that feed these fans have high drainage densities (McKnight, 1986) and contain relatively straight, high-gradient feeder channels that developed along fracture zones or other geologic discontinuities in the escarpment’s original tectonic surface (King, 1948).

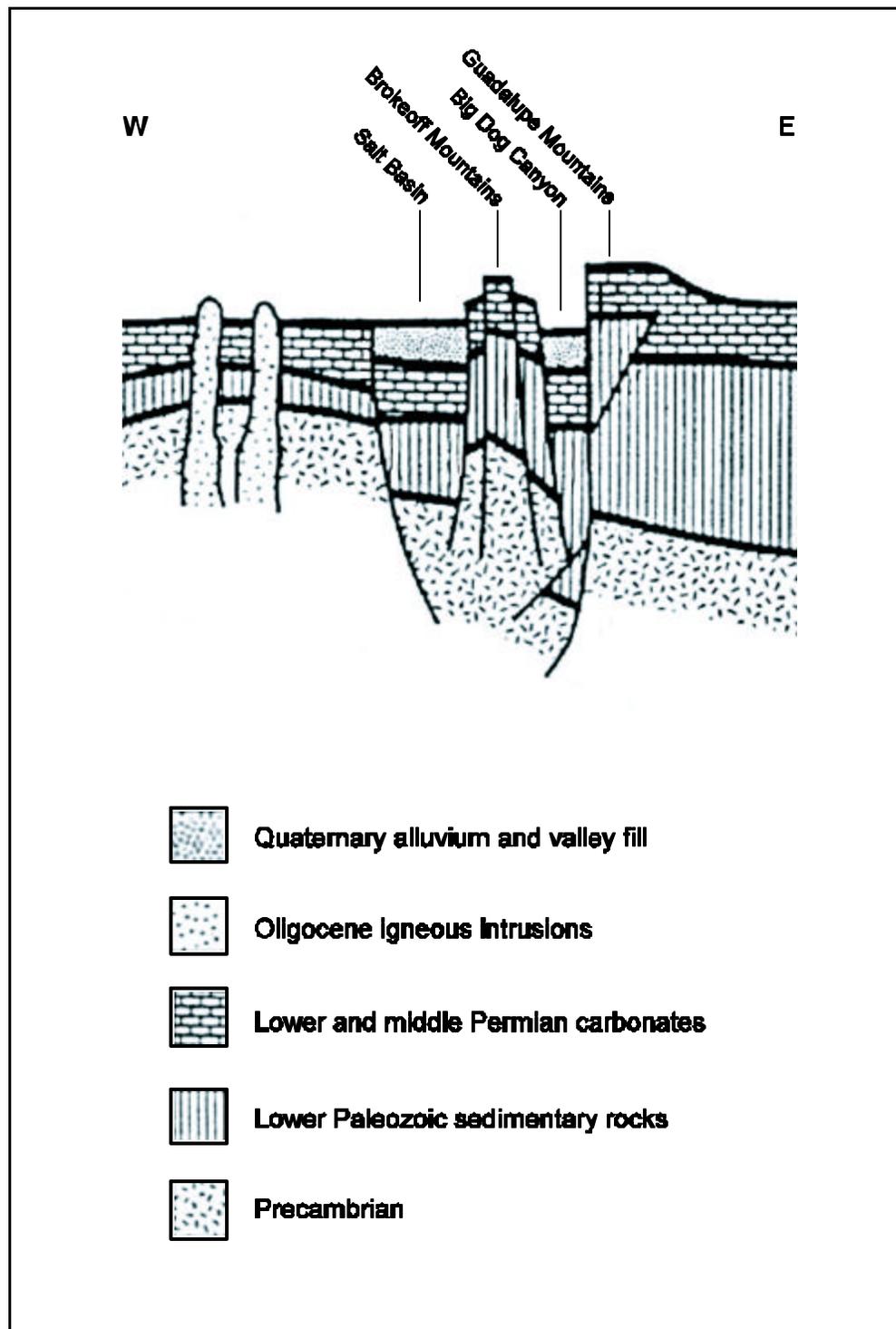


Fig. 6. Present structural configuration of the Guadalupe Mountains Region (modified from McKnight, 1986).

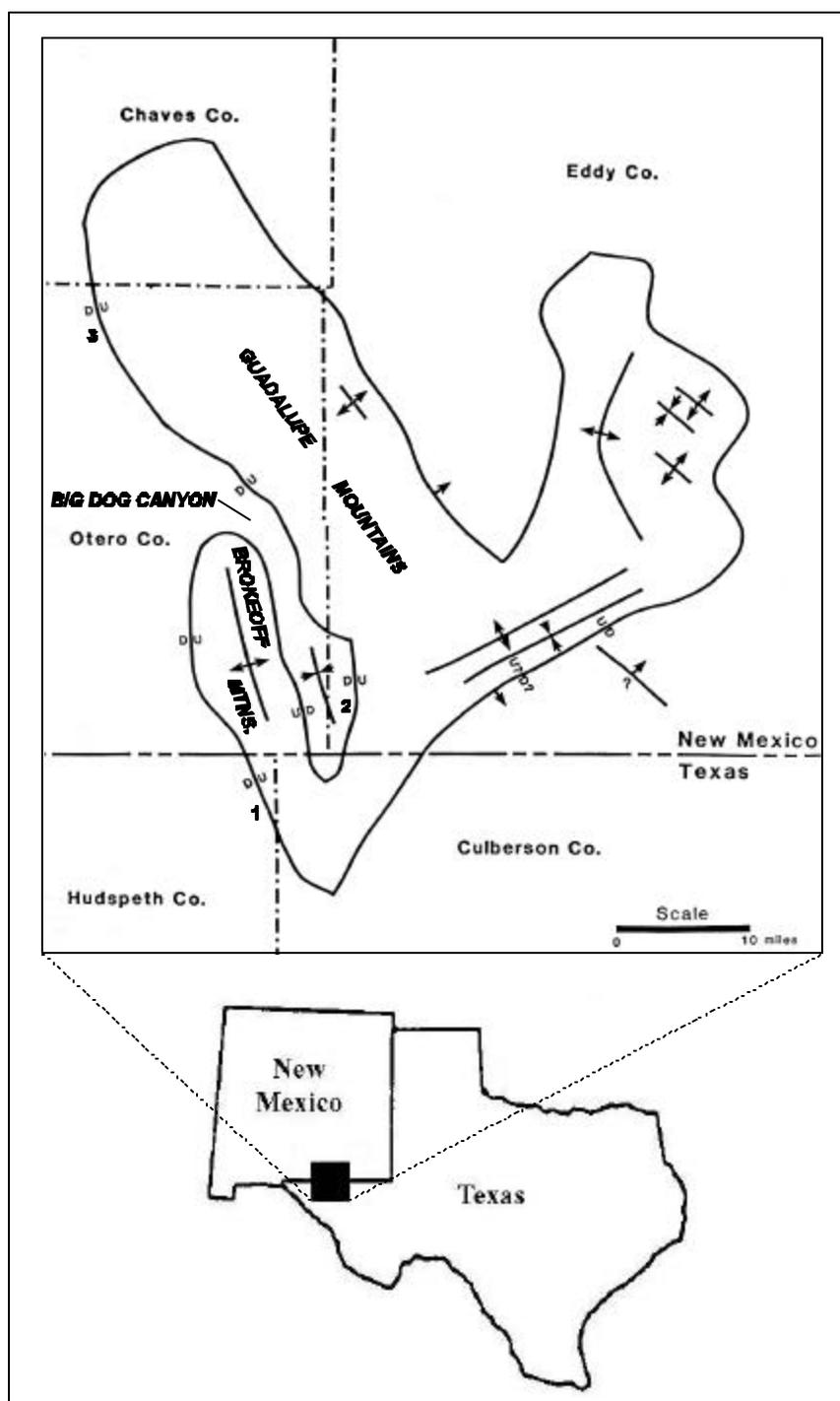


Fig. 7. Fault map of the Guadalupe and Brokeoff Mountains. Note the location of the (1) Border Fault Zone, (2) Dog Canyon Fault Zone, and (3) Guadalupe Fault Zone (modified from McKnight, 1986). D, down. U, up.



Fig. 8. Alluvial fans and bajada in Salt Basin-Crow Flats. Ground-level photographs of (A) alluvial fans along the base of the western escarpment of the Guadalupe Mountains in Salt Basin, and (B) view north of the Salt Basin-Crow Flats bajada from the apex of the alluvial fan located in the center of photograph A.



Fig. 9. Photograph of a drainage basin. Up-slope perspective of the drainage basin of an alluvial fan located at the base of the western escarpment of the Guadalupe Mountains (photograph by P. Rindfleisch).

Although, the fans “tend to be of nearly equal size and gradient,” King (1948: 135) noted that “those [fans] with the flatter gradients and longer radii are fed by canyons that drain the larger areas in the mountains.” The bajada abruptly merges with the nearly-horizontal Salt Basin by descending “100 feet or more in the last mile” (King, 1948: 136).

The bajada is underlain by a complex of deposits laid down during successive stages of the uplift and subsequent erosion of the Guadalupe Mountains (Fig. 10). Most deposits currently exposed on the bajada surface are thought to be late Pleistocene-Holocene in age. However, “older fanglomerates” have been exposed by Quaternary faulting and stream incision and, in some cases, lie above the present bajada surface. This is especially evident on the southeastern margin of the western escarpment, where alluvium has accumulated behind the Patterson Hills (King, 1948).

Near the apexes of these fans and in the lower parts of the drainage basin, angular blocks of bedded or massive limestone 3 meters or more in diameter are common. These blocks are thought to be the result of exceptionally large floods or debris flows. Non-imbricated, unstratified lobes of angular debris dominate the proximal areas (Fig. 11) and are sporadically distributed throughout the medial areas of these fans. These deposits are indurated to varying degrees by calcium carbonate and gypsum and, according to King (1948), were likely deposited by normal flow events. Channels dissecting the medial and distal part of these fans commonly expose imbricated cobbly and pebbly debris flow deposits (Fig. 12A) and interstratified clast-rich and clast-poor sheetflood deposits (Figs. 12B, C). The stratification of these layers

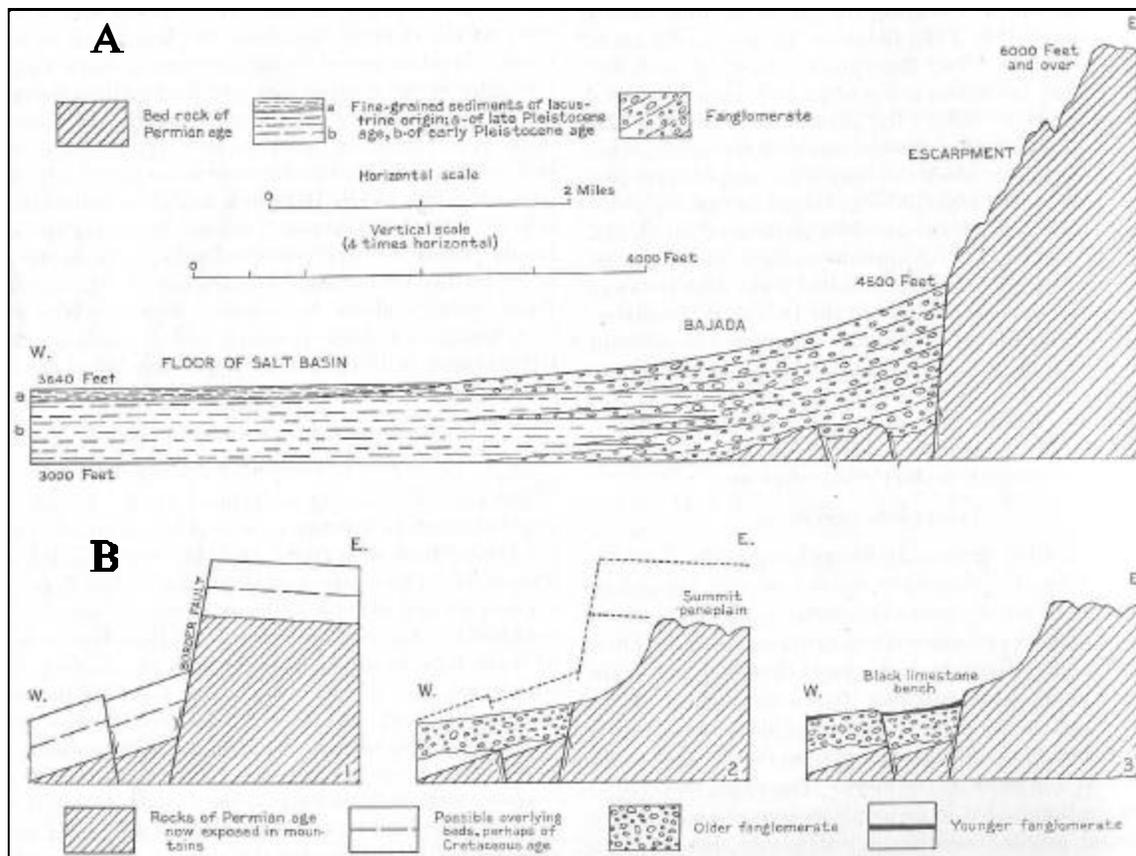


Fig. 10. Stratigraphy and geologic evolution of the western escarpment of the Guadalupe Mountains. (A) Modern relation of alluvial sediments and fanglomerates to other Salt Basin deposits, and (B) early structural and depositional history of the western escarpment (from King, 1948).



Fig. 11. Photographs of proximal debris flow deposits. (A, B) Views from the floor of the incised channel near the apex of an alluvial fan located at the base of the western escarpment of the Guadalupe Mountains. These views show the non-imbricated, poorly-sorted bouldery and cobbly debris flow deposits that compose the proximal areas of these fans.

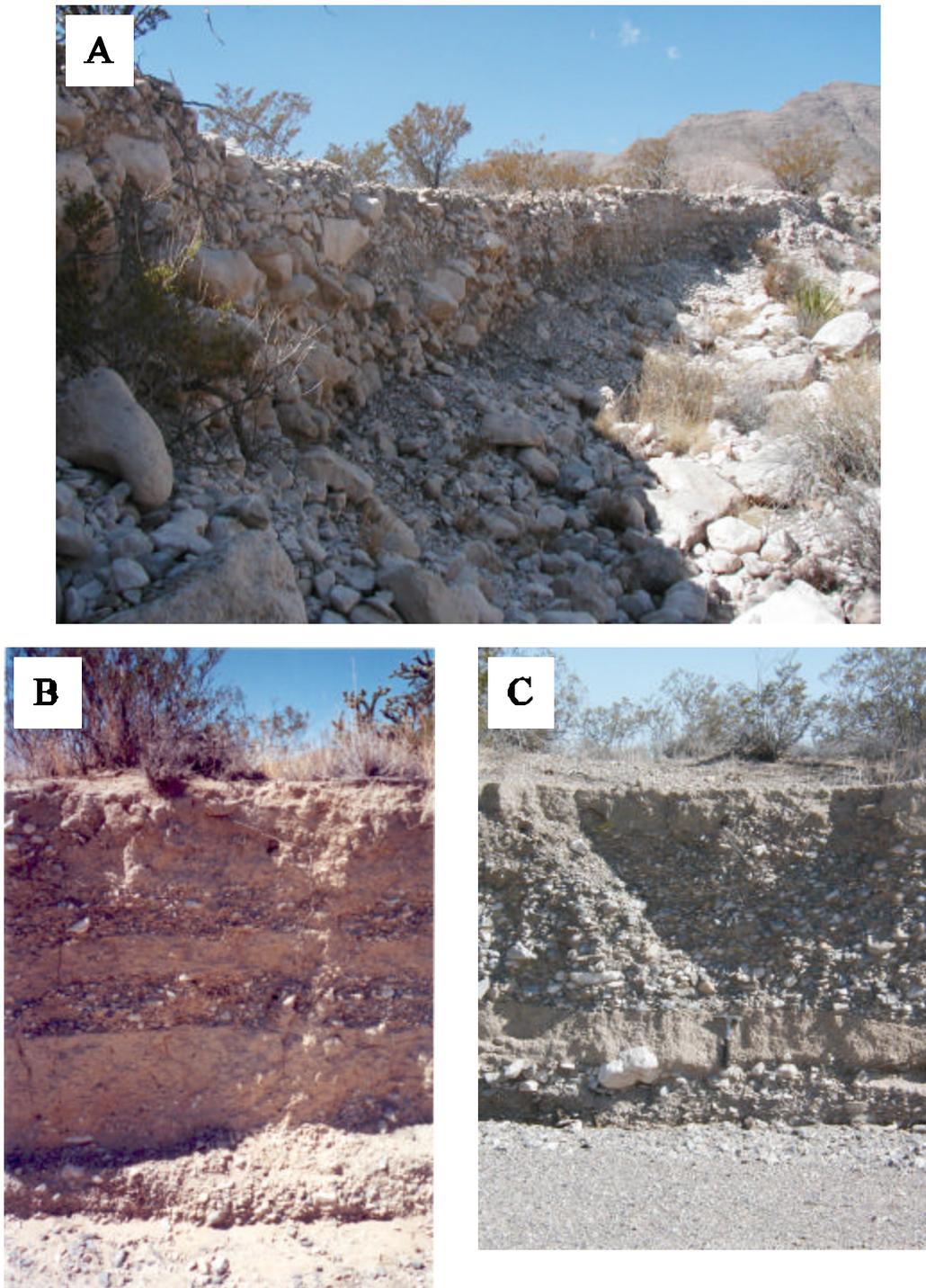


Fig. 12. Photographs of medial and distal debris flow and sheetflood deposits. Views from distributary channels revealing the (A) imbricated cobbly and pebbly debris flow deposits, and (B,C) interstratified clast-rich and clast-poor sheetflood deposits that compose the medial and distal portions of the fans located at the base of the western escarpment of the Guadalupe Mountains.

tends to be gently inclined to the west, parallel to the fan surface (King, 1948).

In the proximal fan areas, the incised channels are narrow and entrenched to depths of 15 meters (Fig. 13). The depths of the incised channels gradually decrease away from apexes, becoming wider and, in some cases, terraced (King, 1948). The location of the incised channel on these fans is largely dependent on the depositional history of the individual fan and the location of tectonic irregularities within the underlying bedrock. On some fans, the incised channel leads directly down the crest of the fan. On others, the incised channel is deflected along or parallel to the mountain front toward the interfan valley. Although it commonly terminates in the proximal or medial part of the fan, the incised channels of these fans often extend a significant distance below the fan apex. In some cases, the incised channels extend completely to the distal margin of the fan or into the neighboring environments fringing the margins of the bajada (discussed further in section 2.6).

The number of channels dissecting the fan surface progressively increases downfan. However, this is typically because of the formation and proximal progression of headward-eroding gullies rather than from the bifurcation of the incised channel. Many of these channels tend to anastomose rather than bifurcate (King, 1948). The entrenchment of the proximal fan areas by prominent incised channels combined with the continual dissection of the bajada by numerous well-developed headward-eroding gullies led King (1948) to presume that the bajadas of the region are in the later stages of development.

The southern end of The Rim, known as the Algerita Escarpment, is bound on



Fig. 13. Photograph of an incised channel. View of the incised channel of the alluvial fan derived from Bone Springs Canyon near Williams Ranch at the base of the western escarpment of the Guadalupe Mountains. Note the approximately 12-meter-high channel walls and the geomorphologist (center) for scale.

the west by the down-to-the-west normal faults of the Dog Canyon Fault Zone (Kelley, 1971) (Fig. 7). Although this portion of The Rim is relatively linear and undissected, the Algerita Escarpment contains of a series of faults and small folds towards the northern end of Big Dog Canyon. The numerous fans located along the piedmont of the Algerita Escarpment are small and steep, giving them a ramp-like appearance (Fig. 14). These alluvial fans are primarily composed of Quaternary alluvium (McKnight, 1986) although Boyd (1958) found a spearhead buried in 2 meters of alluvium near the southern end of Big Dog Canyon, suggesting that some deposits may be Holocene in age.

The fans of the Algerita Escarpment are principally constructed of non-cohesive bouldery and cobbly debris flows that were funneled through steep fracture-controlled channels in the escarpment. These channels were subsequently enlarged and became incipient drainage basins in the form of small and shallow single valleys. The proximal areas of these fans are typically composed of imbricated levee deposits, although evidence of mass wasting, usually in the form of talus and loose boulders, is commonly found near the apex of these fans. Non-sorted and non-bedded debris lobes characterize the medial parts of these fans. Furthermore, these fans generally lack a prominent incised channel and common erosional features such as headward-eroding gullies, which are typically considered signs of fan incipiency (Blair and McPherson, 1994; Blair, 1999).

By contrast, a complexly faulted and folded area of The Rim is located immediately north of the Brokeoff Mountains, near the mouth of Big Dog Canyon (McKnight, 1986). This portion of The Rim, known as the Buckhorn Escarpment, is

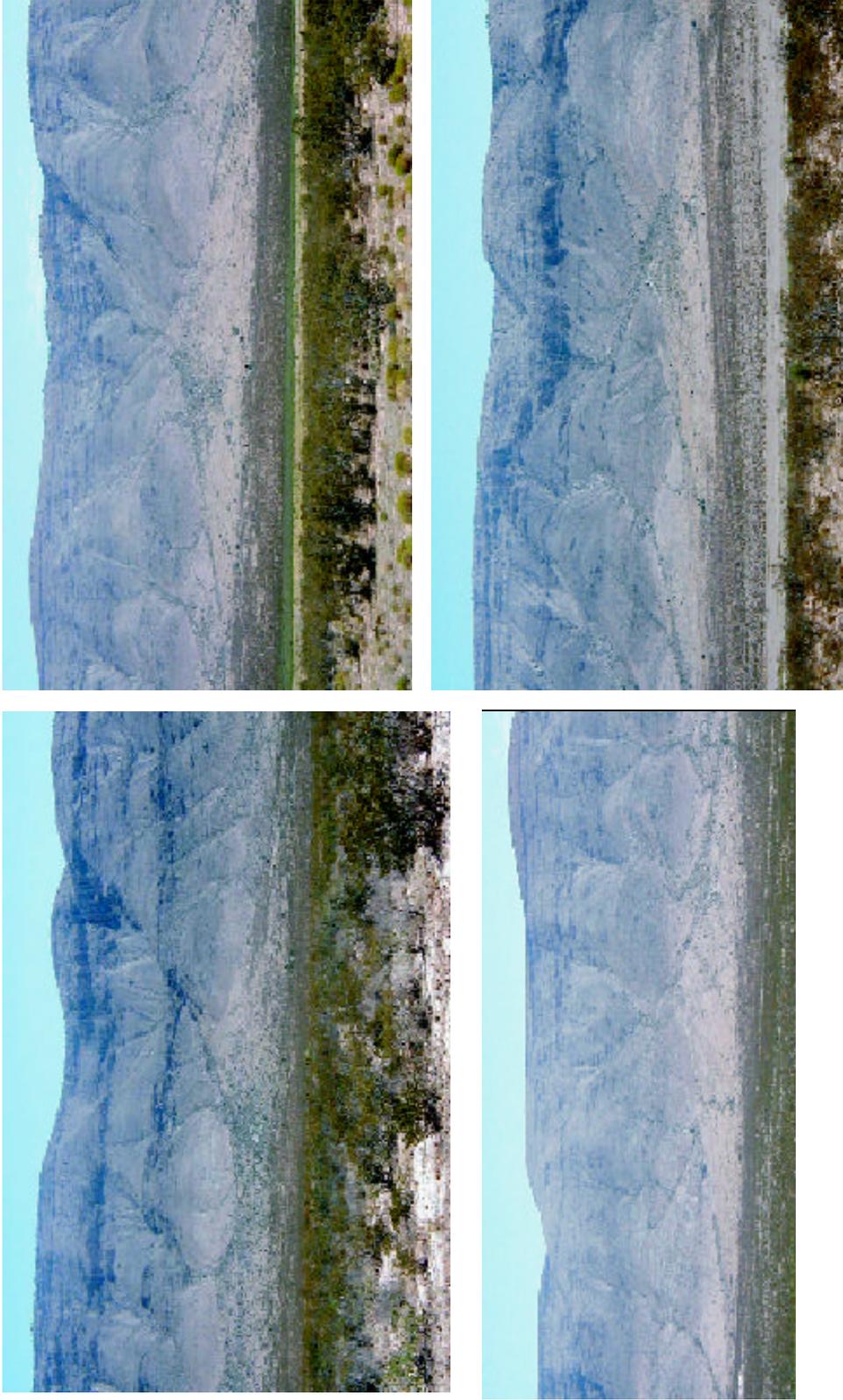


Fig. 14. Alluvial fans along the Guadalupe Mountains in Big Dog Canyon. Photographs of alluvial fans located along the portion of The Rim known as the Algerita Escarpment in Big Dog Canyon.

bound on the west by the north-trending normal faults of the Guadalupe Fault Zone (Fig. 7) and is considerably more dissected than the Algerita Escarpment to the south (Kelley, 1971; McKnight, 1986). The Rim becomes progressively more dissected from south to north because the Algerita Escarpment is relatively younger than the Buckhorn Escarpment (McKnight, 1986).

Three alluvial fans of wide areal extent enter the Crow Flats through wide embayments in the Buckhorn Escarpment, with the two largest extending from the mouths of Little Dog Canyon and Pup Canyon. Backfilling near the apical areas of these fans has caused alluvium to be deposited on the floor of the feeder channel and in the lower reaches of the drainage basin. Although a prominent incised channel is a characteristic feature of these fans, backfilling has promoted the development of multiple feeder channels in the drainage basin, and consequently, multiple incised channels extend from the embayment onto the fan surface. Unlike the fans of the western escarpment, whose surfaces are being dissected by well-developed headward-eroding gullies, the apparent dissection of the surface of these three fans can be largely attributed to multiple incised channels that frequently extend the length of the fan. Slightly northwest of the distal margins of these three fans, 3Ixon Draw, a large, southward flowing arroyo, branches into a series of arroyos collectively known as 3Ixon Wash. Instead of being truncated by PIxon Wash, the distal margins of these fans appear to merge with the floodplain deposits of 3Ixon Wash by a gradual reduction in gradient and diminution of sediment texture. Immediately north of these fans, however, alluvial slopes dominate the piedmont. Here, the piedmont is characterized by long, parallel,

deeply incised channels and tends to lack the distinctive surface form of one or several coalesced alluvial fans (Hawley and Wilson, 1965; Smith, 2000).

#### *2.4.2 Brokeoff Mountains*

The Brokeoff Mountains were intensely fractured and split into many fault blocks by numerous north-south trending normal faults during Plio-Pliocene time (McKnight, 1986). This faulting progressed from west to east as Big Dog Canyon and Salt Basin-Crow Flats subsided around the range (McKnight, 1986; Thuma, 1990). The eastward progression of the Brokeoff Mountains is represented by observable morphologic differences between the alluvial fans found on the eastern and western piedmont of the range (Thuma, 1990).

Streams preceding the faulting have cut extensive canyons through the interior ridges and valleys of the Brokeoff Mountains, producing wide embayments on the western side of the range. The alluvial fans at the mouths of these canyons are of low gradient and progressively decrease in area from south to north. Shallow, headward-eroding gullies are common on the distal and medial parts of these fans. On the larger alluvial fans, especially those to the south, multiple incised channels dissect the fan surface as a result of the backfilling of the mountain embayment. The southernmost fans of the western ridge were built by channels that were deflected by a series of bedrock outcrops that roughly parallel the mountain front. Alluvium accumulated behind these outcrops and was eventually deflected around the ends. As a result of this deflection, channels tend to be concentrated in some places and dispersed in others, producing fans

varying in size and appearance.

Small, relatively steep alluvial fans are found along the sharper and steeper eastern ridge of the Brokeoff Mountains in Big Dog Canyon (Fig. 15). The drainage basins of the fans consist of small distinct valleys carved along a fault or fracture by relatively straight and steep feeder channels (Fig. 16). These feeder channels are entrenched near the apexes of the fans with some entrenched into bedrock (McKnight, 1986). The fans on the eastern ridge of the Brokeoff Mountains are also thought to be composed primarily of Quaternary alluvium, with some potentially Holocene in age (Boyd, 1958; McKnight, 1986). They are constructed principally of clast-rich sheetfloods and clast-rich and clast-poor debris flow deposits. Furthermore, these fans are characterized by the truncation of their distal margins as a result of incision by Upper Dog Canyon Arroyo. The deposition of floodplain sediments has resulted in a prominent slope inflection on the fan surface slightly upfan of the arroyo.

### *2.5 Geomorphology of adjacent environments*

King (1948) proposed that beach ridges on the northeastern margin of Salt Basin were evidence of two late Pleistocene lacustrine highstands and considered the modern playas to be the relict bed of a pluvial lake that reached a maximum depth of 12 meters (Fig. 17A). Subsequent research by Freidman (1966), Miller (1981), and Hawley (1993) confirmed the presence of the late Pleistocene/early Holocene pluvial “Lake King” (Miller, 1981) within Salt Basin-Crow Flats. Wilkins and Currey (1997) used



Fig. 15. Alluvial fans along the Brokeoff Mountains in Big Dog Canyon. Photographs of alluvial fans located along the base of the eastern ridge of the Brokeoff Mountains in Big Dog Canyon.



Fig. 16. View of alluvial fans from their drainage basins. Photographs of the two northernmost fans located along the eastern ridge of the Brokeoff Mountains in Big Dog Canyon.



Fig. 17. Neighboring geomorphic environments. Photographs of the various geomorphic environments bordering the alluvial fans of the Guadalupe and Brokeoff Mountains in Salt Basin-Crow Flat: (A) playa surface, (B) gypsum dunes, and (C) quartz nebkha dunes.

radiocarbon ages of organic material in beach ridge sediments to date four lacustrine transgressions during the late Pleistocene with Lake King's most recent highstand occurring approximately 16,000 years before present (BP). Lake King is also thought to have received significant amounts of groundwater discharge from pluvial Lake Sacramento, a nested sub-basin located 200 m above and about 90 km to the northwest of the center of Salt Basin-Crow Flats (Hawley, 1993; Wilkins and Currey, 1997).

Fine-grained, gray carbonate and sulfate muds are interbedded with thin gypsum and algal beds on the playa surface in Salt Basin-Crow Flats. This interlayering indicates fluctuations in salinity and groundwater level (Clark, 1990). Powers et al. (1987) noted that playa sediments contain gypsum laminations that are 2-3 mm thick and composed of small, upright gypsum crystals up to 1 mm in height. Many of these gypsum layers have been convoluted or contorted. The water table of Salt Basin has been recorded as being as shallow as 1-3 meters below the playa's surface (Boyd and Kreitler, 1986) and as deep as 6-10 meters (King, 1948). However, this depth may be deeper now because of significant amounts of groundwater withdrawal, which averaged  $1.0 \times 10^8 \text{ m}^3$  per year from 1952-1992 (Ashworth, 1995). Because evaporation occurs directly from the water table and potential evaporation is more than 10 times greater than precipitation (Boyd and Kreitler, 1986), gypsum and other evaporite minerals, notably halite, are currently accumulating in the Salt Basin-Crow Flats (Hill, 1996). Wind, not water, is now at work entraining and redistributing the playa and lacustrine sediments in Salt Flat (Hussain et al., 1988).

Gypsum deflated from the playa surface seems to be the source for the  $10 \text{ km}^2$

parabolic dunefield west of the Patterson Hills (Fig. 17B). The northeastern 4 km<sup>2</sup> of the dunefield is active, with four conspicuous parabolic and/or transverse ridges extending to the northeast and reaching heights of nearly 25 meters above the basin floor. To the southwest, closer to the playa margins, the gypsum dunes are considerably smaller (2-5 meters) and have been stabilized by vegetation (Wilkins and Currey, 1999) or cryptobiotic crust in some areas.

An extensive field of quartz sand dunes and sand sheets, known locally as the “Red Dunes,” flank the gypsum dunes to the north and east and cover an area of approximately 100 km<sup>2</sup> (Wilkins and Currey, 1999) (Fig. 17C). They extend for 6 km from the distal areas of the alluvial fans to the margin of Salt Basin and consist of irregularly spaced nebkhas (<2-3 m in height) and blowouts (Hill, 1996; Wilkins and Currey, 1999). While the surface of some of these dunes are characterized by ripples (Hussain et al., 1988), gross dune morphology does not provide any indication of dune orientation or activity, although quartz sand can be seen advancing up the distal deposits of adjacent alluvial fans in an east-northeast direction. The dunes have been incised in several places by arroyos that reach depths of 2-10 meters (Hussain et al., 1988; Wilkins and Currey, 1999) and commonly expose fan toe sediments interfingering with aeolian cross-bedded sands. The beds are commonly directed away from Salt Basin and have dips of up to 30 degrees (Hussain et al., 1988). The quartz dunes mantle three distinct carbonate-cemented, gypsum-sand aeolianites containing well-preserved cross-bedding. Radiocarbon ages acquired from buried soils and hearths exposed in two of the larger arroyos in the area suggest that there were four intervals of aeolian activity during the

mid-to-late Holocene (Wilkins and Currey, 1999).

## 2.6 Vegetation

Although the Chihuahuan Desert has more than 1,000 endemic species of plants (Johnston, 1977), the vegetation of the GMR tends to be sparse, spatially arranged, and well adapted to xeric conditions. The downfan diminution of particle size that results from the sorting of sediment by fluvial processes (Graf, 1988) has traditionally been recognized as the primary environmental control on vegetation patterns on alluvial fans (Shreve, 1964). Numerous studies have also attributed variations in plant species composition on alluvial fans to geomorphic disturbances (Parker and Bendix, 1996), lithology (Shreve, 1964; Parker, 1991), elevation and topographic position (Parker, 1991), and surface age (Burk and Dick-Peddie, 1973; Wierenga et al., 1987; Stein and Ludwig, 1979).

Except for the occasional appearance of Tarbush (*Flourensia cernua*), Soap-tree yucca (*Yucca elatai*), Cane Cholla (*Opuntia imbricata*), or Christmas Cactus (*Opuntia leptocaulis*), the basin floors and fine-textured fan deposits of the GMR are characterized by nearly pure stands of Creosotebush (*Larrea tridentata*). The limestone outcrops, boulder-strewn slopes, and coarser fan deposits upslope of the shrubby flatlands are populated by a number of leaf and stem succulents. The most prevalent leaf succulents are Lechuguilla (*Agave lechugilla*) and Century Plant (*Agave neomexicana*), while the stem succulents are represented by Sotol (*Dasyllirion leiophyllum*), Beargrass (*Nolina*

*microcarp*), and a number of yuccas (*Yucca torreyi*, *Y. baccata*, *Y. faxiona*) and cacti (*Opuntia engelmannii*, *Opuntia macrocentra*, *Echinocereus triglochidalus*). These succulents are frequently accompanied by Ringgrass (*Muhlenbergia torreyi*) and a variety of woody shrubs, notably Ocotillo (*Fouquieria splendens*) and Allthorn (*Koeberlinia spinosa*).

The proximal fan surfaces and drainage basins of the GMR support a greater density and diversity of plants than its alluvial fans and basin floors (Solbrig et al., 1977; Bowers and Lowe, 1986). Woodlands consisting of Ponderosa Pine (*Pinus ponderosa*), Piñon Pine (*Pinus edulis*), Alligator Juniper (*Juniperus deppeana*), and Gray Oak (*Quercus grisea*) are found on the upper limits of the drainage basin while One-seed Juniper (*Juniperus monosperma*) is found sporadically throughout the lower slopes of the drainage basin near the feeder channel and fan apex.

A different group of plants are found in ephemeral channels and arroyos, where conditions of water supply are more favorable. Some of these more common, deep-rooted species include Cutleaf Brickellbush (*Brickellia laciniata*), Catclaw Acacia (*Acacia greggii*), Desert Sumac (*Rhus microphylla*), Desert Willow (*Chilopsis linearis*), and Guadalupe Rabbitbush (*Ericameria nauseosa* var. *texensia*). The nebkhas in Salt Basin are typically capped by Hoary Rosemary Mint (*Poliomintha incana*) and various species of mesquite (*Prosopis* sp.) and further stabilized by cryptobiotic soils in some places. Large portions of the basin floors and gypsum dune field are blanketed by open assemblages of grasses, notably Black Grama (*Bouteloua eripoda*), Alkali Sacaton (*Sporobolus airoides*), Little Bluestem (*Andropogon scoparius*), and some shrubs,

notably Hoary Rosemary Mint (*Poliomintha incana*). Halophytes are also common in the sand flats and playas of the GMR, the most common being Four-wing saltbush (*Atriplex canescens*).

Since the introduction of domestic livestock to the GMR in the late 1800's, a combination of climatic oscillations and overgrazing has altered the distribution, abundance, and dominance of plant species (Buffington and Herbel, 1965; Allnutt et al., 2002). High levels of winter rain, coupled with dry summers appear to have favored the growth of certain shrub species, notably honey mesquite, creosote bush, and tar bush, over grasses (Brown et al., 1997). The contribution of overgrazing to arroyo formation, soil erosion, and vegetative change has been well documented (Hastings and Turner, 1965; Cooke and Reeves, 1976; Bahre, 1991; Bull, 1997; Allnutt et al., 2002). This has resulted in a vegetative assemblage that does not necessarily reflect the natural characteristics of the region. Some environmentalists and conservation biologists have advocated the elimination of livestock grazing in order to preserve what relatively intact (Allnutt et al., 2002), native biodiversity remains (Fleischner, 1994; Donahue, 1999). Others have made notable efforts to integrate ranching with conservation (Western et al., 1994; Curtin, 2002). With ranching being the most extensive land use in the western United States, overgrazing and the continued removal of natural vegetation will continue to influence the operation of geomorphic processes, and consequently, the redistribution of resources (Curtin, 2002).

## 2.7 Soils

Soils of the alluvial fans of the GMR are aridisols and entisols whose spatial distribution is dependent on the interaction of several geomorphic, climatic, and pedogenic processes that function over various time scales. The deepest, most well-developed soils on the alluvial fans of the GMR are typically the gravelly to gravelly sandy loams of the Nickel and Ector series. These soils are found on isolated, erosional remnant fan surfaces and dissected terraces near the proximal areas of the alluvial fan and in the lower parts of the drainage basin immediately upstream from the fan apex. The stone (or desert) pavements that frequently mantle these loams are occasionally covered with rock varnish (desert varnish). These soils often have considerable amounts of gypsum and/or a calcic, petrocalcic or well-developed argillic horizon.

The soils of the mid-fan area are found in stratified alluvium and range from the gravelly sandy loams of the Tencee series to the loams of the Reakor series. While the coarser soils usually contain calcic horizons or indurated deposits, the loamy soils may or may not contain carbonate material. The soils of the distal fan areas, which typically belong to the Reeves series, have formed in sandy or silty sediments derived from multiple parent materials (i.e., playa deposits, dune sand, or fan toe deposits). These soils may contain buried soils and often have considerable amounts of gypsum and/or a calcic or well-developed argillic horizon, depending on the age and stability of the surface (National Resources Conservation Service Official Soil Survey Descriptions Homepage, 2003).

## CHAPTER III

### LITERATURE REVIEW AND METHODOLOGY

#### *3.1 Morphometric analysis of landforms*

Since the introduction of the first concepts by Horton (1945) and Strahler (1957), morphometric analysis of landforms has grown in scope and complexity and played an important role in the understanding of alluvial fan geomorphology. Morphometric data represent a quantitative description of the surface morphology of a geomorphic system and can be used to estimate the relative degree of geomorphic development of a system or a group of systems. Statistical models of the morphometry of geomorphic systems can be used to predict the morphometry of similar geomorphic systems. Furthermore, the quantitative description and morphometric analysis of geomorphic systems provides geomorphologists with an unbiased method of comparing similar landforms from different environments (Horton, 1945; Strahler, 1957; Smith, 1983).

##### *3.1.1 Alluvial fan area*

Prior to the 1960s, alluvial fan research was characterized by a lack of publications and inconsistent methodologies. Publications during this period generally emphasized the recognition and description of alluvial fans and occasionally provided speculations on depositional processes (Lecce, 1990). Few researchers collected quantitative data on fan forming processes and morphology (Blissenbach, 1954).

Eckis (1928) and Blackwelder (1928) were among the first to describe fan-forming processes in detail. Eckis (1928) recognized alluvial fans as temporary features on the landscape that indicated conditions of youth in Davis's geographic cycle (Davis, 1899). Eckis (1928) further speculated on the dynamics of fan trenching and suggested that entrenchment was a sign of maturity and the eventual destruction of the fan. Blackwelder (1928) documented the movement and morphology of active mudflows and debris flows on fans and their role in fan construction. Blissenbach (1954) focused on the spatial distribution of sediments, concentrating on how distance from the fan apex influenced the size, sorting, roundness, and sphericity of alluvial fan deposits.

Beginning in the early 1960s, alluvial fan researchers began to use quantitative data to determine the processes controlling fan development (Lecce, 1990). Fan-basin relationships became a fundamental concern, and empirical models were utilized to describe the rates of change between certain characteristics of an alluvial fan and its drainage basin (Lecce, 1990). The most commonly compared features of the alluvial fan and its drainage basin have been their respective areas (Fig. 18). Bull (1962) was the first to recognize that as drainage basin area increases, the size of the alluvial fan increases. He quantified the relationship with a simple power function:

$$A_f = x(A_d)^y \quad (1)$$

where  $A_f$  is alluvial fan area,  $A_d$  is drainage basin area, and  $x$  is an empirically derived coefficient representing the area of an alluvial fan with a drainage basin area of 1.0

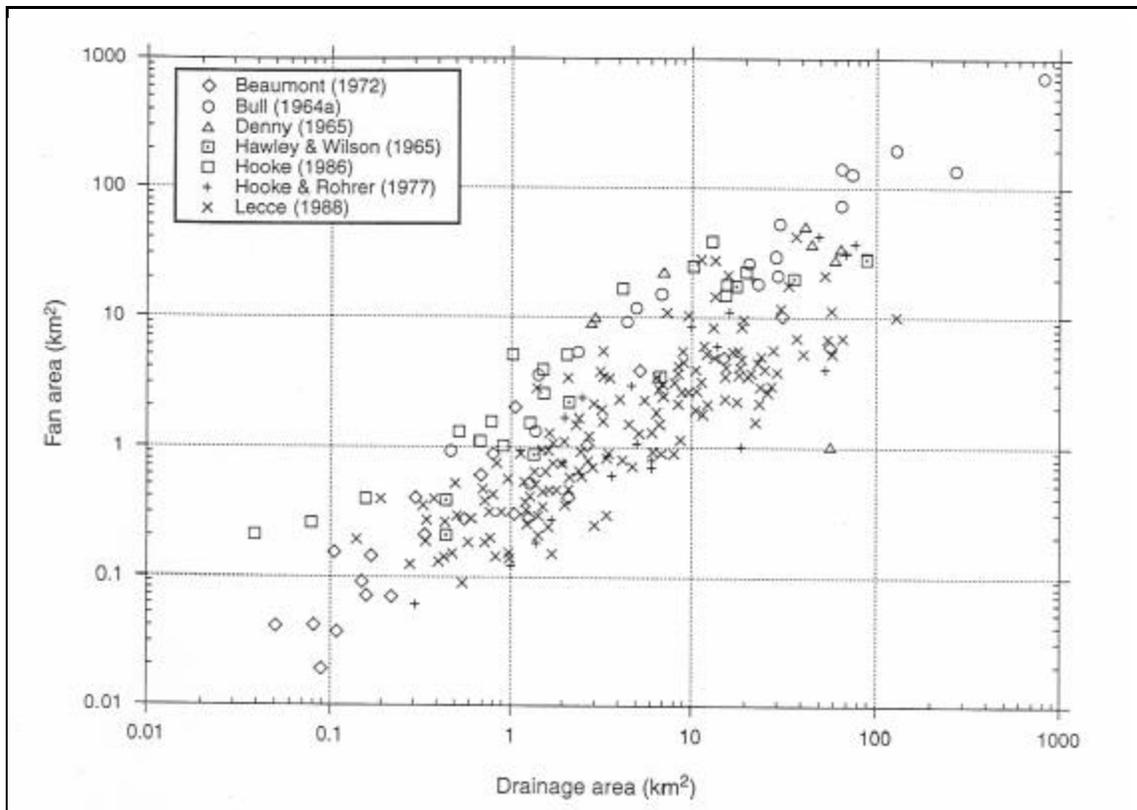


Fig. 18. Drainage basin area versus alluvial fan area. Compilation of data from published sources illustrating the relationship between drainage basin area and alluvial fan area (from Blair and McPherson, 1994).

(Hooke, 1968). The exponent  $y$  is the slope of the regression line and measures the rate of change in fan area with increasing drainage basin area. A number of publications have attempted to isolate the individual effect that the variables  $x$  and  $y$  have on this equation.

The coefficient  $x$  varies geographically (Hooke and Rohrer, 1977) and typically ranges in value from 0.1 to 2.2 (Harvey, 1997). According to Hooke (1968), the primary factor influencing  $x$  is the ratio of depositional area in the collecting basin to erosional area in the drainage basin, with a greater ratio producing a larger  $x$  value. However, the value of  $x$  also depends on the lithology of the bedrock within the drainage basin, tectonic activity, the rate and spatial distribution of subsidence, and precipitation (Harvey, 1997; Cooke et al., 1993).

Lithologic variations in the drainage basin have been the focus of a number of studies (Bull, 1962, 1964a; Hooke, 1968; Hooke and Rohrer, 1977; Lecce, 1988). Bull (1962) demonstrated the effect of drainage basin lithologies on the area and slope of the alluvial fans of San Joaquin Valley in western Fresno County, California. He concluded that drainage basins consisting of erodible lithologies, such as mudstone and shale, produce fans that are steeper than, and almost twice as large, as those produced by basins underlain by more resistant sandstone. In later publications, Bull restated his earlier findings and provided additional morphometric relationships while discussing the role of segmentation (1964a), channel trenching (1964b), and near-surface subsidence (1964c) on alluvial fan morphology. Similarly, Hooke (1968) showed that fans with predominantly quartzite drainage basins are distinctly steeper and roughly one-third the

size of fans associated with dolomite and quartzite drainage basins. Hooke (1968) also indicated that fan area and slope are influenced by the erodibility and sediment yield of the drainage basin as well as the hydraulic characteristics of the transporting medium. Conversely, Lecce (1988) found that drainage basins underlain by predominantly erodible lithologies produce smaller alluvial fans than those composed of more resistant rocks such as quartzite. Lecce (1988) suggested that this is because of the greater sediment storage of the larger, gently-sloping drainage basins composed of less resistant lithologies. Moreover, Hooke and Rohrer (1977) used variations in alluvial fan area to suggest that jointing and fracturing may be more important than mineralogy in determining the relative erodibility of the drainage basin.

Tectonic activity has been shown to affect the coefficient  $x$  by altering drainage basin area and relief (Denny, 1965; Hooke, 1968; Hooke and Rohrer, 1977; Ritter et al., 2000) and accommodation space (Silva et al., 1992; Ferrill et al., 1996; Calvache et al., 1997; Viseras et al., 2003; Harvey, 2002). Denny (1965) and Hooke (1968) showed that the alluvial fans of the Panamint Mountains on the western piedmont of Death Valley were larger than those from the Black Mountains to the east because of the differential subsidence of the valley floor. The eastward tilting of the Panamint Range-Death Valley Block has caused the alluvial fans on the west side of the valley to be extended, whereas the growth of the Black Mountain fans to the east has been restricted by the playa (Hooke, 1968). Findings similar to Denny (1965) and Hooke (1968) were reported more recently by Ritter et al. (2000) in north-central Nevada. Ritter et al. (2000) found that the fans on the western, dip-slope piedmont of Buena Vista Valley, Nevada, are larger

for a given drainage basin area than the fans traversing the range-bounding fault on the eastern piedmont of a valley near Winnemucca, Nevada (Hawley and Wilson, 1965). Silva et al. (1992) and Viseras et al. (2003) demonstrated that morphometric differences between the fans of southeastern Spain reflect different tectonic settings. Silva et al. (1992) used a morphometric analysis to distinguish four types of alluvial fans from the mountain fronts of Murcia's Guadalentin depression, with each type showing broad similarities in their morphology and stratigraphic sequences. Similarly, Viseras et al. (2003) determined that the stratigraphic stacking patterns of alluvial deposits reflect geographic differences in eustasy and tectonics. Fans at tectonically active mountain fronts tend to be smaller and steeper due to the vertical aggradation of alluvial deposits. Fans at moderately active mountain fronts tend to be elongated and large in relation to their drainage basin. Where the fan setting experiences minimal tectonic activity or rising base level, retrogradation is the typical stratigraphic stacking pattern, where alluvial deposits are backfill into the drainage basin and producing low gradient fans that are quite extensive with respect to their drainage basins (Viseras et al. 2003).

Although the value of the exponent  $y$  varies from 0.7 to 1.1 (Harvey, 1997), it is generally less than one (Hooke and Rohrer, 1977). Values less than one imply that larger basins supply proportionately less sediment to alluvial fans than smaller basins (Hooke and Rohrer, 1977). For alluvial fans that have similar lithologies in the contributory drainage basins and similar tectonic and climatic histories, Hooke (1968) found the exponent  $y$  to have a nearly constant value of 0.9.

Several factors may be responsible for reducing  $y$  to below a value of one

(Hooke, 1968; Bull, 1972; Church and Mark, 1980; Lecce, 1988). First, low relief ratios, gentle slopes, and wide valley floors allow larger drainage basins to store more sediment (Hooke, 1968). Second, larger basins are also less likely and may be less frequently covered by a single storm, causing sediment to remain on valley slopes and along channels (Hooke, 1968; Lecce, 1988). Third, large basins may be more likely to generate a discharge capable of transporting sediment beyond the alluvial fan (Bull, 1972). Fourth, larger alluvial fan systems may take longer to adjust to available space and achieve equilibrium than smaller fans. This has been attributed to the shorter distances sediment has to travel to reach the smaller alluvial fans and the bordering of smaller fans by larger fans (Church and Mark, 1980; Harvey, 2002). Fifth, a limited depositional area or physical constraints may inhibit the development of large fans (Kostaschuk et al. 1986).

### *3.1.2 Alluvial fan slope*

Drew (1873) was the first to observe that fans with lower average slopes had relatively larger drainage basins than those with smaller drainage basins (Fig. 19). Bull (1962) expressed this inverse relationship with a simple power function:

$$S_f = a(A_d)^{-b} \quad (2)$$

where  $S_f$  is the slope of the alluvial fan, and  $a$  is an empirically derived coefficient that represents the slope of an alluvial fan with a drainage basin area of 1.0 (Hooke, 1968).

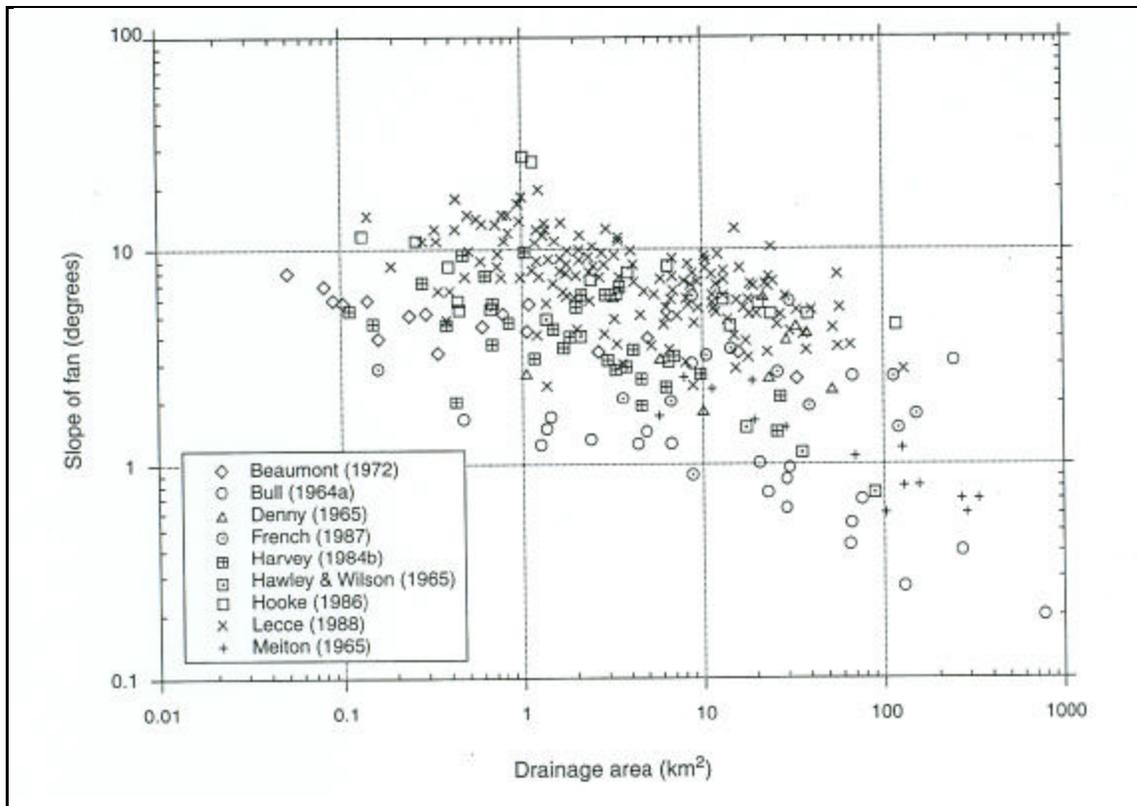


Fig. 19. Drainage basin area versus alluvial fan slope. Compilation of data from published sources illustrating the relationship between drainage basin area and alluvial fan slope (from Blair and McPherson, 1994).

The exponent  $b$  is the slope of the regression line and measures the rate of change in fan slope with increasing drainage basin area. The value of the coefficient  $a$  is normally between 0.03 and 0.17 while the exponent  $b$  typically ranges from -0.35 to -0.15 (Harvey, 1997).

Although the slope of an alluvial fan is primarily related to the size of its drainage basin, the wide scatter of the data in Fig. 19 indicates that there are other variables not accounted for in the plot. Blair and McPherson (1994) suggest that this relationship reflects the greater storage capacity of the larger drainage basins and its effect on the depositional processes that create the surface morphology of the fan. However, these processes are controlled by local variations in sediment size, sediment yield, and sediment concentration in flows reaching the fan (Hooke, 1968), which in turn reflects certain characteristics of the drainage basin (Blair and McPherson, 1994; Harvey, 1997).

Drainage basin lithology, for example, has been shown to influence fan slope by controlling sediment size (Bull, 1964a; Hooke, 1968). On the east side of Death Valley, Hooke (1968) observed that three alluvial fans with drainage basins underlain by sedimentary and igneous rocks were composed of finer sediments and had distinctly lower slopes and than those produced by drainage basins of roughly the same size underlain by metamorphic rocks.

In Fresno County, California, Bull (1964a) demonstrated the influence of drainage basin lithology on sediment size and sediment concentration. Bull (1964a) found that alluvial fans derived from drainage basins underlain by mudstone and shale

were generally steeper than those with drainage basins of comparable size composed predominantly of sandstone. Bull (1964a) attributed these observations to the greater erodibility of the mudstone and shale, demonstrated by the fact that fans produced by mudstone and shale drainage basins were larger than those drainage basins underlain by sandstone. The higher erodibility of the mudstone and shale presumably produce higher sediment concentration.

Hooke (1968) also investigated the effects of depositional process on laboratory and naturally-occurring alluvial fans. Hooke (1968) observed that, under equivalent conditions, laboratory fans on which either debris-flow or sieve deposition occurred were up to five degrees steeper than fans constructed solely by fluvial deposition. In Deep Springs Valley, California, Hooke (1968) found that differences in fan slope are primarily the result of differences in predominant depositional process, where fans with the highest slopes were those primarily composed of sieve and debris-flow deposits. Similar results were found in a study of Spanish Quaternary fans by Harvey (1984), where alluvial fans rich in debris flow deposits derived from smaller drainage basins generally have steeper slopes per drainage area than fluvially-dominated fans.

The slope of an alluvial fan has also been related to the relative relief of the drainage basin (Melton, 1965; Church and Mark, 1980). Melton (1965) introduced the equation:

$$S_f = m \left( \frac{H}{\sqrt{A_d}} \right)^n \quad (3)$$

where  $H$  is the total vertical relief of the drainage basin above the apex of the fan. The coefficient  $m$  is an empirically derived coefficient that represents the slope of an alluvial fan with a drainage basin area of 1.0. The exponent  $n$  is the slope of the regression line and measures the rate of change in fan slope in relation to an increase in Melton's ruggedness number. Previous studies have shown the value of  $n$  to be approximately 1.0 (Kostaschuk et al., 1986).  $\left(H/\sqrt{A_d}\right)$  represents Melton's ruggedness number, a dimensionless measure of the relative relief of the drainage basin that is positively correlated to fan slope (Church and Mark, 1980). It serves as a surrogate measure of the gradient down which material moves toward the fan, incorporating measures of both travel distance and available relief in the drainage basin (Church and Mark, 1980). Although it can theoretically have a value as low as zero, in a very rugged area, Melton's relative relief number can be as high as 2.0 or 3.0 (Melton, 1965).

Alluvial fan slope has also been shown to be influenced by the slope of the drainage basin (Hooke, 1968), tectonics and eustasy (Bull, 1961; Silva et al., 1992; Harvey, 2002; Viseras et al., 2003), characteristics of the feeder channel (Blair and McPherson, 1994; Calvache et al., 1997), the size, strength, and efficiency of the transporting medium (Hooke, 1968; Rodine and Johnson, 1976; Hooke and Rohrer, 1979; Costa, 1984; Milana and Ruzycski, 1999), and the erosional or depositional processes operating in adjacent environments (Blair and McPherson, 1994; Harvey et al., 1999).

### 3.1.3 Channel slope

The feeder channel is defined as the highest order stream in the drainage basin that leads to the apex of the fan. Typically, there is only one prominent feeder channel, although it is not uncommon to have multiple feeder channels (Blair and McPherson 1994). Fan aggradation from drainage basin discharge is dependent upon a decrease in carrying capacity within the transporting fluid-gravity or sediment-gravity flows as they reach the incised channel at the fan apex. This loss of competency is often the result of a lessening of slope as the flow reaches the fan apex, which results in a smaller fan area (Bull, 1977; Blair and McPherson, 1994).

Chamberlain and Salisbury (1909) proposed that the deposition of alluvium was caused by an abrupt change of stream channel gradient. Although it has been shown that a pronounced change in stream channel gradient is responsible for the deposition of alluvium (Trowbridge, 1911; Beaty, 1963), the slopes of the proximal areas of most alluvial fans are roughly equivalent to the feeder channel gradients immediately upstream of the fan apex (Bull, 1977). For 132 Death Valley fans, Blair and McPherson (1994) compared the slope of the feeder channel (1 kilometer upslope of the fan apex) and the slope of the incised channel or proximal fan surface (1 kilometer below the fan apex) (Fig. 20). A majority of the slope values (56%) were within  $\pm 1^\circ$  and 40% had feeder channel slopes significantly greater ( $>1\%$ ) than the upper fan area. Only 4% of the fans had upper fan areas with significantly greater ( $>1\%$ ) slopes than those of the feeder channel.

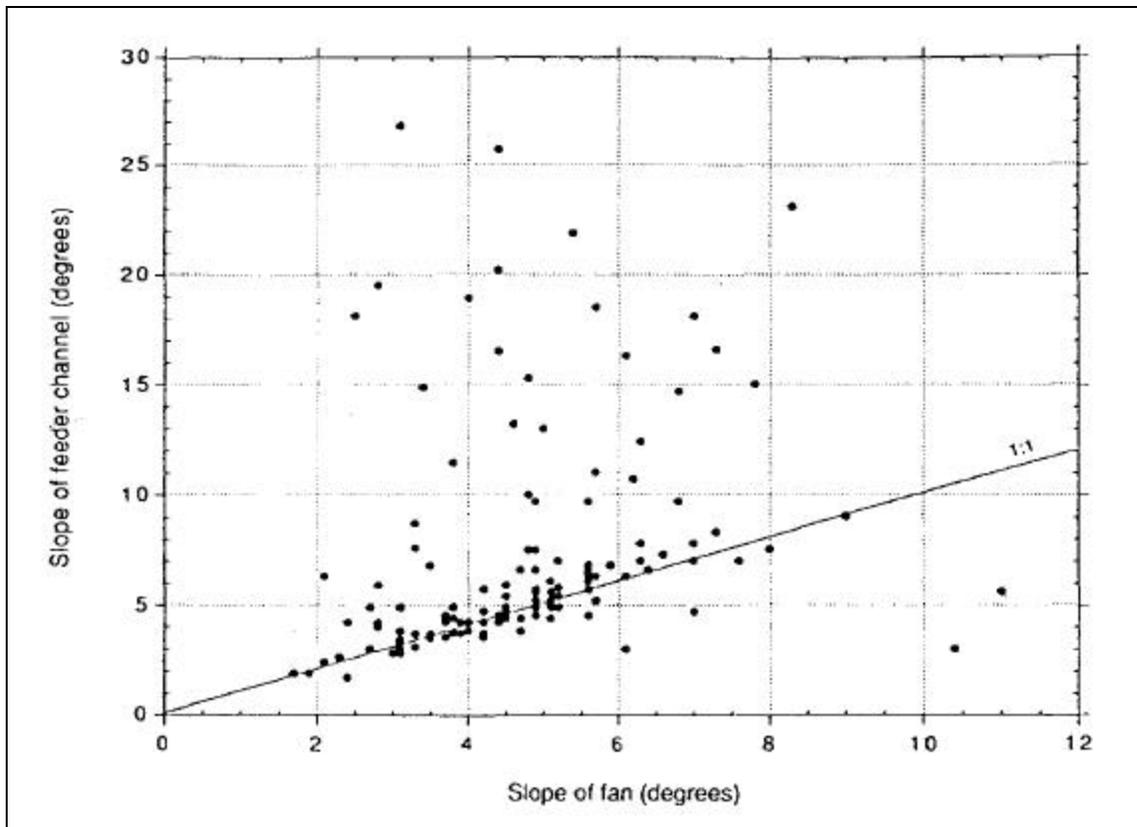


Fig. 20. Alluvial fan slope versus feeder channel slope. Plot of the slope of the 1 km long segment of the feeder channel upslope from the fan apex versus the corresponding slope of the fan or incised channel 1 km downslope of the fan apex for 132 Death Valley alluvial fans (from Blair and McPherson, 1994).

## *3.2 Methodology*

### *3.2.1 Data sources and analytical software*

The methods used to provide answers to the objectives of this study relied primarily on regression analysis of morphometric data. The principal sources of morphometric data were 1:24,000 United States Geological Survey (USGS) Digital Raster Graphics (DRG), 30-meter Digital Elevation Models (DEM), and Digital Orthographic Quarter Quadrangle (DOQQ). The DRGs, DEMs, and DOQQ's used in this study are listed in Tables 1 and 2.

A DRG is a geo-referenced scanned image of a United States Geological Survey topographic map. DEMs are digital maps of elevation data composed of equally sized gridded cells. The 30-meter DEMs used in this study are 1:24,000 USGS quadrangles where each cell in the DEM represents a 30 meter by 30 meter block of terrain. A DOQQ is a geo-referenced, digital representation of an aerial photograph. The DOQQs used in this study are 1:24,000, 3.75-minute USGS gray-scale and color-infrared images. Geographic Information Systems (GIS) software (ArcView 3.1 and ARC/INFO), S+, and Microsoft Excel were used to acquire and process the morphometric data for the alluvial fans selected for this study.

### *3.2.2 Delineating alluvial fan boundaries*

Information obtained through the interpretation of elevation contours and the recognition of currently exposed fan deposits on the DOQQs (Table 2) provided the

Table 1

## Digital Data Sources, Texas

## Texas Natural Resource Information System (TNRIS)

*1:24,000 Digital Raster Graphics (DRG) & 30-meter Digital Elevation Models (DEM)*

Dell City	Independence Spring	Long Point
Guadalupe Pass	Linda Lake North	Patterson Hills
Guadalupe Peak	Linda Lake South	PX Flat

*1-meter Digital Orthophoto Quarter Quadrangles (DOQQ)*

Cienega School NE	Guadalupe Peak NE	Long Point NE
Cienega School NW	Guadalupe Peak NW	Long Point NW
Cienega School SE	Guadalupe Peak SE	Long Point SE
Cienega School SW	Guadalupe Peak SW	Long Point SW
Culp Draw NE	Gunsight Canyon NE	Panther Canyon NE
Culp Draw NW	Gunsight Canyon NW	Panther Canyon NW
Culp Draw SE	Gunsight Canyon SE	Panther Canyon SE
Culp Draw SW	Gunsight Canyon SW	Panther Canyon SW
Dell City NE	Independence Spring NE	Patterson Hills NE
Dell City NW	Independence Spring NW	Patterson Hills NW
Dell City SE	Independence Spring SE	Patterson Hills SE
Dell City SW	Independence Spring SW	Patterson Hills SW
El Paso Gap NE	Linda Lake North NE	PX Flat NE
El Paso Gap NW	Linda Lake North NW	PX Flat NW
El Paso Gap SE	Linda Lake North SE	PX Flat SE
El Paso Gap SW	Linda Lake North SW	PX Flat SW
Guadalupe Pass NE	Linda Lake South NE	
Guadalupe Pass NW	Linda Lake South NW	
Guadalupe Pass SE	Linda Lake South SE	
Guadalupe Pass SW	Linda Lake South SW	

Table 2

## Digital Data Sources, New Mexico

## New Mexico Resource Geographic Information System Program (RGIS)

*1:24,000 Digital Raster Graphics (DRG) & 30-meter Digital Elevation Models (DEM)*

Algerita Canyon	Hackberry Hill	Picket Hill
Ares Peak	La Paloma Canyon	Queen
Cienega School	Lewis Canyon	Red Bluff Draw
Culp Draw	Packsaddle Canyon	Sheep Draw
El Paso Gap	Panama Ranch	Tanner Ranch
Gowdy Ranch	Panther Canyon	Texas Hill
Gunsight Canyon		

*1-meter Digital Orthophoto Quarter Quadrangles (DOQQ)*

Algerita Canyon NE	Lewis Canyon NE	Red Bluff Draw NE
Algerita Canyon NW	Lewis Canyon NW	Red Bluff Draw NW
Algerita Canyon SE	Lewis Canyon SE	Red Bluff Draw SE
Algerita Canyon SW	Lewis Canyon SW	Red Bluff Draw SW
Ares Peak NE	Packsaddle Canyon NE	Sheep Draw NE
Ares Peak NW	Packsaddle Canyon NW	Sheep Draw NW
Ares Peak SE	Packsaddle Canyon SE	Sheep Draw SE
Ares Peak SW	Packsaddle Canyon SW	Sheep Draw SW
Gowdy Ranch NE	Panama Ranch NE	Tanner Ranch NE
Gowdy Ranch NW	Panama Ranch NW	Tanner Ranch NW
Gowdy Ranch SE	Panama Ranch SE	Tanner Ranch SE
Gowdy Ranch SW	Panama Ranch SW	Tanner Ranch SW
Hackberry Hill NE	Picket Hill NE	Texas Hill NE
Hackberry Hill NW	Picket Hill NW	Texas Hill NW
Hackberry Hill SE	Picket Hill SE	Texas Hill SE
Hackberry Hill SW	Picket Hill SW	Texas Hill SW
La Paloma Canyon NE	Queen NE	
La Paloma Canyon NW	Queen NW	
La Paloma Canyon SE	Queen SE	
La Paloma Canyon SW	Queen SW	

means for identifying each fan and measuring the parameters selected for inclusion in the morphometric analysis (Table 3). Semi-circular, convex-basinward elevation contours on the DRG's easily differentiated the alluvial fans of the Guadalupe Mountains Region (GMR) from other landforms (Ferrill et al., 1996; Milana and Ruzycski, 1999), such as alluvial slopes (Smith, 2000). In order to minimize error, field reconnaissance and the examination of the DOQQs helped to verify or modify fan boundaries where topographic evidence was inadequate. In the case of the GMR, the lateral boundary between coalesced or partly coalesced fans tended to be easier to identify on the DOQQ's by using stream channel patterns to locate interfan valleys. Ideally, the distal boundary was designated as the last semi-circular, convex-basinward elevation contour and/or the last elevation contour basinward of the most distal fan deposits currently exposed on the DOQQs. Similarly, the distal boundary of some fans was characterized by the presence of another geomorphic (aeolian or pluvial) environment, where the distal boundary was erratic or ambiguous. For a few of the fans, the distal boundary is represented by an abrupt topographic boundary, such as an arroyo. In these cases, basic remote sensing techniques were employed to interpret the location of the distal fan boundary by using the DOQQs to identify the location and extent of currently exposed fan deposits.

### *3.2.3 Measuring alluvial fan and drainage basin area*

All currently exposed fan deposits, regardless of age or appearance, were included when delineating and measuring alluvial fan area. This was done for three

Table 3

Parameters used in the morphometric analysis

Symbol	Parameters	Unit	Definition
$A_f$	Alluvial fan area	km <sup>2</sup>	The total planimetric area of the alluvial fan downstream from the apex of the fan
$S_f$	Alluvial fan slope	m/m	Average gradient of five radial profiles on the fan surface extending from the apex to the distal boundary of the fan
$I_s$	Incised Channel Slope	m/m	Gradient measured along the 1-km-long segment of the incised channel immediately below the apex of the fan (Blair and McPherson, 1994)
$A_d$	Drainage Basin Area	km <sup>2</sup>	The total planimetric area of the drainage basin upstream from the apex of the fan
$F_s$	Feeder Channel Slope	m/m	Gradient measured along the 1-km-long segment of the feeder channel immediately above the apex of the fan (Blair and McPherson, 1994)

reasons. First, alluvial fan literature presents inconsistent methodologies when studying fan deposits of different ages (Church and Mark, 1980). Additionally, the existing body of literature for the GMR does not contain radiocarbon or radiometric dates for the different geomorphic surfaces and deposits of the alluvial fans of the GMR. Lastly, the only geologic maps of the region are the Van Horn-El Paso Sheet (Bureau of Economic Geology, 1975) and Scholle's (2003), where fan deposits are collectively mapped as "Quaternary colluvium and fans" and "alluvium and other surficial rocks", respectively.

The area of each alluvial fan was delimited on the DRG by using ArcView 3.1 to digitize polygons over each alluvial fan. When a fan was too large to be accurately covered by a single polygon, multiple polygons digitized over the area of that fan were merged using ArcView. The resulting single polygon was then measured using ARC/INFO. To find drainage basin area, a polygon was digitized on the DRG over the area thought to include the contributing drainage basin(s) of each alluvial fan in its entirety. Each individual drainage basin included in the polygon was then delimited and measured from the DEM using ARC/INFO and subsequently imported into ArcView 3.1, where contributing drainage basin(s) were identified and merged into a single polygon. If the individual polygons representing the areas of the alluvial fan and drainage basin happened to overlap, the portion of the drainage basin polygon that is overlapped by the alluvial fan polygon was cropped and not included in the measurement of drainage basin area.

#### *3.2.4 Measuring alluvial fan slope*

The average slope of each alluvial fan was calculated using methods similar to those used to investigate the segmentation of alluvial fans (Bull, 1964a) and in experiments studying fan hydraulics and sedimentation (Whipple et al., 1998). Five radial profiles, extending from the apex of the alluvial fan to its previously delimited distal boundary, were digitized onto the DRG. Although, they were predominantly straight lines, some of the radial profiles consisted of short, straight segments due to the constraints and confines imposed by the fan setting. Points were placed along the five radial profiles at 50-meter intervals and their elevations were extracted from the DEM using ARC/INFO. The elevation values of the points were compiled in Microsoft Excel and then used to calculate the slope of the radial profile in 50-meters segments. The slopes of the 50-meter segments were then averaged to find the slope of the radial profile. The slopes of the five radial profiles were then averaged together to produce an average fan slope.

#### *3.2.5 Measuring channel slope*

A method similar to the one used to find fan slope was employed to find the gradients of the 1-km long segment of the feeder channel upstream of the fan apex and the 1-km long segment downstream of the fan apex. After the feeder and incised channels were identified on the DRGs and confirmed by the DOQQs, a line was digitized onto the DRG through the middle of the two channels. Points were placed along the digitized lines at 10-meter intervals and their elevations were extracted from

the DEM using ARC/INFO. The elevation values of the points were compiled in Microsoft Excel and then used to calculate the slope of the digitized line in 10-meter segments. Any points along these digitized lines that were more than 1-km above or below the fan apex were removed and not included in the calculations. The slopes of the 10-meter segments were then averaged to find the slope of the incised and feeder channels.

### *3.3 Assumptions and reservations*

The morphometric measurements used in this study relied on the accuracy of the data collected from the DRGs, DEMs, DOQQs, geologic maps and the proper interpretation of that data. Delineation of alluvial fan area and slope was the most problematic in terms of proper interpretation because of ambiguities imposed by the fan setting. As previously discussed, neighboring fans and different geomorphic environments have caused the lateral and distal boundaries of some fans to be indistinct on the DRGs and DOQQs. These obstructions have hindered the unrestricted expansion of the alluvial fan or modified the conditions of deposition at the fan setting, altering the shape and size of the fan. Properly and accurately delineating alluvial fan area, in turn, influenced the measured slope of each fan since the five radial profiles used to measure average fan slope ended at the established distal fan boundary. These circumstances proved to be problematic during the delineation process and could be responsible for inexact measurements of alluvial fan area and slope. However, it is unlikely that these

physical constraints are solely responsible for the observed differences in fan area and fan slope. Such problems are typical of most alluvial fan research and error was minimized by the combined use of DRGs, DOQQs, geologic maps, and field reconnaissance. The impact of such physical confines and constraints remains difficult to measure or quantify.

## CHAPTER IV

### RESULTS AND DISCUSSION

Morphometric data for 31 alluvial fans from four locations in the Guadalupe Mountains Region (GMR) were derived and regression analyses were performed on these data (Fig. 21, Table 4). The regression analyses did not attempt to account for every variable affecting the alluvial fans and their contributory drainage basins, but rather to 1) provide a quantitative description of the alluvial fans of the GMR, 2) analyze the relationships that exist between alluvial fans and their contributory drainage basins in the GMR, 3) provide a simple and objective means of comparing alluvial fan morphometry in the GMR to alluvial fan morphometry in the western United States, and 4) demonstrate geographic and geomorphic variations that exist between the alluvial fans of the GMR and provide insight into the factors that control, or strongly influence, their morphology and morphometry. The results and discussion below are based primarily on the regression analysis of the morphometric data and, to a lesser extent, qualitative data from the field and the literature.

#### *4.1 Drainage basin area-alluvial fan area*

##### *4.1.1 Guadalupe Mountains Region*

The 31 alluvial fans in the study have areas ranging from 0.31 to 21.5 km<sup>2</sup> with a mean area of 3.0 km<sup>2</sup>. The regression equation for the entire data set is statistically

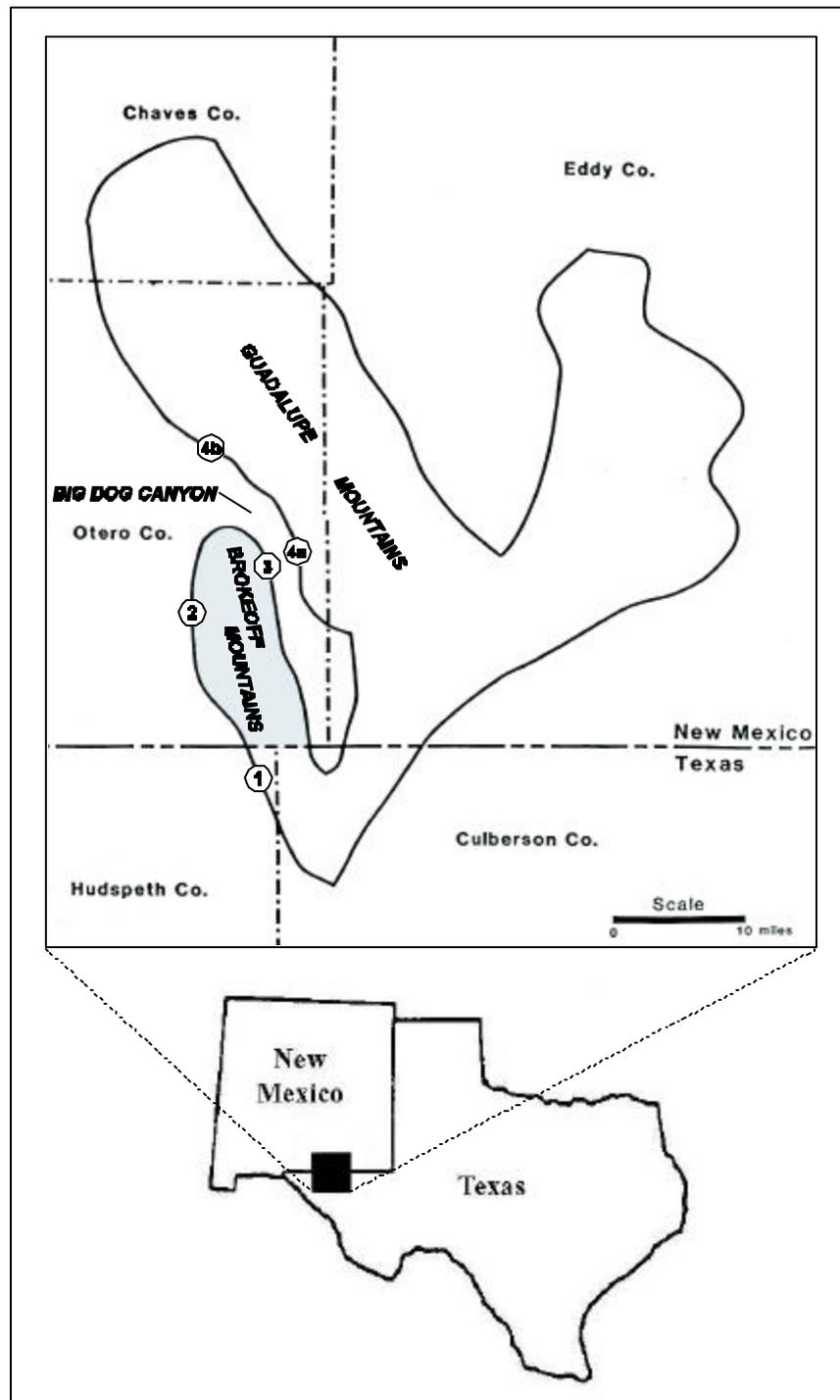


Fig. 21. Location map of the alluvial fans included in the morphometric analysis. Fan groups are indicated by number (1-4): (1) Salt Basin-Guadalupe Mountains, (2) Salt Basin-Brokeoff Mountains, (3) Dog Canyon-Brokeoff Mountains, and (4a, b) Dog Canyon-Guadalupe Mountains (modified from McKnight, 1986).

Table 4  
Morphometric Data, Guadalupe Mountains Region (GMR)

Name	Range	Subgroup	$A_f$	$S_f$	$I_s$	$A_d$	$F_s$
SBGUMO1	GUMO	SBGUMO	6.09	0.051	0.064	4.91	0.065
SBGUMO2	GUMO	SBGUMO	2.38	0.043	0.072	3.43	0.092
SBGUMO3	GUMO	SBGUMO	3.38	0.055	0.066	5.84	0.085
SBGUMO4	GUMO	SBGUMO	1.63	0.053	0.066	1.10	0.172
SBGUMO5	GUMO	SBGUMO	1.95	0.071	0.092	1.63	0.114
SBGUMO6	GUMO	SBGUMO	2.81	0.061	0.074	3.35	0.087
SBGUMO7	GUMO	SBGUMO	1.10	0.095	0.092	1.22	0.119
SBGUMO8	GUMO	SBGUMO	2.65	0.070	0.083	2.74	0.080
SBGUMO9	GUMO	SBGUMO	2.69	0.050	0.056	2.54	0.064
LITTLE	GUMO	DCGUMO	13.02	0.019	0.018	46.26	0.017
BROWNING	GUMO	DCGUMO	3.65	0.036	0.039	5.29	0.044
PUP	GUMO	DCGUMO	5.89	0.046	0.052	9.35	0.047
DCGUMO1	GUMO	DCGUMO	0.72	0.080	0.068	0.51	0.166
DCGUMO2	GUMO	DCGUMO	0.31	0.063	0.082	0.53	0.218
DCGUMO3	GUMO	DCGUMO	0.46	0.047	0.061	1.00	0.147
DCGUMO5	GUMO	DCGUMO	1.08	0.083	0.120	0.63	0.258
DCGUMO6	GUMO	DCGUMO	0.49	0.098	0.084	0.64	0.189
DCGUMO7	GUMO	DCGUMO	0.54	0.082	0.058	0.90	0.160
DCGUMO8	GUMO	DCGUMO	0.49	0.071	0.059	1.58	0.094
WEST	BO	SBBO	21.52	0.018	0.017	90.07	0.020
HUMP	BO	SBBO	1.06	0.021	0.021	2.65	0.024
CHOSIE	BO	SBBO	10.27	0.022	0.018	26.97	0.024
SOUTH	BO	SBBO	1.31	0.019	0.020	5.24	0.026
NORTH	BO	SBBO	1.84	0.021	0.021	5.42	0.025
CAL	BO	SBBO	1.81	0.024	0.022	4.16	0.023
SHEEP	BO	SBBO	0.53	0.026	0.023	0.85	0.042
DCBO1	BO	DCBO	0.56	0.074	0.061	0.25	0.171
DCBO2	BO	DCBO	0.44	0.068	0.053	0.30	0.214
DCBO3	BO	DCBO	0.41	0.088	0.072	0.17	0.238
DCBO4	BO	DCBO	0.87	0.046	0.042	1.27	0.110
DCBO5	BO	DCBO	0.94	0.047	0.046	0.65	0.136

\*Note to Table 4:

Abbreviations: Name = name of individual alluvial fan where SBGUMO = Salt Basin-Guadalupe Mountains, Little = Little Dog Canyon, Browning = Browning Well, Pup = Pup Canyon, DCGUMO = Big Dog Canyon-Guadalupe Mountains, West = West Dog Canyon, Hump = Little Humphrey Canyon, Chosie = Chosie Canyon, South = South Hammock Canyon, North = North Hammock Canyon, Cal = Cal Canyon, Sheep = Sheep Draw, DCBO = Big Dog Canyon-Brokeoff Mountains; Range = mountain range containing drainage basin where GUMO = Guadalupe Mountains and BO = Brokeoff Mountains; Subgroup = geographic location along the Guadalupe and Brokeoff Mountains where SBGUMO = Salt Basin-Guadalupe Mountains alluvial fans, DCGUMO = Big Dog Canyon-Guadalupe Mountains alluvial fans, SBBO = Salt Basin-Brokeoff Mountains alluvial fans, DCBO = Big Dog Canyon-Brokeoff Mountains alluvial fans;  $A_f$ ,  $S_f$ ,  $I_s$ ,  $A_d$ , and  $F_s$  defined in Table 3.

significant ( $p < 0.0001$ ) and demonstrates a strong, positive relationship ( $R = 0.91$ ) between alluvial fan area and drainage basin area in the GMR (Fig. 22). When compared to the range of values for the coefficient  $x$  and the exponent  $y$  proposed by Harvey (1997), the coefficient of the equation in Fig. 22 has an intermediate value of 0.92. However, with a value of 0.69, the exponent is slightly below the lower limit of the range of values for  $y$  (Harvey, 1997).

In comparing this relationship to previously published morphometric analyses conducted in the Basin and Range and Desert Southwest, the regression line developed for the alluvial fans of the GMR is in general accord with the compilation (Figs. 23 and 24). However, it is apparent that the rate of increase in alluvial fan area with an increase in drainage basin area is relatively low for the alluvial fans of the GMR, as evidenced by the value of the exponent  $y$  (0.69). The value of the exponent  $y$  for the GMR is relatively low because fan growth in the GMR has been inhibited by the various geomorphic environments bordering the alluvial fans and/or other physical constraints imposed by GMR (discussed further in section 4.1.3).

#### *4.1.2 Guadalupe and Brokeoff Mountains*

Of the 31 fans selected for this study, 19 are located on the piedmont of the western Guadalupe Mountains, while the remaining 12 are found along the east and west sides of the Brokeoff Mountains. The slopes of the regression equations for the two ranges in Fig. 25 are statistically significantly different from each other ( $p < 0.0001$ ) and show a distinction between alluvial fans from the Guadalupe and Brokeoff Mountains.

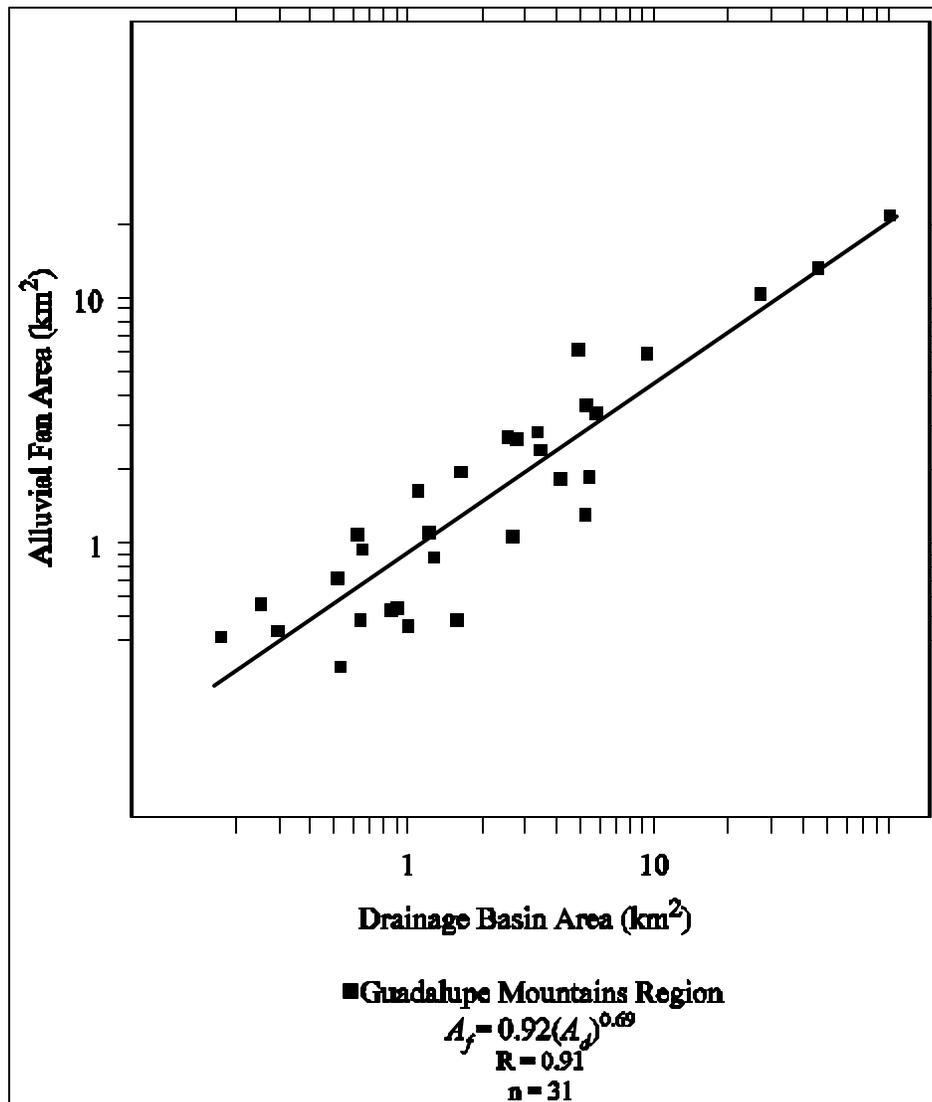


Fig. 22. Drainage basin area versus alluvial fan area, Guadalupe Mountains Region. Log-log plot demonstrating the relationship between drainage basin area and alluvial fan area for 31 alluvial fans from the Guadalupe Mountains Region.

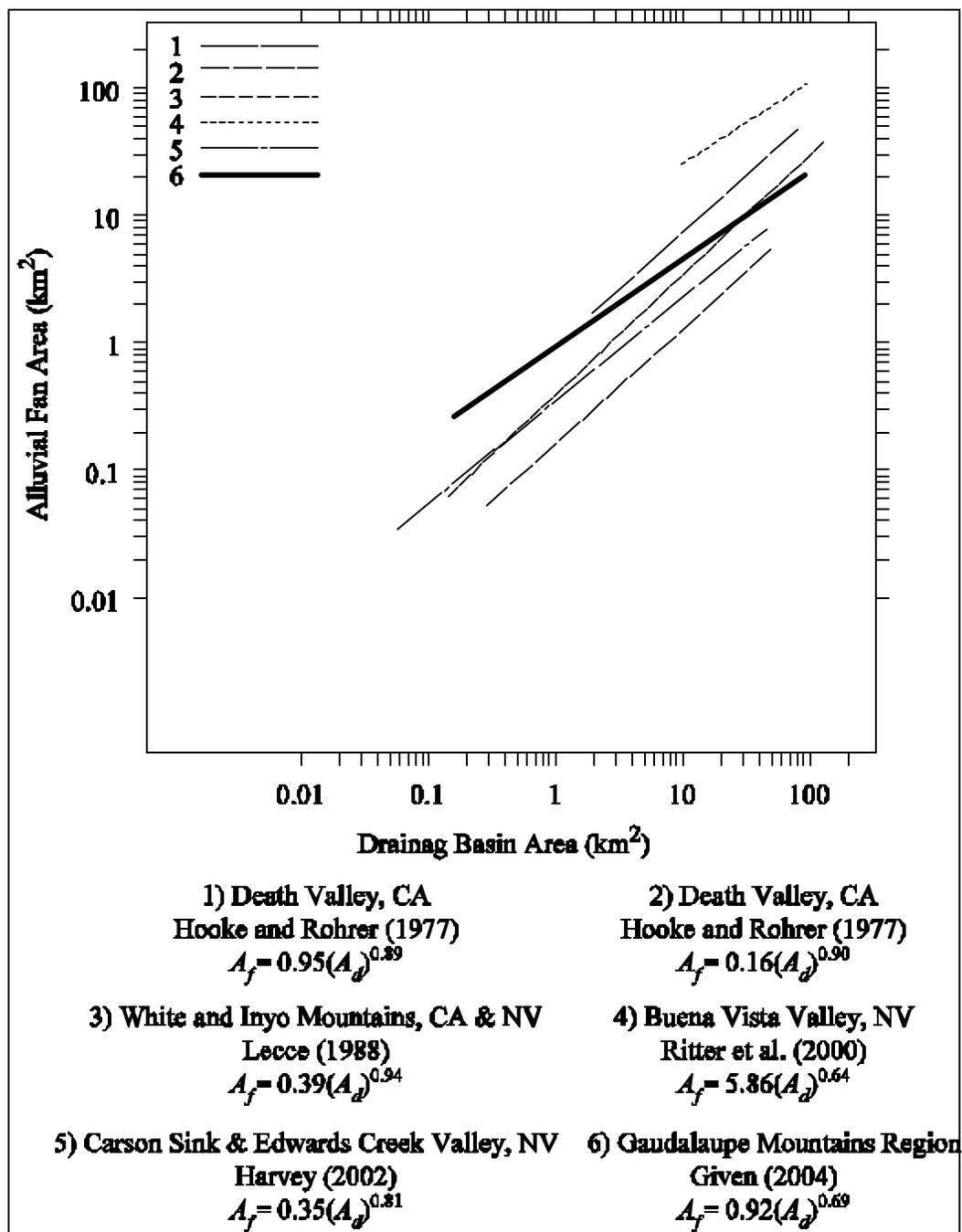


Fig. 23. Drainage basin area versus alluvial fan area ( $\text{km}^2$ ), western United States and this study. Log-log plot comparing the relationship between drainage basin area and alluvial fan area for alluvial fans from the western United States and this study.

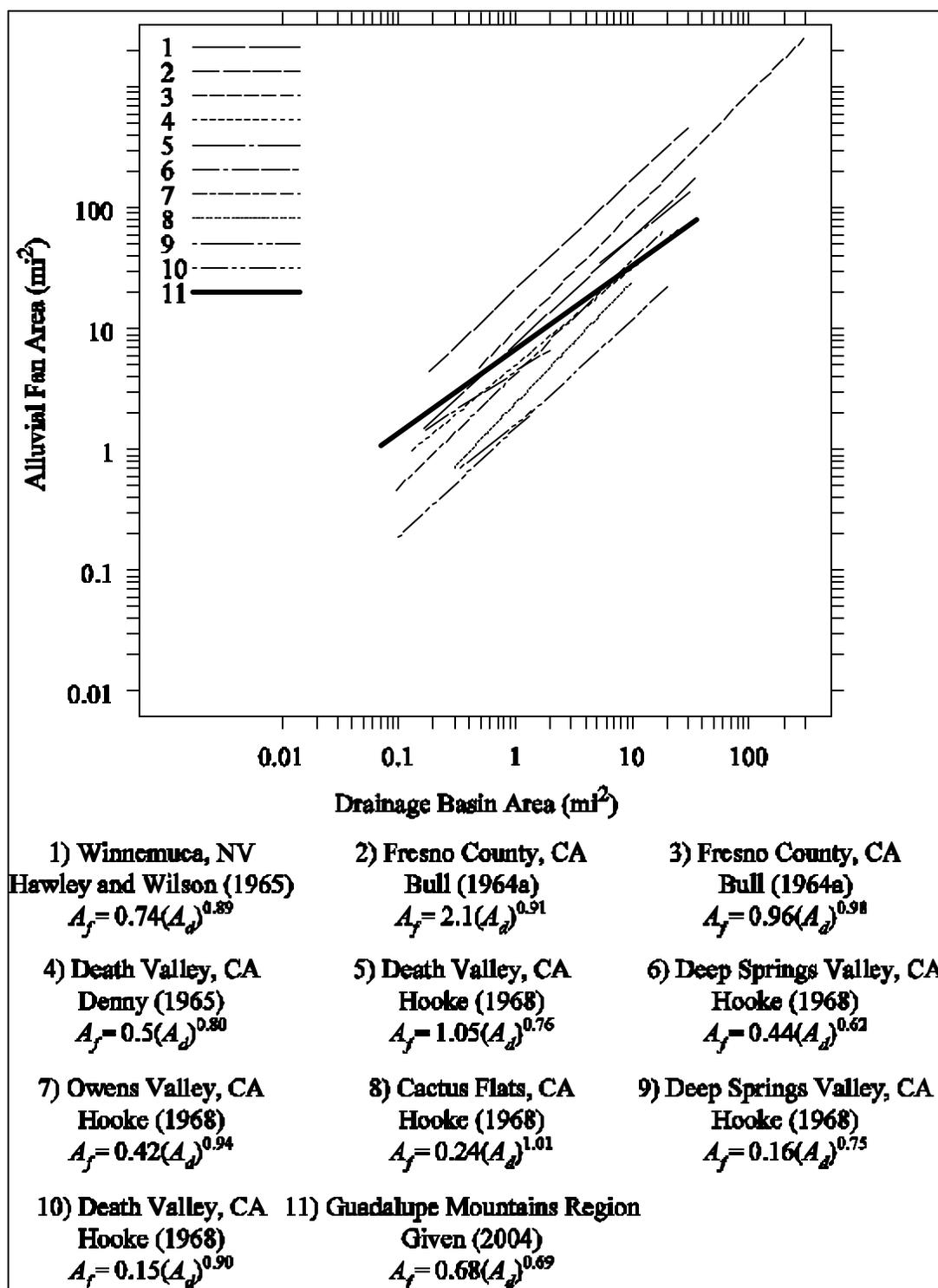


Fig. 24 Drainage basin area versus alluvial fan area ( $\text{mi}^2$ ), western United States and this study. Log-log plot comparing the relationship between drainage basin area and alluvial fan area for alluvial fans from the western United States and this study.

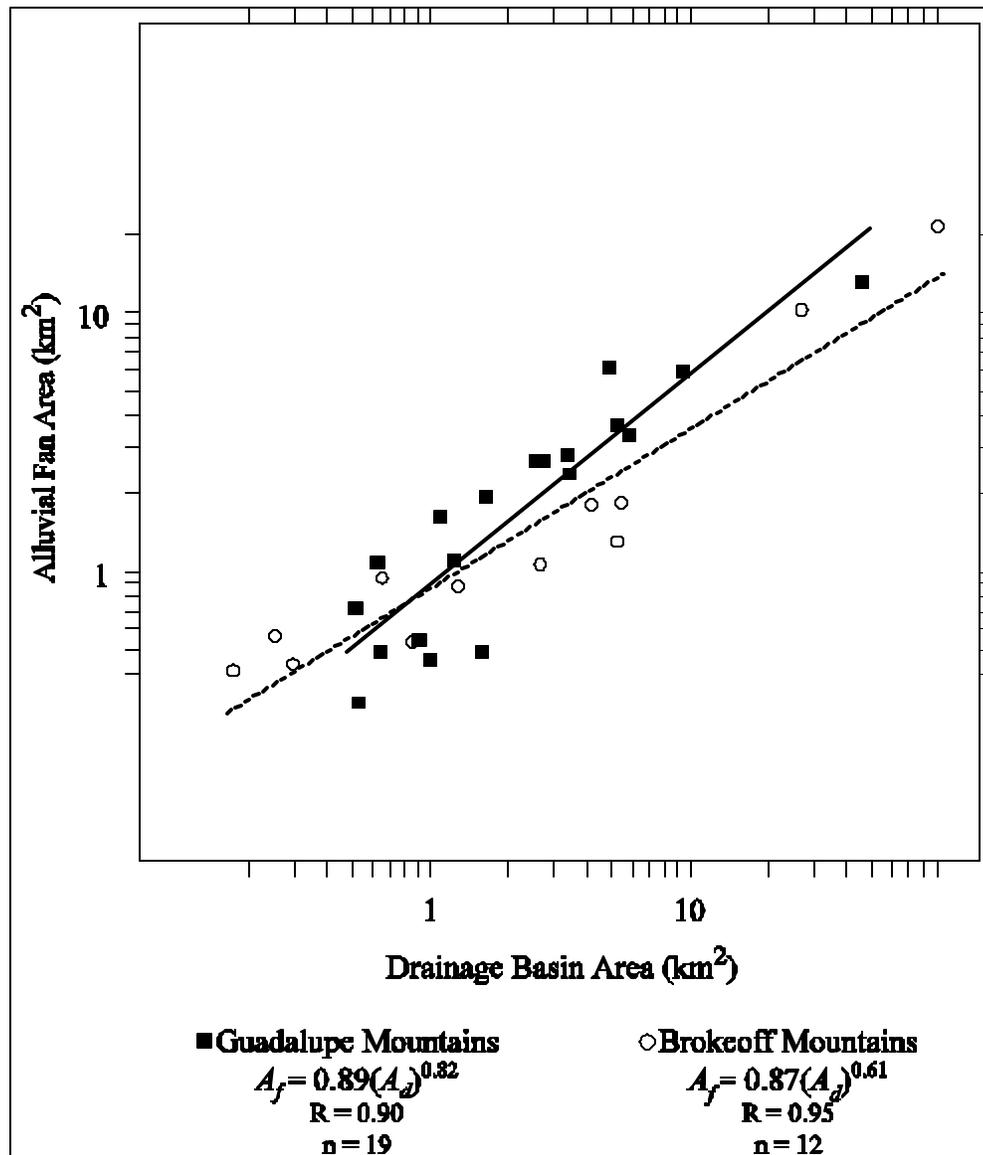


Fig. 25. Drainage basin area versus alluvial fan area, Guadalupe and Brokeoff Mountains. Log-log plot demonstrating the relationship between drainage basin area and alluvial fan area for alluvial fans of the Guadalupe and Brokeoff Mountains.

While the coefficients of the equations indicate that the alluvial fans of the Guadalupe and Brokeoff Mountains are, on average, fairly close in size ( $x = 0.89$  and  $0.87$ , respectively), the values for the exponent  $y$  ( $0.82$  and  $0.61$  for the Guadalupe and Brokeoff Mountains, respectively) suggest that the area of the alluvial fans of the Guadalupe Mountains increases with drainage basin area at a considerably higher rate than the alluvial fans of the Brokeoff Mountains.

Initially, the relatively low value of the exponent  $y$  for the Brokeoff Mountains was attributed to the ability of the larger drainage basins of the Brokeoff Mountains to store more sediment in the channels and on the slopes of tributary canyons. However, it appears that the confinement and distal erosion of the Brokeoff Mountains fans by neighboring pluvial and fluvial environments, rather than the effects of sediment storage, has lowered the value of the exponent  $y$  for the Brokeoff Mountains (discussed further in section 4.1.3).

#### *4.1.3 Four alluvial fan groups*

In an attempt to more adequately control geographic variations in drainage basin structure and lithology, tectonics, and base-level change (tectonically and/or climatically induced), the data set was further subdivided into four fan groups based on their location along the two mountain ranges. They are referred to in the text and figures as: Salt Basin-Guadalupe Mountains, Salt Basin-Brokeoff Mountains, Big Dog Canyon-Brokeoff Mountains, and Big Dog Canyon-Guadalupe Mountains (Figs. 26-29).

There is a strong correlation between alluvial fan area and drainage basin area for

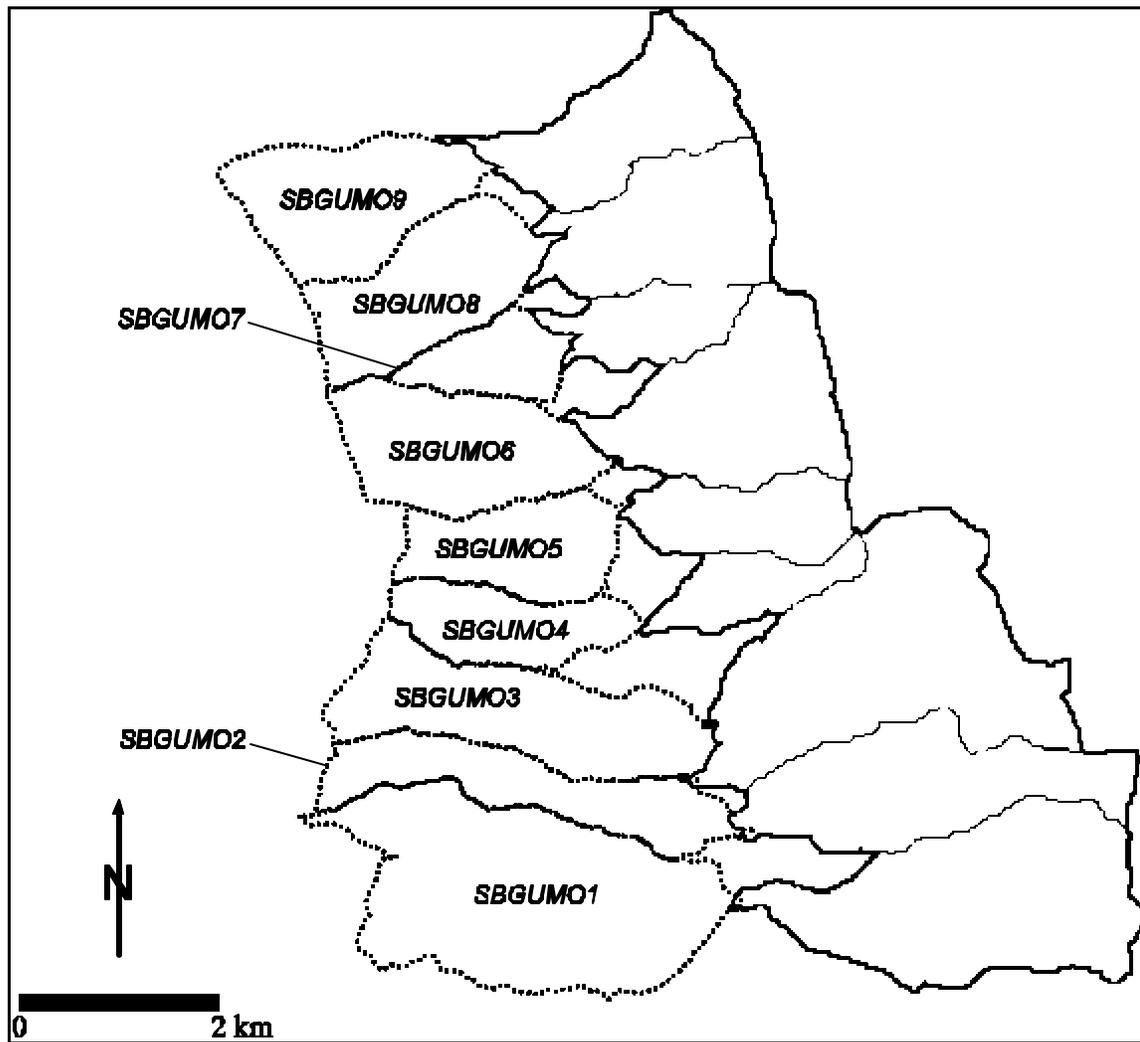


Fig. 26. Salt Basin-Guadalupe Mountains alluvial fan group. Planview line sketch of the nine alluvial fans of the Salt Basin-Guadalupe Mountains group.

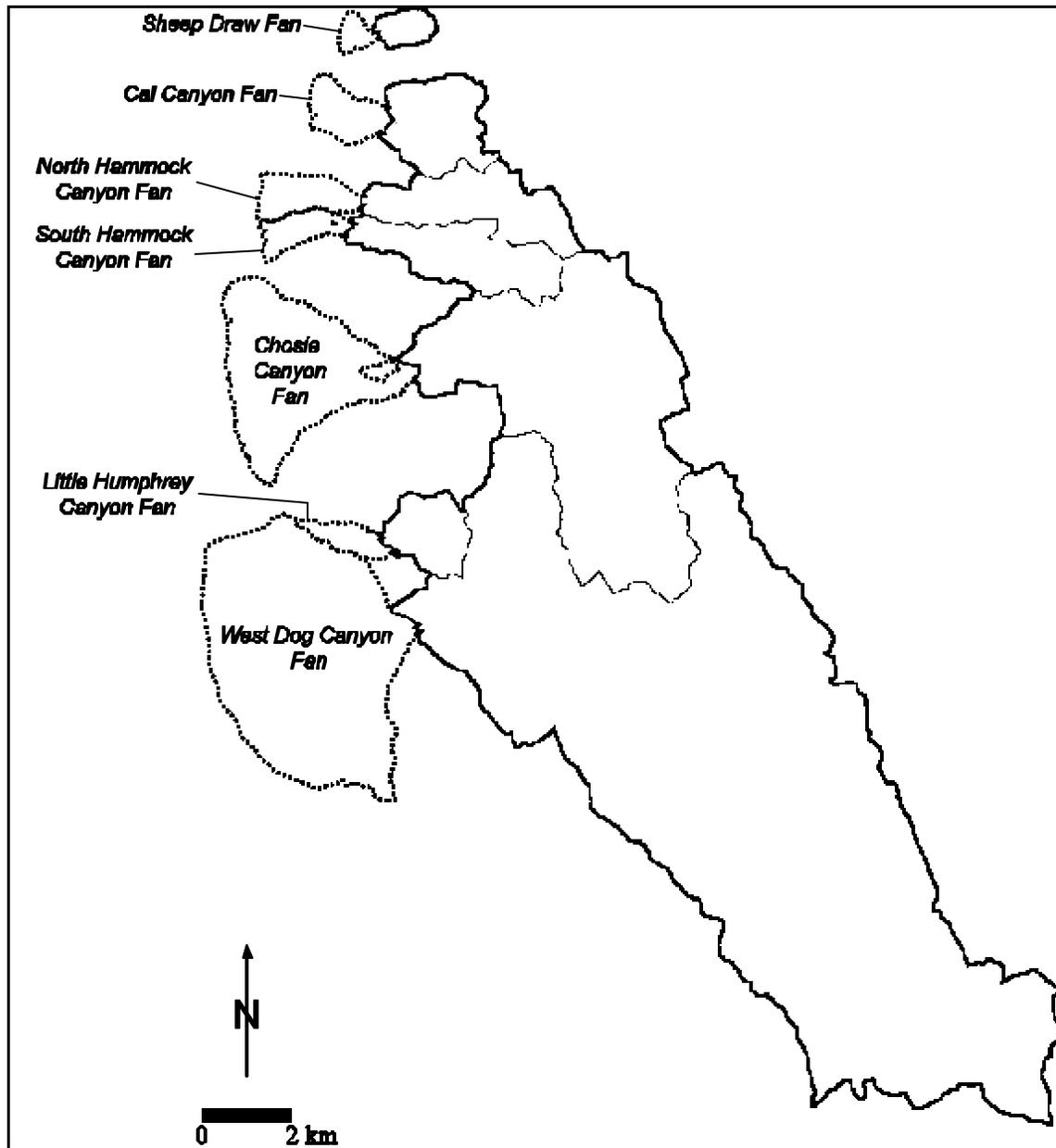


Fig. 27. Salt Basin-Brokeoff Mountains alluvial fan group. Planview line sketch of the seven alluvial fans of the Salt Basin-Brokeoff Mountains group.

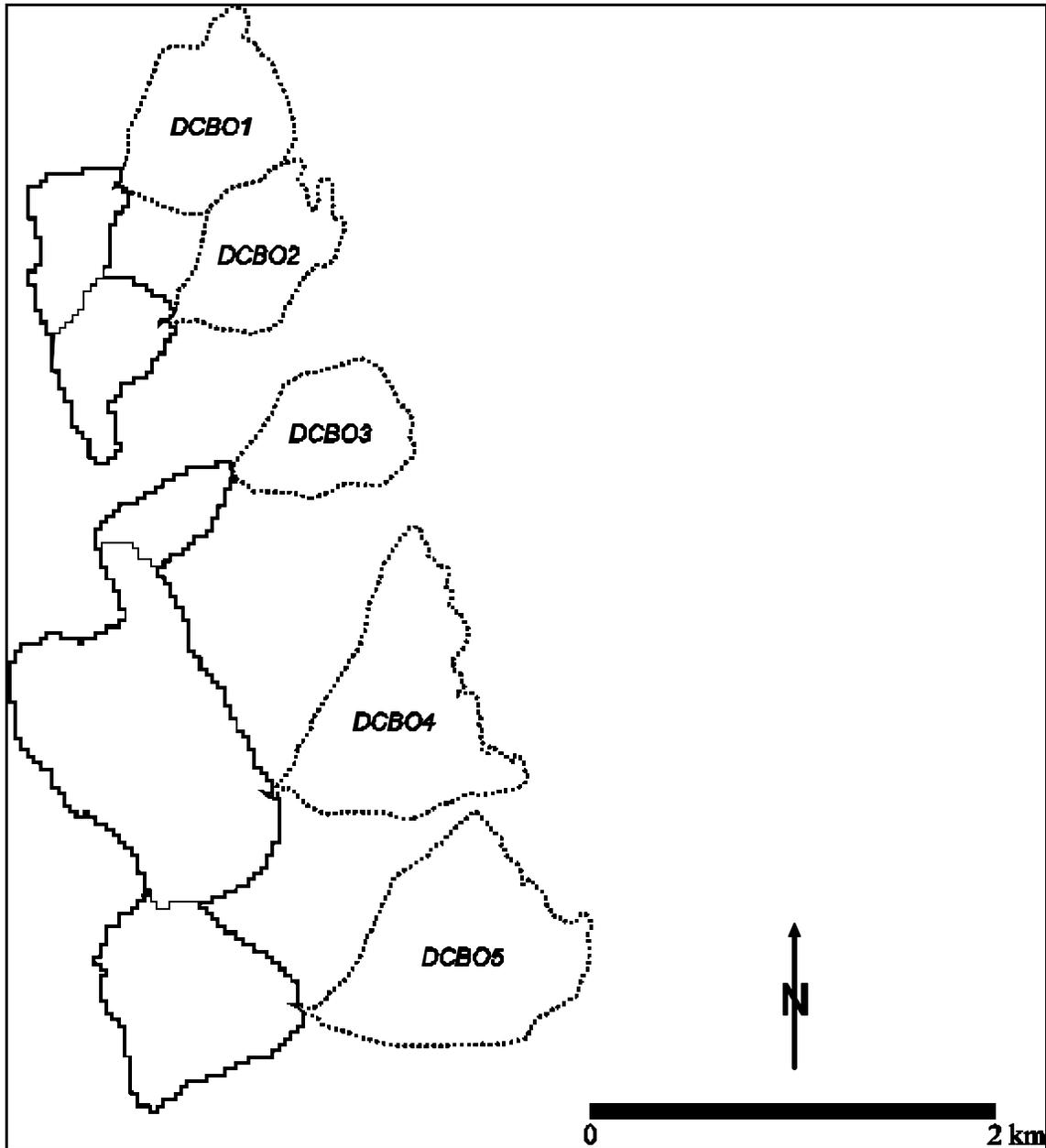


Fig. 28. Big Dog Canyon-Brokeoff Mountains alluvial fan group. Planview line sketch of the five alluvial fans of the Big Dog Canyon-Brokeoff Mountains group.

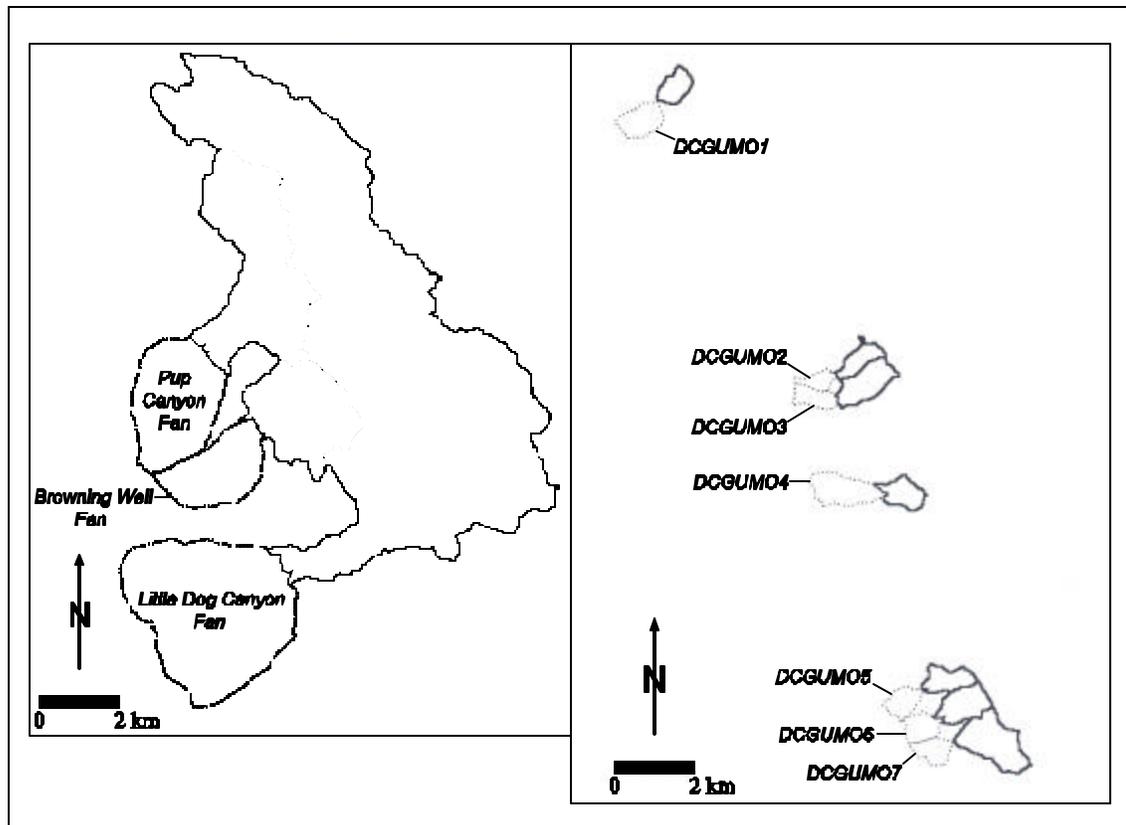


Fig. 29. Big Dog Canyon-Guadalupe Mountains alluvial fan group. Planview line sketch of the ten alluvial fans of the Big Dog Canyon-Guadalupe Mountains group.

the four alluvial fan groups analyzed, as evidenced by the high correlation coefficients obtained (Fig. 30). As shown in Fig. 30, the coefficients for the Big Dog Canyon groups differ less from each other than they do from those of the Salt Basin groups. Although relatively low, the coefficients for the Big Dog Canyon fan groups ( $x = 0.72$  and  $0.89$  for the Guadalupe and Brokeoff Mountains, respectively) are within the range of values suggested by Harvey (1997). However, the value of the coefficient for the Salt Basin-Brokeoff Mountains group ( $x = 0.49$ ) suggests that the alluvial fans of the group are only half of the size of their drainage basins while the higher value of the coefficient for the Salt Basin-Guadalupe Mountains group ( $x = 1.27$ ) indicates that the alluvial fans of the group are very extensive in relation to their drainage basins.

There are a number of explanations for variations of  $x$  within the Salt Basin. Tectonic movements have affected different parts of the Salt Basin in different ways. For instance, episodic uplift of the western escarpment since the late Miocene or early Pliocene (King, 1948), coupled with the active subsidence of the western margin of the Salt Basin (Muehlberger et al., 1978), could have caused the fans of the Salt Basin-Guadalupe Mountains group to be extended, whereas those fans to the north, in the Salt Basin-Brokeoff Mountains group, seem to have been restricted during pluvial intervals. The drainage basins of the Salt Basin-Guadalupe Mountains fan group are significantly higher in elevation than the drainage basins of the Salt Basin-Brokeoff Mountains fan group and, therefore, receive more rainfall and are frequently exposed to other forms of physical weathering processes such as freeze-thaw. The markedly higher value of the coefficient for the Salt Basin-Guadalupe Mountains undoubtedly reflects, at least in part,

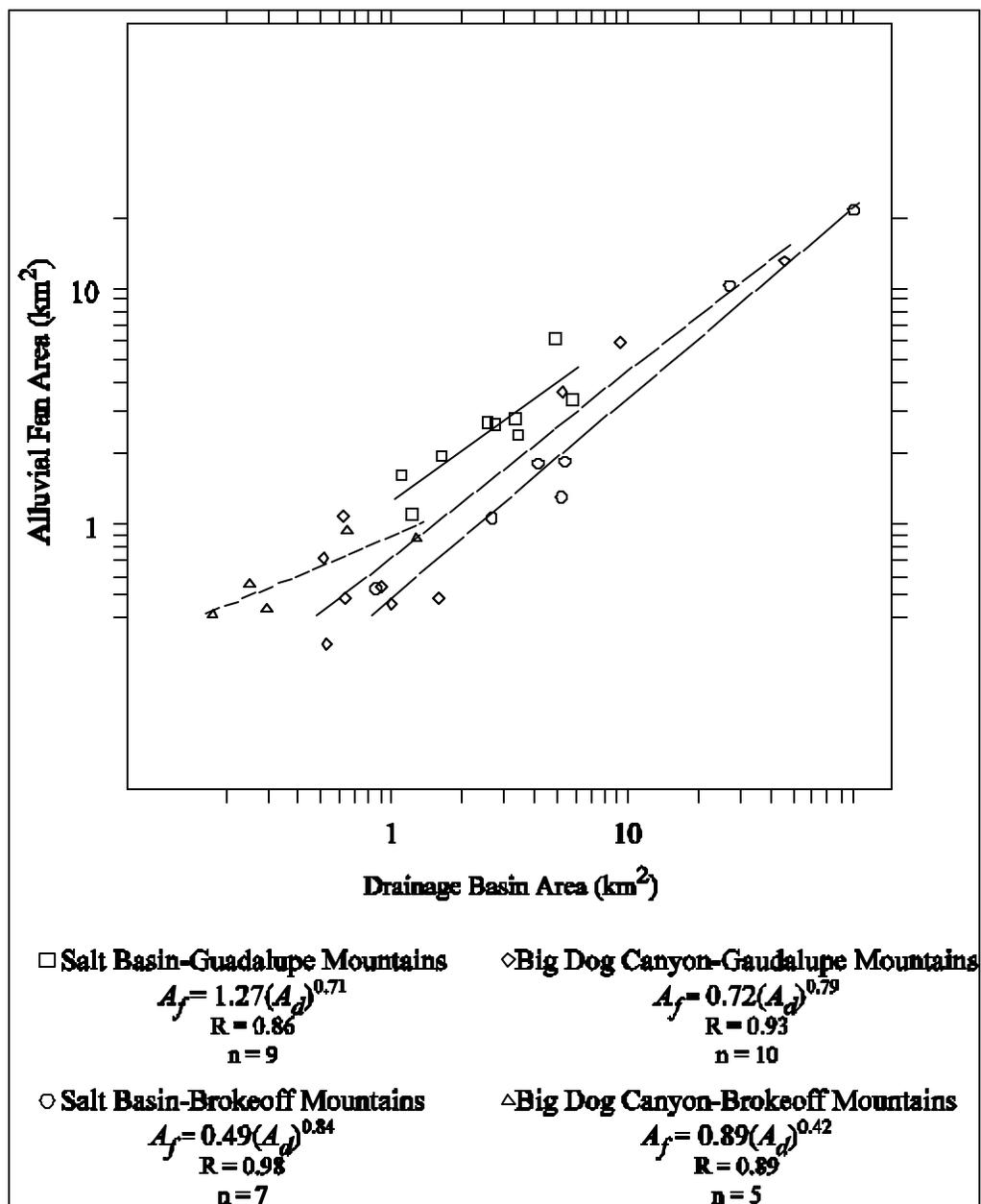


Fig. 30. Drainage basin area versus alluvial fan area, four fan groups. Log-log plot demonstrating the relationship between drainage basin area and alluvial fan area for the four alluvial fans groups of the Guadalupe Mountains Region.

higher sediment yield from the drainage basins. Furthermore, high relative relief and narrow and/or steep slopes have minimized the ability of these drainage basins to internally store sediment, further contributing to the high value of  $x$ .

Additionally, alluvial fans that have formed along mountain fronts where tectonic movement is episodic or moderate tend to be extensive in relation to their drainage basins and have elongated morphologies perpendicular to the mountain front (Calvache et al., 1997; Viseras et al., 2003). In the case of the alluvial fans of the Salt Basin-Guadalupe Mountains group, their elongated forms are primarily the result of lateral channelization by adjacent fans or the strengthening of incised and distributary channel walls by allogenic or authogenic carbonates and migrating aeolian fine sediments, which has extended the fans length by transporting alluvium in a progressively more distal direction.

Restriction of the Salt Basin-Brokeoff Mountains group is inferred to involve a climatically-controlled rise in base-level associated with the presence of pluvial Lake King in the Salt Basin and an influx of fluvial sediment from Big Dog Canyon and 3Ixon Draw. Fragments of shorelines preserved on the alluvial fans of the Salt Basin have provided geomorphic evidence of the timing and extent of pluvial Lake King during the Pleistocene (Wilkins and Currey, 1997). During pluvial intervals, the transgression of the playa-fan boundary would cause the deposition of alluvial sediments to be concentrated in a smaller area near the proximal portions of the fan and, in some cases, backfilled into the drainage basin and along the floor of the feeder channel (Hooke, 1968; Viseras et al., 2003). The principal effects of these circumstances include lower

fan sedimentation rates (Blair and McPherson, 1994) and the subsequent development of multiple feeder channels, and consequently, more than one incised channel (Viseras et al., 2003). It should be noted, however, that the relatively small area of West Dog Canyon (21.5 km<sup>2</sup>) with respect to its drainage basin (90.0 km<sup>2</sup>) could at least partly account for the value of the coefficient for the Salt Basin-Brokeoff Mountains fan group.

For the alluvial fans of the Big Dog Canyon groups, the coefficient values probably reflect the relatively small size and high gradients of their drainage basins and the dominance and low runout distances of debris-flow and mass-wasting processes on these fans. Furthermore, the fans of the Big Dog Canyon-Brokeoff Mountains group, along with the three southernmost fans of the Big Dog Canyon-Guadalupe Mountains group (Fig. 31), have been reduced in area by Upper Dog Canyon Arroyo. The lateral migration of the arroyo through Big Dog Canyon has eroded the distal margins of these fans, producing 2-4 meter high near-vertical channel walls that are typically oriented parallel to the mountain front. The relatively small size of the Big Dog Canyon-Brokeoff Mountains group may also reflect the relative youth of the fans, since the uplift and subsequent faulting of the Brokeoff Mountains progressed in an eastward direction (Thuma, 1990).

In the case of the Big Dog Canyon-Guadalupe Mountains group, the value of the coefficient is relatively low, in large part because their drainage basins for seven fans included in the group have developed along the relatively unfractured Algoritia Escarpment. The coefficient for the group would be presumably lower if the three fans from the Buckhorn Escarpment were omitted from the analysis. Little Dog Canyon fan



Fig. 31. Distally truncated alluvial fans in Big Dog Canyon. Photographs of the three southernmost fans of the Algerita Escarpment in Big Dog Canyon. These three fans, along with the five fans from the Big Dog Canyon-Brokeoff Mountains groups, have been truncated during the lateral migration of Upper Dog Canyon Arroyo along the floor of Big Dog Canyon. Note the prominent fluvial scarp (left of center) at the toe of the alluvial fan in the lower picture.

and Browning Well fan have areas of 13.0 and 3.65 km<sup>2</sup>, respectively, while the Pup Canyon fan is 5.89 km<sup>2</sup>, an area ten times greater than the average area of the other seven fans of the group located along the Algerita Escarpment.

It is also possible that the relatively low value of the coefficient for the Big Dog Canyon-Guadalupe Mountains group may be related to the uplift of the Algerita Escarpment. At tectonically active mountain fronts, where the mountains are rising with respect to the adjacent basin, alluvial fans tend to aggrade vertically (as opposed to extending and expanding), resulting in fans that are relatively small in relation to the contributory drainage basin (Silva et al., 1992; Ferrill et al., 1996; Viseras et al., 2003). The rapid and/or constant uplift of the Algerita Escarpment relative to Big Dog Canyon during the late Pliocene or early Pleistocene could have caused debris flow and mass wasting deposits to accumulate directly against the resulting escarpment. The relative youth and/or incipiency of these fans is further evidenced by the absence of fan head trenches, conspicuous incised channels and common erosional features, such as headward-eroding gullies. The presence of these features is generally considered a sign of fan maturity (Blair and McPherson, 1994; Blair, 1999).

The slopes of the regression lines for each group are statistically significantly different from each other ( $p < 0.0001$ ). The exponents for the Guadalupe Mountains fan groups (0.71 and 0.79 for Salt Basin and Big Dog Canyon, respectively) have values close to the lower limit of the examples described by Harvey (1997), while the exponent for the Salt Basin-Brokeoff Mountains group has an intermediate value ( $y = 0.84$ ). However, the value of the exponent for the Big Dog Canyon-Brokeoff Mountains fan

group is markedly lower ( $y = 0.42$ ) than the lower limit of the range suggested by Harvey (1997), indicating that these fans increase little in area when their drainage basin increases.

Previous alluvial fan research has maintained that the value of  $y$  is largely controlled by the sediment yield of the drainage basin. A value of  $y$  less than 1.0 implies that larger drainage basins supply less sediment per unit area than smaller drainage basins, primarily because of the larger drainage basins' ability to store more sediment (Hooke, 1968). Although the magnitude of the influence of sediment storage has not been quantified, the value of the exponent generally becomes lower as drainage basin area increases. However, previous research has suggested that this scale-related decline in sediment yield may also be influenced by the relative relief and slope of the drainage basin. Opportunities for sediment storage generally increase as drainage basin slope and relative relief decrease (Hooke, 1968, Dunne and Leopold, 1978; Church and Mark, 1980; Lecce, 1988).

The value of the exponents for the four fan groups of the GMR, however, are not in general accord with previous published analyses on the influence of sediment storage on alluvial fan morphometry (Bull, 1964a; Hooke, 1968; Lecce, 1988). In a seemingly anomalous situation, the value of the exponent increases (0.84, 0.79, 0.71, 0.42 for the Salt Basin-Brokeoff Mountains, Big Dog Canyon-Guadalupe Mountains, Salt Basin-Guadalupe Mountains, Big Dog Canyon-Brokeoff Mountains, respectively) with an increase in mean drainage basin area (19.34 km<sup>2</sup>, 6.67 km<sup>2</sup>, 2.97 km<sup>2</sup>, and 0.53 km<sup>2</sup> for the Salt Basin-Brokeoff Mountains, Big Dog Canyon-Guadalupe Mountains, Salt Basin-

Guadalupe Mountains, Big Dog Canyon-Brokeoff Mountains, respectively). Thus, sediment storage in the drainage basins does not appear to significantly influence the value of the exponent, as evidenced by the inverse relationship that  $y$  has with the drainage basin area, and instead seems to be more heavily influenced by physical constraints imposed by the fan setting.

For the alluvial fans of the Big Dog Canyon groups, the value of the exponent most likely reflects the dominance of debris flow and mass-wasting processes on these fans (Church and Mark, 1980) and the physical constraints provided by Big Dog Canyon (Kostaschuk et al., 1986). Furthermore, the available depositional area for the Big Dog Canyon groups have been limited by the narrowness of Big Dog Canyon and the presence of bedrock outcrops along the canyon floor, causing the alluvial fans to extend in a direction parallel to the canyon rather than perpendicular to it. It is also possible that the exponent for the Big Dog Canyon-Brokeoff Mountains group further reflects the effects of fan confinement by the alluvial deposits of neighboring incipient drainage basins.

#### *4.2 Drainage basin area-alluvial fan slope*

##### *4.2.1 Guadalupe Mountains Region*

The 31 alluvial fans of this study have slopes ranging from 0.0176 to 0.098. The regression equation relating drainage basin area and alluvial fan slope for the entire data set is statistically significant ( $p < 0.0001$ ) and has a moderate correlation coefficient of

0.72 (Fig. 32). In this equation, both the values for the exponent  $b$  (-0.27) and the coefficient  $a$  (0.057) are within the normal range of values proposed by Harvey (1997).

When compared to similar morphometric analyses conducted in the Basin and Range and Desert Southwest (Figs. 33-34), though the value of the exponent  $b$  is moderate, relative differences for the coefficient  $a$  might reflect the weathering characteristics of the various lithologies underlying the drainage basins. For a given drainage basin area, the predominantly carbonate drainage basins of the GMR have produced fans with relatively higher slopes than alluvial fans derived from sedimentary lithologies in western California (Bull, 1964a), and relatively lower slopes than alluvial fans with drainage basins consisting primarily of igneous lithologies in north-central Nevada (Hawley and Wilson, 1965; Harvey, 2002). Presumably, these differences may be attributed largely to the greater erodibility of the sedimentary lithologies and the finer sediments comprising the fans (Bull, 1964a) and greater resistance of the igneous lithologies, which tend to weather into particles varying from sand to angular, very coarse boulders in response to tectonically influenced fracturing and jointing, exfoliation, and granular disintegration (Hooke, 1968; Blair and McPherson, 1994).

#### *4.2.2 Guadalupe and Brokeoff Mountains*

When the 31 alluvial fans are separated by mountain range, the regression equations relating drainage basin area and alluvial fan slope (Fig. 35) have improved correlation coefficients ( $R = 0.82$  and  $0.86$  for the Guadalupe and Brokeoff Mountains, respectively). The slopes of the regression lines are statistically significantly different

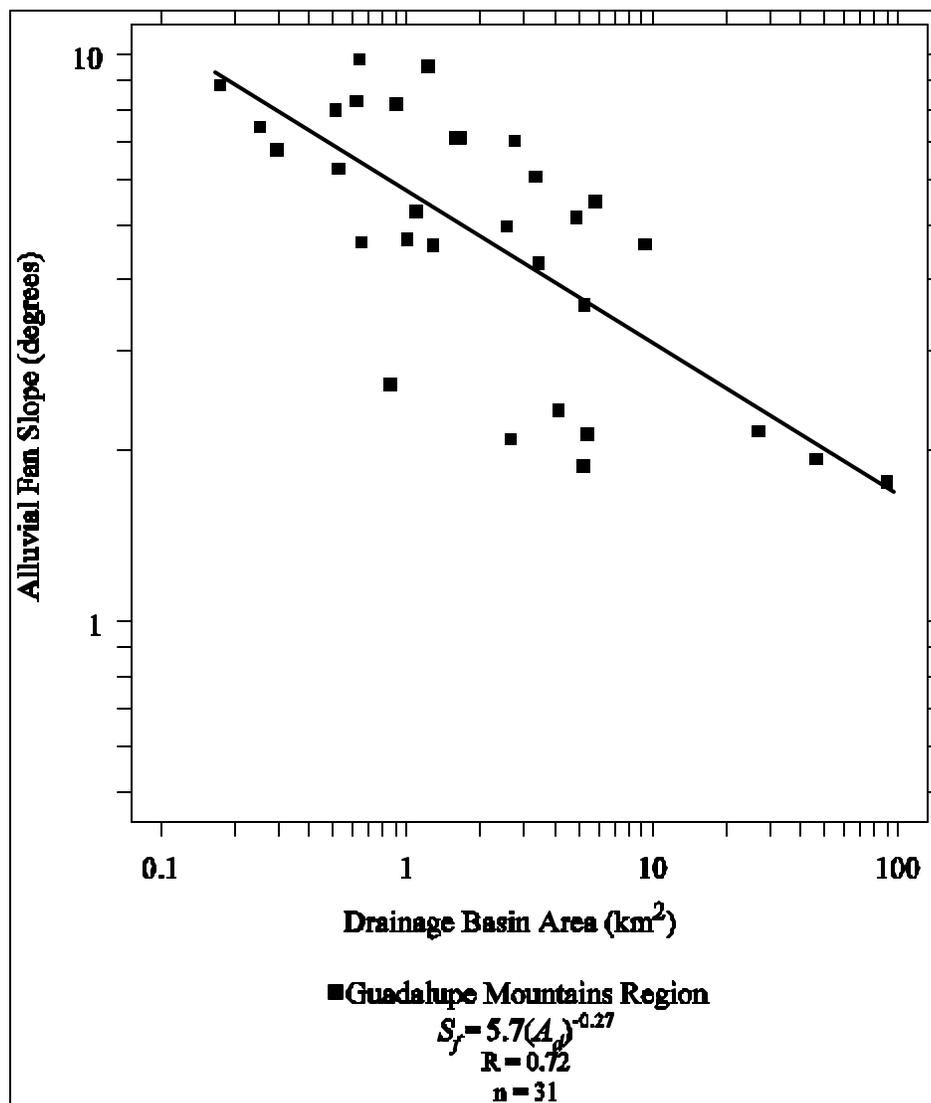


Fig. 32. Drainage basin area versus alluvial fan slope, Guadalupe Mountains Region. Log-log plot demonstrating the relationship between drainage basin area versus alluvial fan slope for 31 alluvial fans from the Guadalupe Mountains Region.

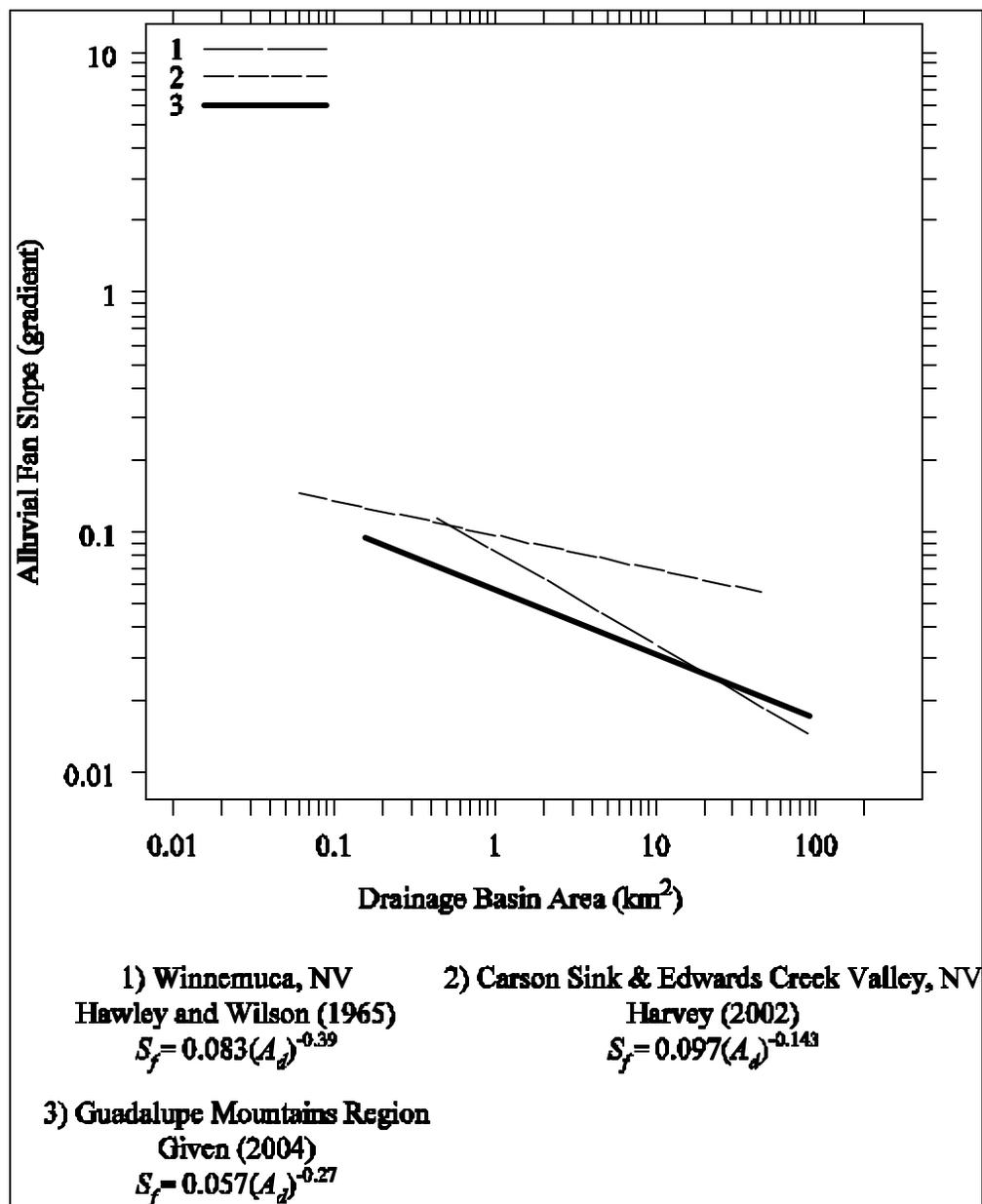


Fig. 33. Drainage basin area versus alluvial fan slope ( $\text{km}^2$ ), western United States and this study. Log-log plot comparing the relationship between drainage basin area and alluvial fan slope for alluvial fans from the western United States and this study.

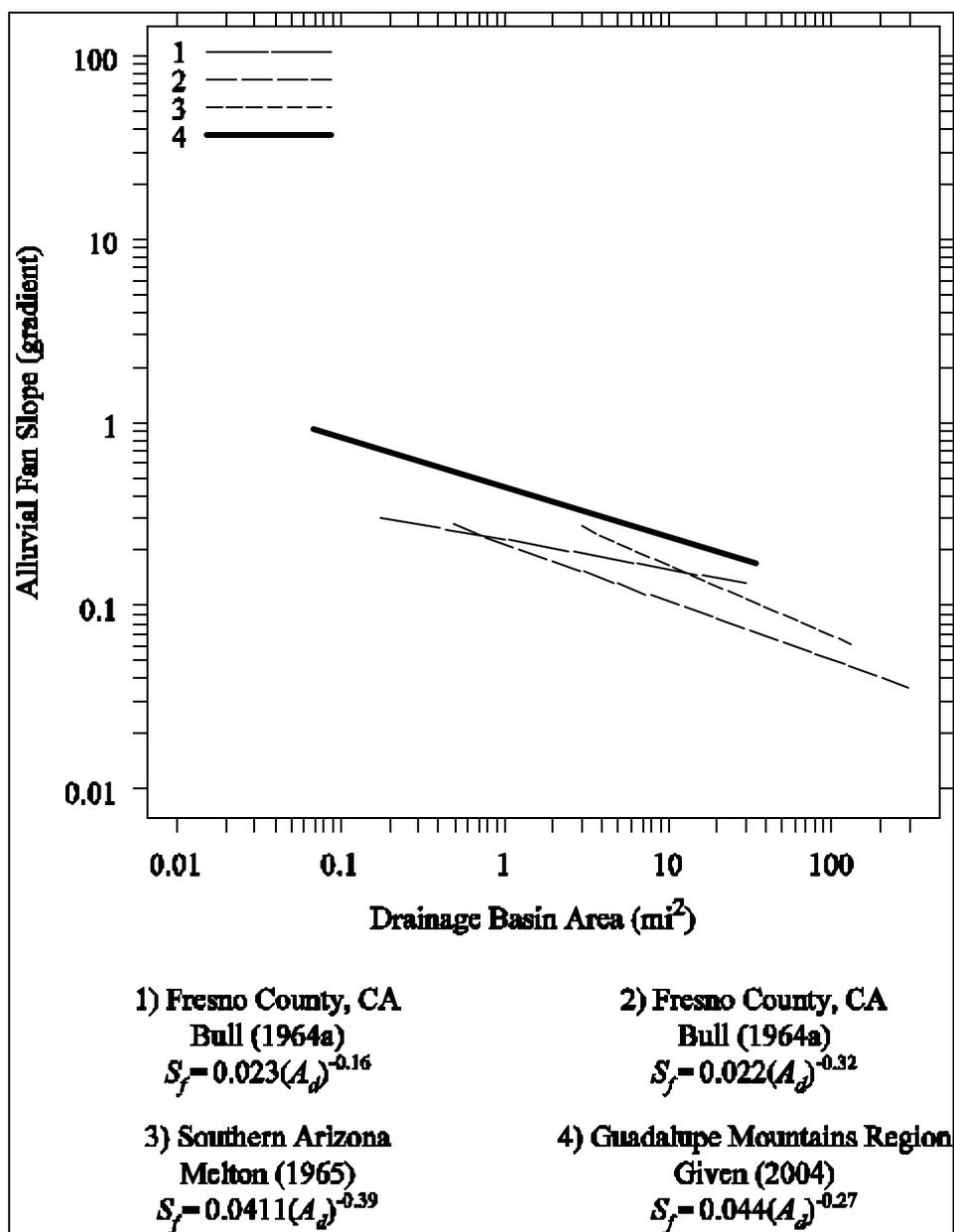


Fig. 34. Drainage basin area versus alluvial fan slope ( $\text{mi}^2$ ), western United States and this study. Log-log plot comparing the relationship between drainage basin area and alluvial fan slope for alluvial fans from the western United States and this study.

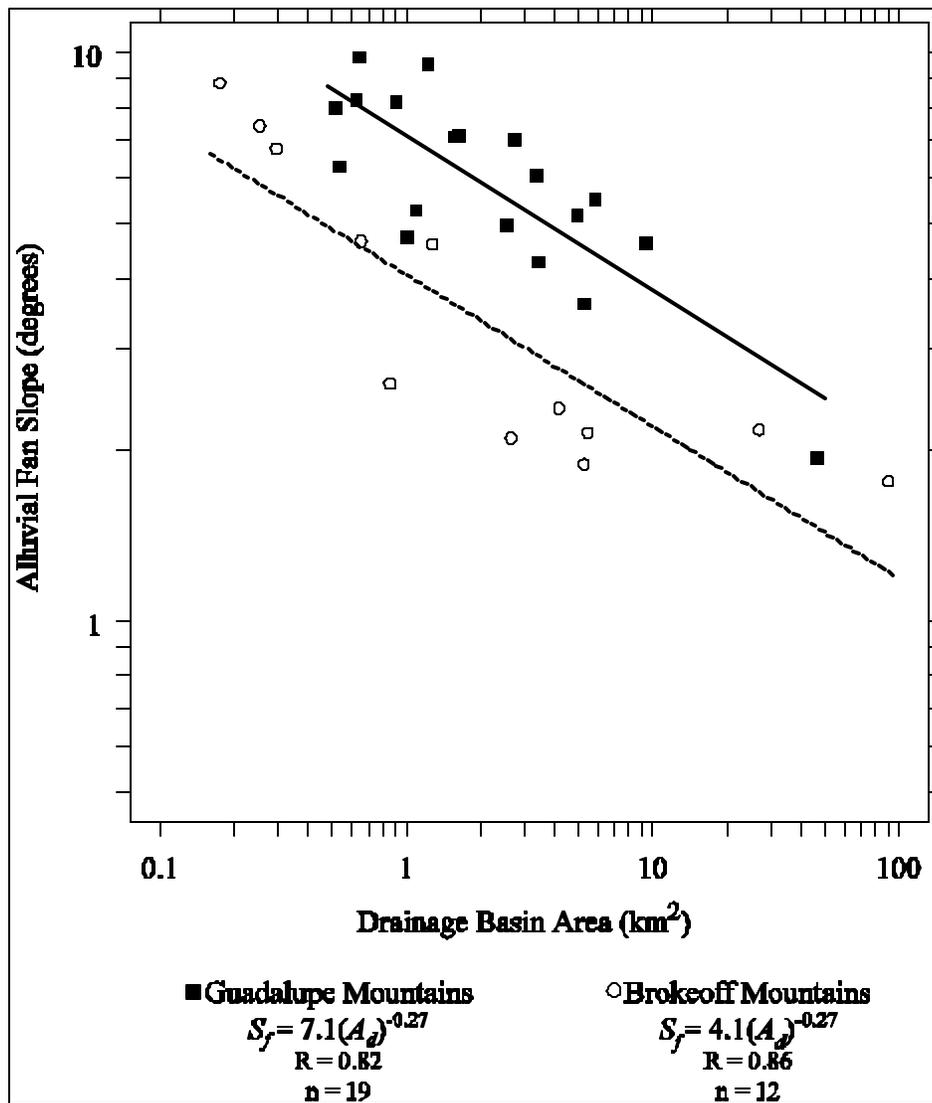


Fig. 35. Drainage basin area versus alluvial fan slope, Guadalupe and Brokeoff Mountains. Log-log plot demonstrating the relationship between drainage basin area and alluvial fan slope for alluvial fans of the Guadalupe and Brokeoff Mountains.

from each other ( $p = 0$ ), despite having the same value for the exponent  $b$  (-0.27). However, the values for the coefficient  $a$  indicate that the alluvial fans of the Guadalupe Mountains are, on average, nearly twice as steep as those of the Brokeoff Mountains (0.071 and 0.041 for the Guadalupe and Brokeoff Mountains, respectively). The lower value of the coefficient for the Brokeoff Mountains might relate to the weathering characteristics of the lithologies underlying the drainage basins (Blair and McPherson, 1994; Harvey et al., 1999). The drainage basins of the Guadalupe and Brokeoff Mountains have grossly similar lithologies, consisting primarily of marine limestones, dolomites, sandstones, and shales that formed on the northwest shelf of the Delaware Basin during the early and middle Permian (King, 1948). However, the Brokeoff Mountains are composed of proportionally more sandstone and shale (approximately 50%) than the Guadalupe Mountains (McKnight, 1986). The intense fracturing of the bedrock of the Brokeoff Mountains, combined with the higher concentrations of sandstone and shale in the drainage basin, could result in a higher yield of finer-grained sediments, hence producing fans with lower gradients (Hooke, 1968; Calvache et al., 1997; Harvey et al., 1999).

#### *4.2.3 Four alluvial fan groups*

The regression equations in Fig. 36 have slopes that are statistically significantly different from one another ( $p = 0$ ) and show a strong correlation between drainage basin area and alluvial fan slope for three of the four groups analyzed ( $R = 0.96, 0.90, 0.74$  for the Big Dog Canyon-Brokeoff Mountains, Big Dog Canyon-Guadalupe Mountains, and

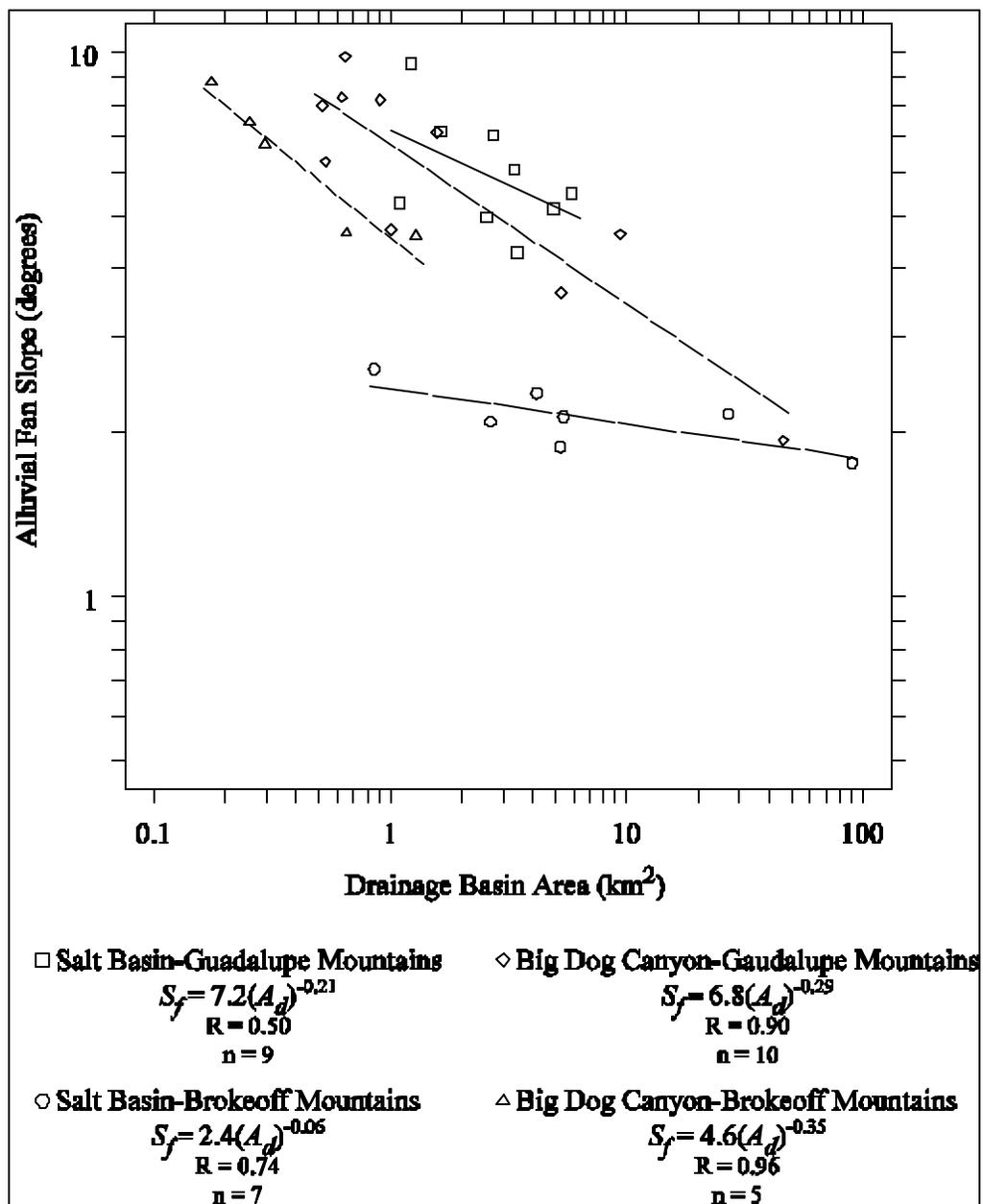


Fig. 36. Drainage basin area versus alluvial fan slope, four fan groups. Log-log plot demonstrating the relationship between drainage basin area and alluvial fan slope for the four alluvial fans groups of the Guadalupe Mountains Region.

Salt Basin-Brokeoff Mountains fan groups, respectively). However, the slopes of the Salt Basin-Guadalupe Mountains fan group appear to be weakly related to area of their drainage basins, as evidenced by the low correlation coefficient ( $R = 0.50$ ).

The morphometric properties of the two Guadalupe Mountains fan groups differ less from each other than the two Brokeoff Mountains fan groups. Regarding the coefficients of the equations, the value of  $a$  for the Salt Basin-Brokeoff Mountains group (0.024) is slightly below the lower limit of Harvey's (1997) range, indicating that these fans have markedly low gradients. Furthermore, the value of the exponent  $b$  for the group is quite high (-0.06), exceeding the upper limit of the range suggested by Harvey (1997). This indicates that the slopes of the alluvial fans of the Salt Basin-Brokeoff Mountains group decrease very little in relation to an increase in their drainage basin areas. By contrast, with an exponent value of  $-0.35$ , the fans of the Big Dog Canyon-Brokeoff Mountains decrease significantly when their drainage basins increase in area.

In general, the values of the coefficients of the four fan groups appear to reflect the sedimentary processes that constructed the fans. It has frequently been demonstrated that fans composed predominantly of debris flow deposits not only have higher gradients, but also tend toward lower values for the exponent (Harvey, 1992). For the two Guadalupe Mountains fan groups, the higher values of the coefficients (0.072 and 0.068 for Salt Basin and Big Dog Canyon, respectively) and relatively low value of the exponent for the Big Dog Canyon group ( $b = -0.29$ ) at least partially reflect the size of the sediments comprising these fans which, in turn, can be attributed to the higher relative relief, steeper gradient, and weathering characteristics of their drainage basins.

The value of the coefficient and exponent for the Big Dog Canyon-Guadalupe Mountains group would be presumably higher and lower, respectively, if the three gently sloping fans of the Buckhorn Escarpment were omitted from the group. These values have been further influenced by the three southernmost fans of the group, where the slope of the fans has been steepened due to the truncation of their distal margins by Upper Dog Canyon Arroyo.

For the two Brokeoff Mountain fan groups, the large distinction between the values of  $a$  (0.024 and 0.046 for Salt Basin and Big Dog Canyon, respectively) and  $b$  (-0.06 and -0.35 for Salt Basin and Big Dog Canyon, respectively) can be primarily attributed to erosional and depositional processes related to adjacent environments. The low coefficient and markedly high exponent for the Salt Basin group probably reflect the backfilling of the feeder channel and lower reaches of the drainage basin and the subsequent development of multiple incised channels on the fan surface. The distal accumulation of playa sediments from Lake King and fluvial sediments from Big Dog Canyon and 3Ixon Draw has decreased average fan slope, as have the multiple incised channels, thus promoting sedimentation in a progressively more distal direction. In Big Dog Canyon, the value for the exponent most likely reflects the confinement of the fans by the deposits of neighboring fans and the truncation of their distal margins by Upper Dog Canyon Arroyo.

### *4.3 Feeder channels slope-incised channel slope*

Fig. 37 plots the slope of the 1-km-long segment of the feeder channel upslope of the fan apex versus the corresponding slope of the 1-km-long incised channel for 28 of the 31 fans in the data set. Three of the fans from the Big Dog Canyon-Guadalupe Mountains were excluded from the plot because their feeder channels do not extend 1-km above the fan apex. Fig. 37 shows that, for the majority of the alluvial fans selected for this study, the slope of the 1-km long segment of the feeder channel immediately upstream of the fan apex coincides with or is slightly higher than the 1-km slope of the incised channel directly downstream of the fan apex. The slope of the 1-km-long segment of the feeder channel adjoining the fan apex is significantly greater ( $>1$ ) than the slope of the incised channel in 57% of these alluvial fans. There is no significant difference ( $\pm 1$ ) in 32% of the cases, and on three of the fans ( $\sim 11\%$ ) the slope of the incised channel is actually steeper than the slope of the feeder channel adjoining the fan apex. These results further support the arguments and evidence published by a number of authors (Trowbridge, 1911; Beaty, 1963; Bull, 1977). As evidenced by Fig. 37, although there is not always a break in slope between the feeder channel and the incised channel on the fans of the GMR, deposition on many of these fans may have been instigated by pronounced changes in slope.

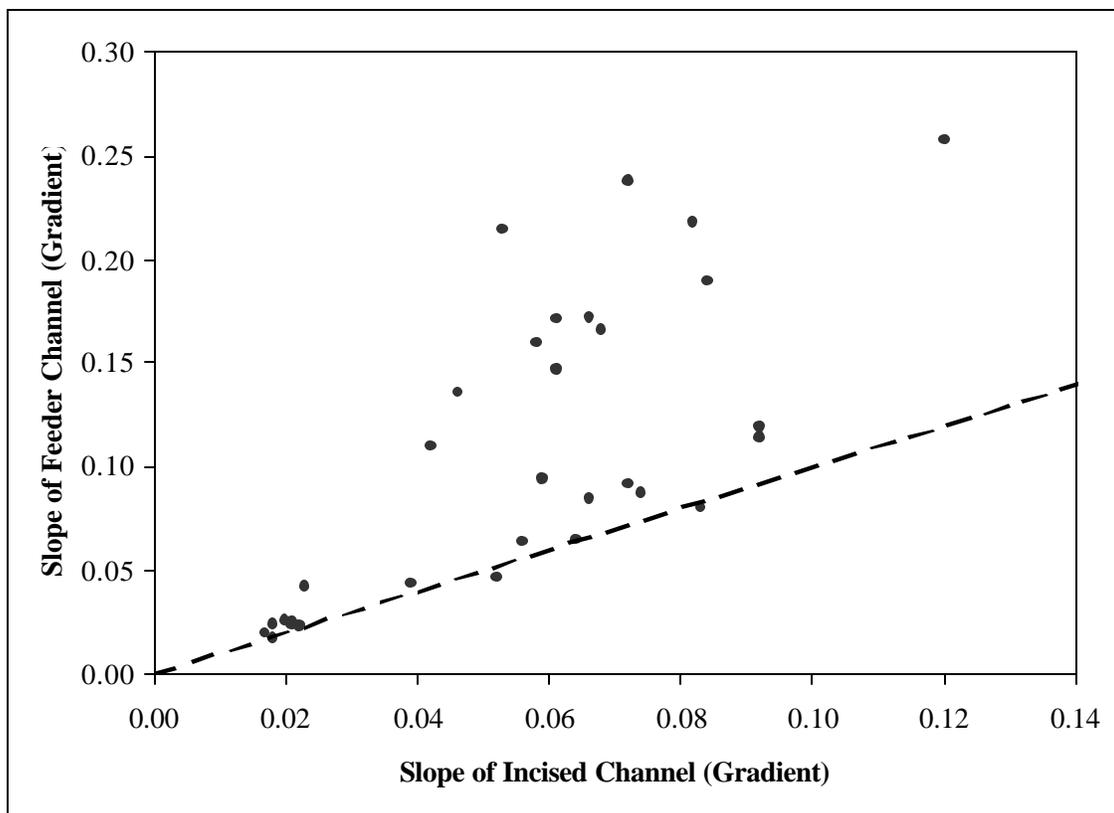


Fig. 37. Incised channel slope versus feeder channel slope, Guadalupe Mountains Region. Plot of the slope of the 1-km-long segment of the feeder channel upslope from the fan apex versus the corresponding slope of the 1-km-long segment of the incised channel for the 31 fans from the Guadalupe Mountains Region included in this study.

## CHAPTER V

### CONCLUSIONS AND FUTURE RESEARCH

The following general conclusions can be drawn from this study:

(1) This study was the first to both qualitatively and quantitatively analyze the geomorphology of the Quaternary alluvial fans of the Guadalupe Mountains Region (GMR) in west Texas and south-central New Mexico. Alluvial fans are widespread in the GMR, occurring at the mouths of drainage basins that have developed in the Permian-aged, predominantly carbonate bedrock of the Guadalupe and Brokeoff Mountains. In Salt Basin-Crow Flat, a series of alluvial fans at the base of the western escarpment of the Guadalupe Mountains have coalesced with alluvial fans extending from wide embayments in the western Brokeoff Mountains to form an extensive bajada. Noticeably smaller alluvial fans are also found at the base of The Rim and along the eastern ridge of the Brokeoff Mountains in Big Dog Canyon.

(2) The study was primarily based on regression analyses of morphometric data for 31 alluvial fans in the GMR and, to a lesser extent, qualitative data taken in the field and from the literature. In general, it appears that the morphology and morphometry of the alluvial fans of the GMR are principally influenced by the physiography and lithology of the contributory drainage basin, tectonics, and the physical constraints imposed by the GMR and the aeolian, pluvial, and fluvial environments bordering the fans.

(a) Regression analyses relating drainage basin area to alluvial fan area and slope

indicate that the alluvial fans of the GMR have morphometric characteristics comparable to those of alluvial fans from the western United States. For the fan area regression, although the alluvial fans of the GMR have intermediate areas for a given drainage basin area, the physical constraints imposed by the GMR and the aeolian, pluvial, and fluvial environments bordering the fans have caused the rate at which they increases with drainage basin area to be relatively low.

In a similar regression comparing drainage basin area to alluvial fan slope, alluvial fan slopes are higher in the GMR for a given drainage basin area than those supplied by sedimentary drainage basins in western California (Bull, 1964a) and lower than those produced by drainage basins underlain by predominantly igneous lithologies in north-central Nevada (Hawley and Wilson, 1965; Harvey, 2002). These differences might relate to the lithologic erodibility of the drainage basins.

(b) For a given drainage basin area, the 19 alluvial fans of the Guadalupe Mountains and the 12 alluvial fans of the Brokeoff Mountains are relatively similar in size. However, the rate at which the alluvial fans of the Brokeoff Mountains increase with increasing drainage basin area has been adversely affected by the physical constraints produced by Salt Basin-Crow Flats and Big Dog Canyon and the pluvial and fluvial environments bordering the fans.

The relationship between drainage basin area and alluvial fan slope demonstrates that the slopes of the alluvial fans of the Guadalupe and Brokeoff Mountains decrease in about the same exponential manner as drainage basin area increases, despite the fact that the alluvial fans of the Guadalupe Mountains are noticeably steeper than those of the

Brokeoff Mountains. The drainage basins from which the alluvial fans of the Brokeoff Mountains are derived have been intensely fractured and are composed of proportionately more sandstone and shale, presumably producing a higher yield of finer sediments. On the other hand, the fracturing and jointing properties and, to some extent, the higher relative relief of the predominantly limestone and dolomite drainage basins of the Guadalupe Mountains have produced considerably steeper alluvial fans.

(c) The alluvial fans at the base of the western escarpment of the Guadalupe Mountains in Salt Basin-Crow Flat are very extensive in relation to their drainage basins. The elongated morphologies and relatively steep slopes of these nine fans primarily result from their lateral confinement by neighboring fans, the stabilization of their incised and distributary channels, as well as the lithology, relative relief and steep slopes of the drainage basins. The episodic tectonic history of the western escarpment since the late Miocene or early Pliocene and the active subsidence of the western border of the Salt Basin graben have also influenced the morphology and morphometry of these fans.

Although relatively large, the seven alluvial fans on the west side of the Brokeoff Mountains in Salt Basin-Crow Flat are only one-half the size of their drainage basins. As Salt Basin-Crow Flat experienced a climatically-controlled rise in base-level, the depositional area on the surface of these fans became limited and their slopes were reduced. The consequent backfilling of the drainage basins and feeder channels appear to have inhibited the coarsest sediments from reaching the fan surface and might also have induced another series of circumstances, such as the development of multiple incised channels on the same fan.

The ten alluvial fans located along the base of The Rim in Big Dog Canyon include the seven relatively steep and small fans of the Algerita Escarpment and three large, unconfined, and gently sloping fans extending from mountain embayments in the Buckhorn Escarpment. The morphometric relationships for this group is primarily a consequence of the different debris flow and mass-wasting processes that comprise the fans of the Algerita Escarpment and the physical constraints imposed by Big Dog Canyon. However, the morphology and morphometric characteristics of the group also suggest that the Algerita Escarpment may have been uplifted in a rapid and/or constant manner during the late Pliocene or early Pleistocene. Because the Buckhorn Escarpment is relatively older and more intensely faulted and fractured, the other fans of the group - The Little Dog Canyon, Browning Well, and Pup Canyon fans - more closely resemble the fans on the west side of the Brokeoff Mountains in Salt Basin.

The relatively small size of the five alluvial fans located along the eastern ridge of the Brokeoff Mountains in Big Dog Canyon probably reflects the tectonic progression of the range, the dominance of debris flow processes on these fans, and the distal erosion of these fans by Upper Dog Canyon Arroyo. Although these fans are only slightly smaller than their contributory drainage basins, the physical constraints imposed by Big Dog Canyon and the lateral confinement of these fans by neighboring fans and the deposits of adjacent incipient drainage basins cause these fans to increase little in area when their drainage basin increases. The high rate at which these fans decrease in slope with an increase in drainage basin area might relate to the weathering characteristics of the lithologies comprising the Brokeoff Mountains.

### *5.1 Future research*

This study precludes a more definitive examination on the factors controlling or strongly influencing the alluvial fans of the Guadalupe Mountains Region (GMR). More specifically, this study suggests that future research should continue to quantitatively assess how alluvial fan morphology and morphometry in the GMR is affected by 1) drainage basin lithology and structure, 2) relative relief of the drainage basin, 3) base-level change and the creation of accommodation space, and 4) climatic fluctuations during the late Quaternary.

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- Chin, A., Harris, D.L., Trice, T.H., and Given, J.L., 2002. Adjustment of Stream Channel Capacity Downstream of a Dam, Yegua Creek, Texas. *Journal of the American Water Resources Association* 38(6): 1521-1531.

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