THE INFLUENCE OF AN IGNEOUS DIKE ON STREAM CAPTURE AND TERRACE DEVELOPMENT: MAVERICK BADLANDS BIG BEND NATIONAL PARK, TEXAS

THESIS

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Dedicated to my children.

Tiffany

Ryan

Andrew

Ashley

You have all been very patient and understanding of the time I have put into this study. Thank you to each of you.

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The purpose of this study is to build a research framework to aid in answering the question: What influence does a dike have on local drainage and base levels in the Maverick Badlands of Big Bend National Park, Texas? In the drainage of Rough Run Creek a resistant igneous dike cuts through relatively non-resistant badland forming sediments. This dike runs orthogonal to local stream flow and has three breaches at different stages, which indicate the history of stream diversion. As the downstream side of the dike is uncovered through headward erosion, a collapse occurs resulting in stream diversion and capture. Several strath terraces, remnants from former erosional sequences on Rough Run Creek, record the impact and erosional history of the terraces related to breaching of the dike. GIS was applied to map these terraces, to piece together the history of terrace development of the small badland valley that comprises the study area. In the

field the length, width, and slope of the terraces were measured and then the location of each is recorded with GPS.

CHAPTER I

INTRODUCTION

Big Bend National Park (BBNP), located in west Texas, is dominated by a mountainous landscape with sweeping pediment surfaces that have a complex history of stream dissection by tributaries to the Rio Grande. The park, located in the Chihuahuan Desert region, encompasses an area of 3,242km (NPS 2007). The geology of the park was mapped (1:62,500) and described by Ross Maxwell (1968), and a geologic map revision at a scale of 1:100,000 is currently in progress by the United States Geological Survey (USGS). Though well mapped, many aspects of the geology are not fully understood because of the region's complex geologic history, particularly concerning the Quaternary. This study examines the geomorphology of an area dissected by fluvial erosion from ephemeral stream flow and the development of fluvial terraces.

The two major objectives of this study were to: 1) determine what influence a structural dike has on stream capture and base level, and 2) map the fluvial terraces that remain upstream of the dike after fluvial incision. This research may contribute to our knowledge of fluvial geomorphic processes in an arid environment and increase our understanding of the development of strath terraces and pedimented topography in this part of Big Bend National Park. Improved knowledge of the effects of geomorphic processes on paleoerosional surfaces may help us understand the paleoclimatic environment that acted upon these surfaces.

This study examined terrace development as influenced by base level control by an igneous dike truncated by a major pediment surface on the west side of Big Bend National Park. The large sweeping pediment, graded southwestward from the Chisos Mountains, and then trending south to the Rio Grande, has been incised by fluvial erosion to form badlands, thus exposing the underlying geology and exposing the dike. No previous geomorphic research has been performed in the Maverick Badlands.

CHAPTER II

STUDY AREA

The study area is a part of the Rough Run Creek drainage centered on 29°19' N 103°26' W and encompasses 400 hectares in western Big Bend National Park, Texas and lies between the park headquarters at Panther Junction and the west park entrance (Figure 1). Radial drainage from the northern slopes of the Chisos Mountains enters creeks, Tornillo and Rough Run, which flow around two sides of the Chisos. The Rough Run Creek drainage wraps around the western side. The area under investigation includes two small drainages, both tributaries to Rough Run, that dissect a dike, before their confluence with Rough Run, which deeply breaches the dike at a third location. The dike is oriented orthogonal to stream flow.

Rough Run Creek has a large drainage area with much potential stream flow and breaches the dike to the gradient of Rough Run. The two drainages under examination have small basins and both breaches caused by these two tributaries to Rough Run have pouroffs. Rough Run Creek affects the study area, though it does not flow through the study area.

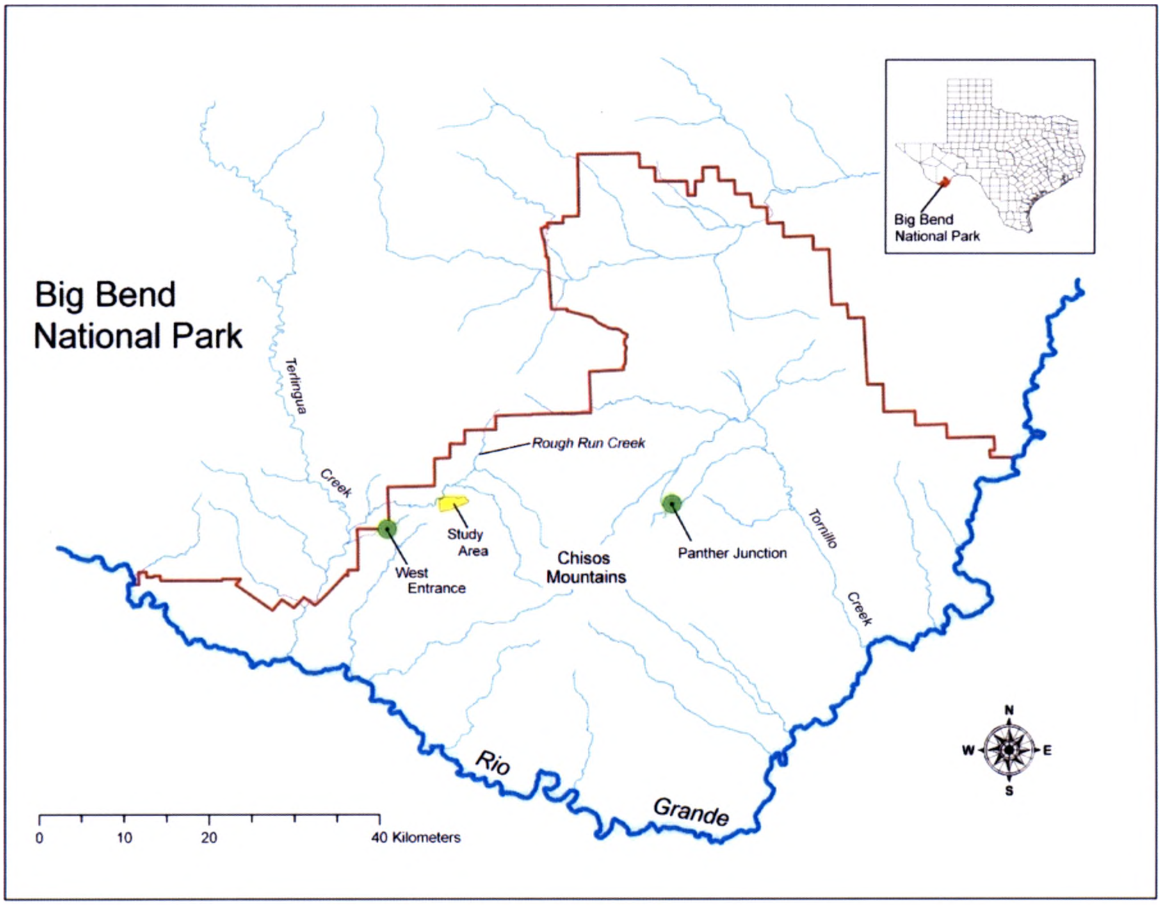

Figure 1. Big Bend National Park location map.

Rough Run Creek begins east of Slickrock Mountain on the western side of a dike that divides the Terlingua and Tornillo drainage basins and then flows to its confluence with Terlingua Creek south of Study Butte. Rough Run is an ephemeral stream that receives Oak Creek, which drains a portion of the Chisos Mountains, and Cottonwood Creek, which flows north along the Burro Mesa fault. These two creeks enter Rough Run upstream of the breached dike under study.

Climate and Environment

The Köppen climate classification of the study area is subtropical desert (BWh). The following climate data were recorded at the Panther Junction, Texas weather station at an elevation of 1140 m. The mean January temperature is 9.4°C, and the mean for July is 27.3°C (NCDC 2004). In winter, a high-pressure ridge that inhibits precipitation tends to dominate BBNP. During the summer the regional weather can be influenced by a low-pressure thermal system, which brings in a maritime tropical air mass and convective precipitation. This region is typically hot and dry and is periodically subject to prolonged droughts (Herbert 2004). The mean annual temperature is 19.2°C. Mean annual precipitation is 362 mm, occurring mostly as rain from thunderstorms that primarily occur during the months of July and August (NCDC 2004). The Panther Junction, Texas weather station is the nearest station to the study area, 23 km away.

The Chisos Mountains, which receive more moisture, and experience lower evaporation than the adjoining lowlands, support broadleaf and coniferous woodlands and forest. The broadleaves include madrone (*Arbutus xalapensis*), maple (*Acer grandidentatum*), hackberry (*Celtis laevigata*), buckeye (*Ungnadia speciosa*), aspen (*Populus tremuloides*), ash (*Fraxinus greggii, F. cuspidata*), mountain laurel (*Sophora secundiflora*), and twelve species of oak (*Quercus family*). The conifers include three species of juniper (*Juniperus flaccida, J. deppeana, J. coahuilensis*), two species of pine (*Pinus cembroides, P. arizonica var. stormiae*), and one cypress (*Cupressus arizonica*) species (Wauer and Fleming 2002).

Piñon pines that now grow only in the high elevations of the Chisos Mountains are similar to an extinct piñon pine that was well established in the lowlands 11,500 years ago. This date was determined by radiocarbon dating of vegetative material from wood rat (*Neotoma species*) middens found in dry caves in the foothills of the Chisos Mountains and Burro Mesa (Wells 1974). Thirty-five middens have been examined in BBNP. The presence of piñon pines at these lower foothill elevations represents a climate that was more cool and moist than the modern climatic regime. Today, these foothill regions support desert vegetation: shrubs, grasses, and cacti. Vertical life zones have retreated upslope to higher elevations resulting in mountain islands of remnant vegetation. Some of the many plant species that grow today in the surrounding desert region are: lechuguilla (*Agave lechuguilla*) an indicator species of the Chihuahuan Desert, creosote bush (*Larrea tridentata*), ocotillo (*Fouquieria splendens*), silver leaf (*Leucophyllum frutescens*), honey mesquite (*Prosopis glandulosa*), and several species of cholla and prickly pear cacti (*Opuntia family*) (Wauer and Fleming 2002).

Big Bend Regional Geology

The Big Bend region is a landscape of faulting, debris flows, lava flows, explosive volcanic eruptions, erosion, deposition, stability, and more erosion. Big Bend National Park is the southernmost extension of the Basin and Range Province in the United States, and faulting in the park region was related to the development of that physiographic province. Much of the park, including the area under examination, lies in a northwest trending down-dropped block. Faulting resulting from tensional stress caused the formation of basins as part of the surface dropped leaving parallel ranges standing on the east and west sides of the BBNP forming what Udden (1907) termed the "Sunken Block." The Dead Horse Mountains, on the eastern edge of the park, began forming around 60 Ma (million years ago) concurrent with the development of the Rockies in the United States and the Sierra Madre Oriental in Mexico (USGS 2008). Tremendous erosion has occurred in this region since tectonic and volcanic activity ceased (Hill 1901). This topography that developed from this faulting, and the Chisos Mountains, have strongly influenced the stream channels of the region. The igneous activity in the region left dikes, sills, intrusions, laccoliths, calderas, and volcanic necks. After long term erosion, these resistant landforms have been uncovered and now greatly affect drainage. The study area was preserved because of the presence of the dike, downstream, and a small intrusion, upstream. Together these two resistant, igneous landforms protected the terrain under investigation.

Volcanism has been a major influence in shaping BBNP. Volcanic activity occurred during the Paleogene (Oligocene and Miocene) approximately from 46.5 Ma to 17 Ma (Miggins et al. 2008). At the end of this period a layer of volcanic materials 1800 meters thick covered most of the region (MacLeod 2002). The sources for much of the lava flows and ash falls were the numerous calderas in the vicinity of the park. Two calderas have been identified within BBNP. These are the Pine Canyon and Sierra Quemada calderas. The Pine Canyon Caldera emptied its magma chamber around 32 Ma (USGS 2008).

Much of the volcanic activity that occurred in the region was related to the subduction of the Farallon Plate under the North American Plate, along the Pacific coast. The Farallon Plate has been nearly completely consumed with only two fragments remaining. These are the Juan de Fuca and Cocos plates, which are being overridden by the North American Plate (MacLeod 2003).

Expansion of the North American continent after the Laramide Orogeny resulted in the formation of the Basin and Range Province. Tensional stress during this period caused normal faults and some of these faults filled from below with magma forming dikes. In a recent USGS study in Big Bend, Argon/Argon dating was used to yield an age of 29 Ma for an exposed rhyolite dike 12 km southeast of the dike examined for this thesis (Miggins et al. 2008).

Burro Mesa is adjacent to and south of the study area. According to Maxwell (1968) this feature is a topographically inverted graben with a caprock of riebeckite rhyolite. The harder material of the rhyolite has resisted erosion while the softer materials of the up thrown block have eroded away, leaving Burro Mesa higher. The rhyolite flow unit on Burro Mesa matches the rhyolite that caps Emory Peak, the highest elevation in the park. A 1067-meter vertical offset separates these two locations.

Long-term erosion has sculpted the land into the scene that we witness today. The arid environment and sparse vegetative cover, except in riparian zones, allow excellent observations of the results of geomorphic processes. The native peoples who lived here had a legend for this terrain. They said that when the Great Creator was finished shaping Earth the remaining materials were tossed on this region causing the varied topography. The topography is so rugged that it has been used to simulate the moon surface for astronaut training (Maxwell 1968).

A broad and continuous pediment capped by gravels once covered the section of the park in the study area but today is incised by active, but ephemeral, fluvial erosion. Stream erosion formed steep gullies and rills and has formed a badland landscape, particularly on the valley side walls. The pediment gravels in the study area are the upper layers of an angular unconformity. The materials deposited from the Paleogene to mid Pleistocene, have been removed through erosion. The two Cretaceous sedimentary formations deposited prior to 66 Ma that outcrop at the site are the Aguja Formation (c. 75 to 70 Ma) and the Javelina Formation (c. 70 to 66 Ma). These are badland forming sediments that have been tilted, beveled by erosion, and capped by the cemented gravels on the pediment surface (USGS 2008). The layers were tilted by the intrusion of the Maverick Mountain laccolith, estimated at 34 Ma, which has now been unroofed by erosion with pediment remnants surrounding the mountain's edge. Although skirted by pediments, pedimentation does not extend into the igneous rocks of Maverick Mountain, which are much more resistant than the Cretaceous sediments in its vicinity. Terraces within the incised drainage area also remain as small relicts of surfaces formed at other levels below the pediment throughout the actively developing fluvial incision (Figure 2).

Figure 2. Downstream view of a breach in the dike.

While the pediment was intact, fluvial processes completely beveled and graded an igneous dike within the pediment and to the level of the pediment surface, which suggests a relatively long term period of erosional stability because the dike is quite resistant. The dike has a width of 7 m and an essentially vertical dip with a north-south strike that is orthogonal to the direction of local stream flow. Though dikes can feed surface lava flows they generally do not break the surface and cool at depth under pressure forming, in this case, a basaltic igneous rock. The area chosen for study includes the dike that has been exposed as fluvial processes dissect the pediment and the easily erodible badland forming units. The dike forms a strong local base level control for the upstream reaches of the drainage channels that cross it.

CHAPTER III

PEDIMENTS AND TERRACE DEVELOPMENT

G.K. Gilbert (1877) was the first to describe the landform that is now known as a pediment. The precise wording that Gilbert used was "hills of planation" and he believed these were formed by the "planation of streams." The pediments that Gilbert studied surround the Henry Mountains in Utah, and are similar to the pediments in BBNP. Both are comprised of soft badland forming sedimentary layers, beveled by a dissected gravel-capped pediment (Hunt 1988). McGee (1897) suggested alternative terms that included "base level plain" and "torrential plain." McGee, however in that same article, was the first to use the word pediment and he hypothesized that they were formed by sheetfloods (Tator 1953, Rahn 1966, Adams 1975).

Abrahams and Parsons (1994) list several attributes of pediment morphology in a desert geomorphic environment:

- Type of boundary between the pediment and the underlying materials.
- Surface characteristics.
- Drainage patterns and drainage dissection.
- Extent and characteristics of the source regolith or geologic formation.

Weise (1977), while studying "fossil weathering profiles" in Iran, determined that pediments are "lowered and flattened" by rills and washes eroding laterally. His study revealed that degradation occurred mainly as a result of erosion related to extreme precipitation events. Adams (1975) explained that planation surfaces are graded to a base level.

Stream terraces represent former valley floors and floodplains. Terraces develop through episodes of down cutting or deposition by a stream, and may be caused by: base level change, tectonic uplift, and climatic or vegetative changes that alter the discharge and load characteristics of a stream. Vegetative changes may be the result of climate, fire, or overgrazing. Easterbrook (1999) explained four types of terraces: cut-in-bedrock, fill, cut-in-fill, and nested fill terraces. The latter three types occur after aggradation in a valley. Cut-in-bedrock, or strath, terraces have a veneer of alluvium (Bucher 1935). Cooke et al. (1993) explained that drainage abandonment may occur if a stream changes from perennial to ephemeral and that this change may leave terraces standing above the new drainage valley. Campbell (in Thomas 1997) stated that gullying is a major mechanism among the processes of geomorphic change in badlands. Gully incision may result in stream piracy and terrace development. In a recent study, the USGS (2008) has identified six fluvial terrace levels adjacent to the Rio Grande. They have generally correlated these terraces to five pediment levels in BBNP. When their individual gradients are projected to the current Rio Grande flood plain, the terraces and pediments identified by the USGS range in height from 3 m to 60 m above the Rio Grande flood plain. Two of these are major terraces, which demonstrate the river was at these levels for longer periods of time.

The terraces that exist in the study area are strath terraces that have been incised by fluvial processes that have dissected the major pediment surface in this part of the park. These terraces have a veneer of alluvium resting unconformably on Cretaceous clays and mudstones of the Aguja, Javelina, and Pen Formations (Maxwell et al. 1967). Field observations indicated that five terrace levels exist in the study area including those formed by the current drainage channels. Figure 3 shows the general topography and environment of the study area as well as the pediment surface.

Figure 3. General topography and environment of the study area.

Gravels and Calcium Carbonate Veneers

Places that have an arid climate and a sufficient source of carbonates develop calcite horizons, or coatings on clasts, in the subsurface. The carbonates, in solution, descend through the ground as water infiltrates and are deposited as percolation reaches its maximum extent. This is known as calcification, a common process in arid and semiarid regions that occurs because there is insufficient precipitation for leaching out the carbonates (Schaetzl and Anderson 2005). According to the Texas Parks and Wildlife Department (2009) the regional average net evaporation is 142-172 cm. In the American Southwest research has shown that airborne calcium is also delivered to the surface and then dissolved in rainwater (Machette 1985). Airborne delivery is the most probable process occurring in the area under investigation. The gravels that mantle the pediment have an igneous lithology and because the clasts are igneous, eolian deposition of calcium is the most potential source for the calcium coating found on the gravels here. The nearest dust sources of calcium are the uplifted calcium carbonate mountains on either side of the sunken block that are southwest and northeast of this location and the Boquillas Formation in Terlingua, to the west. Although the Big Bend Regional Aerosol and Visibility Observational Study (BRAVO) found that dust from Sahara Africa settles in the park in summer (NPS 2008). The BRAVO study showed that dust from far distant sources may be deposited in Big Bend. Wind circulation patterns may have been different during the Pleistocene and though the local calcium carbonate mountains are the most probable source of eolian calcium, other sources are possible.

Calcite deposits in regolith are categorized by four stages of accumulation:

- Stage I occurs in the zone that receives the most wetting and appears as calcite coatings on root filaments.
- Stage II produces nodules of calcite, which occupy 10% of the soil and coats voids made by roots and insects.
- Stage III 50%-90% of the matrix is coated and 40% of the pores are filled with calcite. Coarse grained material require less calcium to reach this stage

than do fine grained materials because fine grained sediments have more pore space to fill.

- Stage IV completely cemented or plugged horizon. 75%-90% coating of matrix and 50%-75% of the pores are plugged (Monger et al. 1991).

In southern New Mexico, a sequence of fluvial terraces along the Rio Grande has been derived using calcium carbonate accumulation stages. This is a relative dating technique, not an absolute dating method. Though when properly calibrated to known dates of the region, the results can be very reliable. The Jornada I surface along the Rio Grande floodplain in southern New Mexico is estimated to be from the late middle Pleistocene between 250,000 to 400,000 years before present and exhibits stage IV calcium carbonate accumulation. The age of this surface has been determined through paleontological interpretation of fossil vertebrates and mollusk fauna (Gile et al. 1981). Based on sites in the Mojave Desert, the northwestern Sonoran Desert, and the southern Great Basin, Amoroso (2006) demonstrated that dense carbonate was deposited during the Pleistocene in gravels of these three areas. Measurements of rind thicknesses on clasts taken from deposits with an independently determined age derived the information recorded by Amoroso.

Badlands

Erosion of the badland forming units in the Rough Run drainage exposed the dike that was beveled within the pediment. The dike hindered flow through the area and created local base levels, which influenced terrace development in the area. A new set of terraces developed each time base level changed at the dike.

Badland topography is a dynamic erosional environment that has a high density of drainage channels. Early French trappers in North America created the term badlands when they encountered lands that were difficult to cross. The maze-like gully systems of these environments make travel in these areas very difficult (Abrahams & Parsons 1999).

Increased aridity, when coupled with unwise land use practices, has the potential to initiate badland formation in areas that are currently economically productive. Badlands have formed in Classical Greece and modern Turkey as a result of human impacts on the land (Thomas 1997). Carson and Tam (1977) demonstrated that human-induced changes, through deforestation, have caused badland formation in Barbados and resulted in "accelerated erosion, channel incision, stream capture, gullying, and extensive mass movement." Human impacts are of particular concern because they can accelerate the natural rates of change. In badlands, low order streams can produce large amounts of sediment (Schumm et al. 1984).

Badlands can also result from base level changes (Abrahams & Parsons 1999). Base level is the lower limit of stream erosion (Powell 1895). Uplift, climate change, human impacts, and sea level changes can cause base level changes, which can lead to badland development. A lower base level in a stream causes its tributaries to incise their valleys. This event may destabilize the valley and in some materials can cause badland topography. Badlands form in soft materials, such as clays, that do not easily allow water percolation and are subject to high volumes of precipitation runoff (Easterbrook 1999). A rugged badland landscape expands through the process of headward erosion, eroding up slope, by gullying.

Several factors to consider while examining badlands are: the runoff-erosion model, stream power, and scale. Abrahams (1980) suggested that the Hortonian runoff-erosion model is the best for badland applications. The reason for this is because fluvial erosion in the form of overland flow occurs over the entire badland landscape. Graf (1983), in his classic paper on stream power, stated that stream power is a function of both channel dimensions and discharge and is a better data set than channel dimensions alone. Couper (2004) examined issues of scale in her review of space and time in river erosion research. Funding and time constraints may have much to do with the scale that we choose to study. Couper (2004) also pointed out that research of a drainage system at a small scale without considering upstream and downstream properties may produce invalid results (Couper 2004). Schumm et al. (1987) stated that badlands are an ideal place to study basin dynamics because processes that take decades or centuries in large basins may occur in one or two years in the smaller scale basins of badlands. Butzer (1976) showed that slope morphology in badlands is also a function of slope materials. Hillslopes with low permeability displayed parallel retreat while permeable slopes were subject to creep resulting in shorter and steeper slopes.

Stream Capture

Stream capture or stream piracy occurs when extension of a stream through headward erosion intercepts the channel of another stream, diverting the flow and capturing the headwaters of the cut off stream (Glock 1931). Crosby (1937) listed three types of stream capture: piracy through headward erosion, planation piracy, and underground methods of piracy. The lower stream will eventually cut through the divide and pirate the upper course of the higher stream. If these two streams are separated by a pervious divide, the upper stream will lose some of its groundwater flow to the lower, which will increase the erosive power of the lower stream. Factors that influence the rate of erosion in a stream system are the amount and velocity of the water and the materials over which it flows (Crosby 1937).

Planation capture occurs when a stream cuts laterally through a fluvial divide into the valley of an adjacent stream. Dake (1914), working in Missouri, examined loess deposits that have formed badlands. He described a stream that had undercut a divide, opening a small gap, and captured the adjacent stream, leaving a natural bridge in the loess.

Woodruff (1977) outlined three periods of stream piracy that have occurred in the Balcones Fault Zone of Central Texas. Evidence of these captures includes "asymmetrical drainage-basin geometry" in addition to erosional features and fluvial deposits on drainage divides. Schoewe (1925) found evidence that a wind gap in Colorado was once a stream valley that was captured by a stream at a lower level. The gap is in sedimentary material and has very little talus or weathered fragments of sedimentary origin, yet there is an abundance of igneous material. The igneous materials include granite, quartz, and schist. These igneous rocks are sub-angular to rounded clasts of granite, quartz, and schist, rocks that form the mountains upstream of the gap. Erosion has lowered the terrain in the area of the gap by 100 m.

Branson and Batch (1971) studied stream piracy in Kentucky. The evidence that they have recorded includes the visible outline of an old stream channel with fluvial gravels on the low terraces adjacent to this channel. The researchers consider this capture responsible for the existence of two species of fish in a small portion of the Dix River system. Bryan and McCann (1936) found that the upper Rio Puerco, a tributary to the Rio Grande in New Mexico, was created by stream piracy. They concluded that after the main capture formed the upper Rio Puerco, "there have been a series of piracies at the headwaters of its eastern tributaries, recurring at each lowering of base level."

The valley chosen for this study in BBNP has also been affected by stream capture. In the soft clays of the badlands this can occur frequently with ephemeral flow events, changing the drainage pattern of the locality. In the study area, the breaches in the dike influence stream capture because a lower and temporary base level develops when a collapse happens. This results in channel down cutting upstream of the breach in the dike, a condition that also may encourage new stream captures.

CHAPTER IV

METHODS AND DATA CONSIDERATIONS

Methods

Preliminary investigations indicated that the dike influences local drainage because in areas where the dike has become exposed by fluvial erosion it divides the drainages with a vertical nickpoint until a breach occurs. Once a breach occurs the more resistant materials of the dike, perhaps less fractured, resist slope retreat of the channel walls of the breach. The methodology used to test these statements included remote sensing analysis, field investigations, and a review of related work by other researchers. Remote sensing was accomplished with the digital images and data, supplemented by hard copy maps of the geology and topography. The digital data used included hillshaded relief maps, digital ortho quarter quads (DOQQs), and digital raster graphics (DRGs). Relevant paper maps were digitally scanned and georeferenced with the electronic data in a geographic information system (Figure 4).

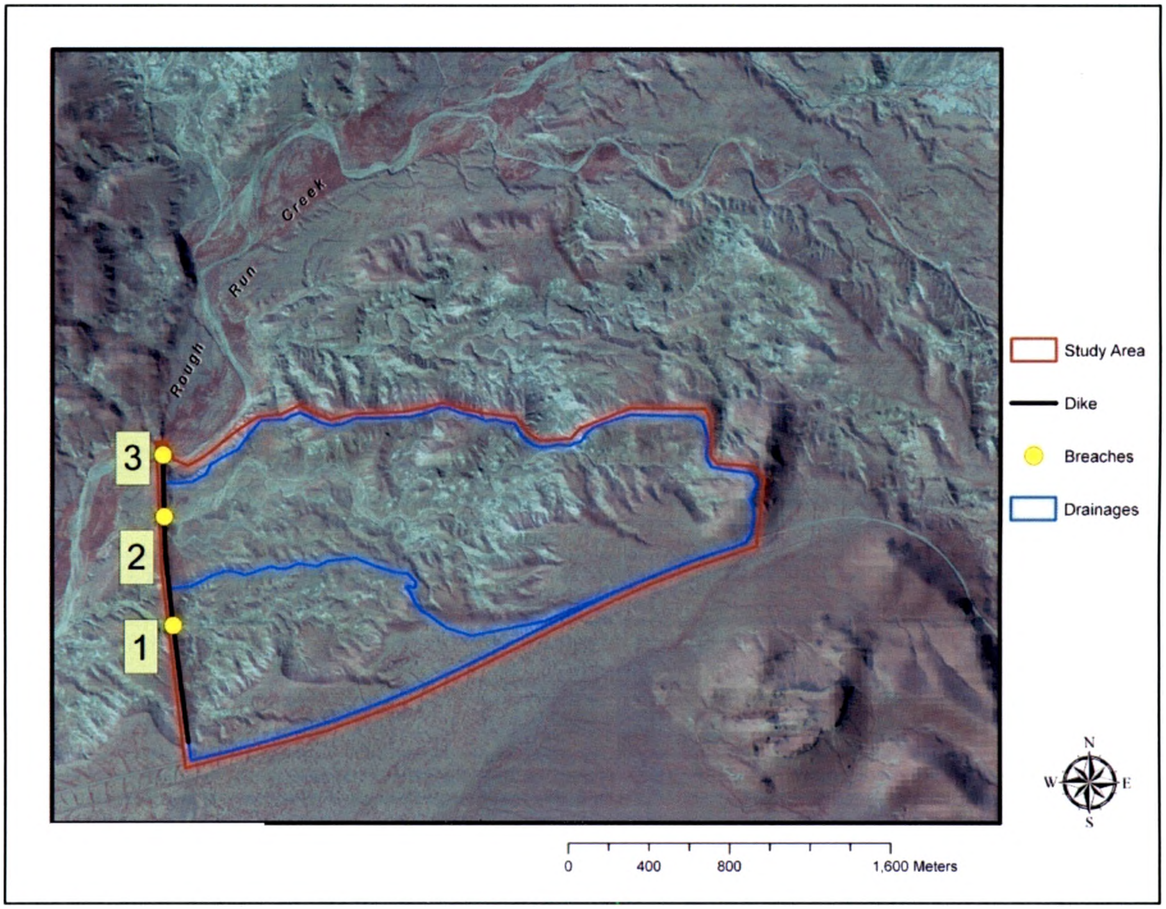

Figure 4. The study area displayed on a DOQQ.

Data and Information Sources

The following data and information sources were used to support this study.

- Data obtained from the Texas Natural Resources Information System (TNRIS) - electronic data derived from remote sensing. These data include: digital aerial photos, hydrology, hillshade, and digital topographic maps.
- Cartographic data and information created - electronic data and information digitized or developed in a GIS specifically for this study. These include mapping of: the orientation of the dike, outline of the pediment surface, study area boundaries, drainage basins, panoramic photo positions, and geology (which was

scanned from a 1:62,500 scale geologic map (Maxwell 1968) and then georeferenced in a GIS).

- Field Data and Information sources - These include: field investigation and photography of breaches (in profile and along the strike), GPS positions of photo locations, field survey of drainage basin boundaries, and GPS positions of two drainage basin boundaries to ground-proof aerial photos.

Research Limitations and Problems

This research has limitations: these include accessibility, extreme climatic conditions, data availability, and no known geomorphic research had been conducted in the Maverick Badlands. The accessibility issue is primarily due to the remote location of BBNP and the great distances between settlements in the region west of the Pecos River. The climatic extreme is most evident in late spring and early summer when daily maximum temperatures are above 40°C (104° F). Geographical data are available in digital form for the study area, though very little historical data are available. Much geological research has been done in BBNP, however none has been published about the badland area, other than paleontological studies in the Cretaceous, Paleogene and Neogene sediments. The USGS is currently working on a publication regarding Quaternary geology of BBNP though at this time a final report has not been released.

CHAPTER V

ANALYSIS

Terraces

Some of the techniques and methods of analysis that were utilized are: development of digital elevation models to examine the terrain, analysis of Digital Ortho Quarter Quads, topographic maps, geologic maps, and vegetation distributions. Evidence of archaeological and historic use of terraces was also examined. All spatial data and information were analyzed and prepared for visual display using a GIS. Six terraces were examined using the methods described and the results are in the findings section.

The strath terrace levels were mapped in the field. The data and information collected for each terrace at this location included: length of long axis and short axis, compass bearing of long axis, GPS coordinates of centroid, elevation, angle from horizontal of long axis and degree of rock varnish on the surface. Examination of a test pit on each terrace provided data and information on the surface and subsurface deposits, including color, color change, clast sizes, degree of weathering of clasts, stage of calcium carbonate coating if present, and clast-supported vs. matrix-supported structure. A matrix-supported structure has a matrix of fine grained materials that supports individual clasts while a clast-supported structure is clast matrix with fine materials filling the voids (Reading 1981). Depths to bedrock of the terrace gravels were measured on the exposed terrace slopes. Measurements of the dike thickness at each breach were used to determine any potential variation, and the average thickness of the dike (what if any variation existed?). Fracture density and the nature of each breach were assessed. Two transects of the valley controlled by one of the breaches were recorded. The relative characteristics of rock varnish in the study area will be addressed in the next section.

Rock Varnish

Rock varnish coats bedrock and gravel mantled surfaces in many areas of BBNP and the surrounding region. The pediment gravels, the relic terrace remnants, and the igneous intrusions all have red-brown varnish. This varnish forms in a wetter environment when air fall of iron and manganese dust lands on rock surfaces and is fixed to the surface by microbial action (Dorn and Oberlander 1981, Cook et al. 1993, Thomas 1997). Varnish coatings typically consist of 70 percent clay with the remainder consisting of manganese, iron, and calcium carbonate deposits. The manganese produces blacker varnish while iron produces red hues (Thomas 1997).

The characteristics of rock varnish can demonstrate stability. Mabbutt (1979) explained the "degree of darkening" by varnish can indicate the stability of a desert pavement. Studies in the Mojave Desert show that late Pleistocene alluvial fan surfaces display strong, well-developed varnish. Holocene fan surfaces in the Mojave area are thinly varnished, which apparently illustrates a climatic transition from the Pleistocene to the Holocene (Thomas 1997).

Rock varnish can be indicative of the relative age of a surface (Mabbutt 1979). Petroglyphs can establish a minimum age for varnish. The Anasazi Indians in the Four Corners Region of the United States: Utah, New Mexico, Arizona, and Colorado scratched varnish off of surfaces, creating rock art. No varnish has reformed on these petroglyphs and the Anasazi migrated out of this area 1,000 years ago (NPS 2008). Varnishes in the southwestern United States have a minimum age of 10,000 BP. This date was established using a cation-ratio technique that measures the ratio of titanium to those of calcium and potassium in manganese-rich varnishes (Cooke et al. 1993).

The desert pavement on the surface of the pediment gravels in the study area has a coat of varnish. This is an indicator of the stability of this surface. The Maverick Mountain intrusion and the pediment remnants attached to the mountain and at the dike are also coated with varnish. Both Maverick Mountain and the dike display small areas where fluvial action has eroded below the varnish line, exposing unvarnished rock. The exposed areas are proof that varnishing is not active today and the small number of these unvarnished exposures is further evidence of relative geomorphic stability of the pediment surface. Blocks that have fallen from the dike and are now in a pile of debris at one of the breaches are not varnished on all sides, only on surfaces that were exposed when these blocks were part of the dike. This is a strong indicator that this breach expanded by collapse after the conditions for rock varnish formation changed.

Paleoclimatic information from packrat middens in the Southwestern deserts provides evidence of a time that was moist enough for rock varnish to form. Anasazi petroglyphs indicate that no varnish has accumulated in Four Corners Region for 1,000 years. Big Bend has some petroglyphs etched into rock varnish at Indian Head Springs. These glyphs were made at least 1000 years ago and show no signs of new varnish. This evidence illustrates that no varnish has formed in the last 1000 years and suggest that the last time varnishing was active was during the end of the Pleistocene.

CHAPTER VI

FINDINGS

The small valley, upstream of the dike, that is the study area has preserved evidence of erosional events that, outside the valley, have been removed by erosion. The valley is confined at its headward terminus by a small, but resistant igneous intrusion. The dike, which forms the downstream terminus of this valley, confines and creates two local base levels. The local base levels of the dike have isolated and protected this area from the deeper erosion experienced by the badland sediments adjacent to, and downstream of, the study area. This isolation, upstream of the dike, has allowed terraces to record the erosional sequences here that have been erased outside of this valley.

The study area has three geomorphic zones, the pediment surface, the badland slopes, channels, and the strath terraces developed by fluvial erosion. The strath terraces are remnants of former erosional cycles. A profile was measured just below the Maverick Badlands overlook, which is 5 km southwest of the dike. The gravels on the major pediment are three to four meters thick and the structure is a clast-supported carbonate matrix that has become cemented. The clasts vary from rounded to sub-rounded and are deposited in layers. The layers display vastly different depositional environments. The range of depositional characteristics of the layers includes; strata of sorted and unsorted clasts and layers of all 30 mm clasts, with very fine material in the voids between clasts; to layers containing mixed clasts ranging from 2 mm to 15 cm. An exposure of fine-grained, microlaminated sediment layers in a concave lens underlies the cemented gravels at the overlook location.

The pediment surface is also a deflated desert pavement with rock varnish coating the exposed clasts. Plants that grow here include: lechuguilla (*Agave lechuguilla*), creosote bush (*Larrea tridentata*), ocotillo (*Fouquieria splendens*), purple sage (*Leucophyllum frutescens*), and several species of prickly pear cactus (*Opuntia family*) (Wauer and Fleming 2002). Many small burrows were observed, these were created by unknown fauna that have bioturbated the surface at the burrow location. Butler (1995) pointed out that protection from climatic stress is one of the many advantages of burrowing. All of the burrows observed were at the bases of plants. This may be because it is easier to dig where the plant has already broken the surface or perhaps the plant helps reduce the climatic stress on the burrow. These burrows have certainly disturbed and mixed the subsurface materials of the pediment as well, though the degree of disturbance has not yet been investigated. The smallest breach in the dike is a pouroff that is that has created a plunge pool at its base. The dike also impedes ground water flow that follows the downstream contours of this valley. As this water slowly passes through the dike it seeps into the plunge pool forming a perennial spring. Numerous game trails lead to this spring and abundant animal tracks are compelling evidence that this water hole is well used.

The badland slopes are mainly comprised of the clays and mudstones of the Aguja and Javelina Formations. Slopes adjoining the remaining pediment have a cover of colluvium where the gravels on the pediment have collapsed, obscuring the contact between the gravel mantle and the underlying clays. Vegetation on the slopes appears to be a function of slope stability and erosion rates rather than aspect. Plant species supported on the slopes are similar to those on the pediment gravels, though much less dense. The colluvium, from the gravels that mantle the pediment, supports more vegetation than the clay slopes of the badlands.

The badland floors are fine-grained materials re-deposited when precipitation and surface runoff events occur. The floors are cut with many channels of various sizes that range from rills to gullies more than two meters deep. Vegetation on the badland floors is mostly creosote bushes (*Larrea tridentata*), honey mesquite (*Prosopis glanulosa*), and dog cholla (*Opuntia grahamii*). The larger streams support the same vegetation as the pediment on their beds and banks.

The dike is breached in three places by stream dissection in the Rough Run Creek drainage and is forming a pouroff at two of the breaches (Figure 5). Two of the three

Figure 5. Upstream view of pouroff at a breach in the dike.

breaches and the drainage channels upstream these two breaches were examined. Characteristics of the terraces were used to determine the relative maturity of each breach, the erosional history and what effect the dike has had on stream capture and the terraces left during episodes of breaching in the dike.

Breach Development

Before being exposed by fluvial erosion, the dike was graded by pedimentation processes, level with the surface of the pediment, and covered by the pediment gravels. In the areas where the pediment is still intact, the dike is not visible at the surface. The dike is 4 km long and less than 2 km has been uncovered in places by headward erosion of the downstream reach of the valley's drainage system and by badland formation. The dike, seven meters thick, is a very resistant structure that lies within soft, and easily erodible badland forming clays. Much energy over an apparently long period of base level stability was required to transport the coarse pediment gravels that graded this dike to the level of the pediment surface.

The location of the breaches, termed breach one, breach two, and breach three are shown in Figure 6 and are at different stages of collapse. Breach three, at the base of Doggie Mountain, is graded to the level of Rough Run Creek and is the largest of the three. This breach formed from the consolidation of two breaches with a small remnant of the dike standing as a pillar between the two, one is active and the other has been abandoned. The channel floor of the abandoned section is 70 cm higher than the active channel and is vegetated with grasses and small trees. Many of these trees are tilted downstream indicating that this channel receives flow in times of extreme precipitation.

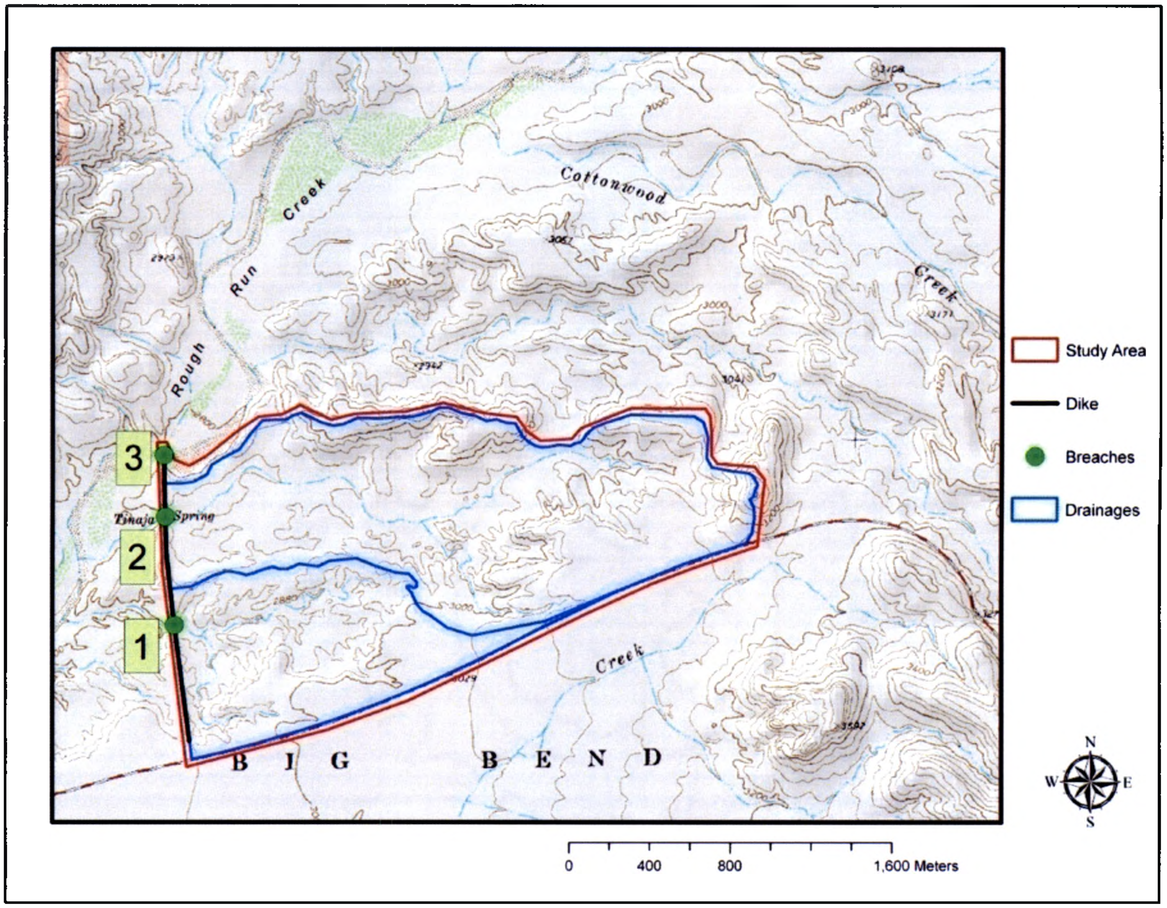

Figure 6. The study area displayed on a topographic map.

Breach two is the smallest of the three and has formed a pouroff. This pouroff is 10 m above the Rough Run base level and is the local base level for 75 percent of the study area valley. Breach one is the local base level for 25 percent of the study area and is the only breach that displays evidence of collapse. The majority of the existing strath terraces were formed by the changing base levels associated with collapse or downcutting of breach one.

Together these three breaches demonstrate their sequence of development. First water flows over a low area of the dike which becomes a base level for the upstream drainage. Next, erosion removes the soft badland sediments downstream of dike. Without the supporting material on its downstream side, blocks fall from the dike, forming a new upstream base level and eventually a deep pouroff. As more supporting material is removed on the downstream side of the dike, additional blocks fall from the dike expanding the breach in width and depth, changing the base level. Eventually the opening collapses to the lowest local regional base level, Rough Run, and then expands laterally. Fractures in the dike influence where a stream channel will form. Fracture density is higher at these three breach locations which makes the dike weaker and more susceptible to collapse at those sites. Ground water flow from beneath a stream bed will also find these fractures, which further weakens the dike and facilitates a collapse after material that braces the dike is removed.

Drainages

The badlands between Hanold Hill and the Chisos Pen Anticline are eroded to small hills and are now vegetated, slowing erosion. The streams are in established channels and are beginning the slow sweep of planation across the landscape, creating a new pediment. This new pediment will be 75 m below the original surface which once matched the intact pediment at the top of Hanold Hill.

Streams emanating from the Chisos Mountains flow into Oak and Cottonwood Creeks. Oak Creek originates at the Window pouroff, which drains the Chisos Basin, it flows around the northern end of the Chisos Pen Anticline and then joins Rough Run Creek. Cottonwood Creek is controlled by the Burro Mesa Fault and flows along this fault and then through a gap in the Chisos Pen Anticline and then combines with Rough Run slightly upstream of the dike in the study area (Figure 7). Rough Run flows through

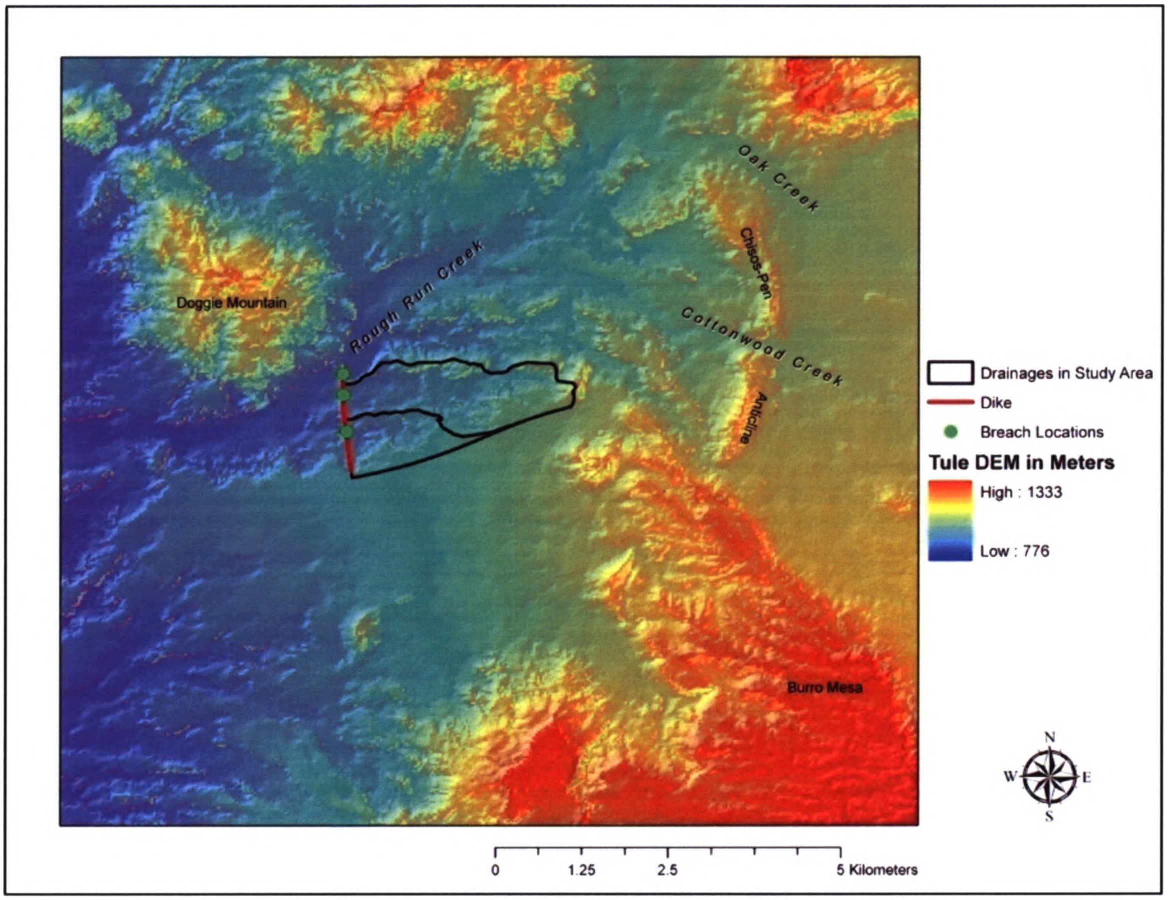

Figure 7. Study area displayed on a digital elevation model.

breach three in the dike after receiving waters from Oak and Cottonwood Creeks. Rough Run drains a very large area and the tributaries studied drain a small area.

The Chisos Pen Anticline, in a manner similar to the dike in the area examined, affects the drainage both upstream and downstream of the anticline. The badlands above the anticline are covered with vegetation and have become stable while the badlands downstream of the anticline are much deeper, have very little vegetation, and are actively eroding by fluvial action.

Terrace Development in the Study Area

Five terrace levels were observed in the study area, and these were termed T_0, the lowest terrace level, through T_4, the highest terrace level (Figure 8). The terraces are not

Figure 8. The five terrace levels.

continuous, rather they are comprised of fragments that correlate to the same level. All of these terrace levels have been extensively dissected by fluvial activity and levels T_3 and T_4 are the best preserved. Terrace level T_4 is the level with the most remaining remnants of its former valley floor. Because terraces T_3 and T_4 are the best preserved levels, these two were chosen for detailed examination, though all levels were used to obtain geomorphic evidence about this area. Because of minimal difference in varnish and modest calcium carbonate accumulation differences between these two levels, topographic position was used to determine that T_4 is older than T_3 From this point on these terrace fragments will be referred to simply as 3.1, 3.2, etc.

Terraces 3.1, 3.2, 4.1, and 4.2 are generally parallel to the dike and are oriented towards the long axis of the valley where a trunk stream once flowed through the breach. The gradient measurements show that the terraces parallel to the dike slope towards the center of the valley and the terraces orthogonal to the dike slope towards the dike. Terraces 4.3 and 4.4 are generally orthogonal to the dike and are oriented along the length of the valley. The rounded nature of the clasts in the test excavations indicate that these were deposited by fluvial action, though the lack of sorting suggests sheet wash and not consolidated flow deposited these materials. The only area that exhibits some sorting is a layer of 2 mm clasts in terrace 4.3 that suggest a low energy channel once existed here and is now buried. Evidence of ponding was observed on terrace level T_2 slightly upstream of the dike. This indicates small-scale variation of the surface. A smoothly undulating surface with a 30 cm to 50 cm variation allowed the existence of ponds.

Six terrace remnants, related to breaches of the dike, were examined in detail for this project. Two terrace remnants of the T_3 level were examined and were assigned the numbers of 3.1 and 3.2. Four terrace remnants of the T_4 level were examined and these were assigned the numbers 4.1, 4.2, 4.3, and 4.4. The data recorded for each of the six terrace remnants included long axis length, short axis length, long axis compass bearing, GPS coordinates, elevation, long axis angle from horizontal, degree of varnish, degree of weathering, size of surface clasts, and vegetation present. A small test pit was excavated on the surface of each of the six terrace remnants and the information gathered from the excavations included Munsell color, clast size, degree of weathering of clasts, calcium carbonate stage, depth to bedrock, presence and depth of root filaments, structure, and texture. The data collected are displayed in Tables 1 and 2.

Table 1. Terrace surface data.

Terrace #	Long axis	Short axis	Bearing	Elevation	Gradient	Varnish
3.1	58.7	24.6	2°	877.5	4°	99%
3.2	117.3	14.3	355°	874.7	0°	5%
4.1	9.7	3.3	350°	885.1	4°	10%
4.2	68.5	14.9	330°	887.8	4.5°	10%
4.3	91.4	14	275°	880.8	3.5°	15%
4.4	1280	200	210°	878.7	3°	75%

Table 2. Terrace test excavation data.

Terrace #	Color	Clast Size	Weathering Degree	$CaCo_3$ Stage	Depth to Bedrock
3.1	2.5YR 6/2	No clasts	N/A	N/A	0 m
3.2	7.5YR 6/2	1-40 mm	blocky-well rounded	II	1-2 m
4.1	7.5YR 5/3	1-40 mm	semi round-rounded	II	27 cm
4.2	7.5YR 6/2	1-40 mm	semi round-rounded	II	1.5 m
4.3	7.5YR 6/3	1-40 mm	semi round-rounded	II	1.3 m
4.4	7.5YR 5/3	1-15 mm	semi round-rounded	II	1 m

Terrace 3.1 has a compass bearing of 2° (of its gradient) and a gradient of 4°. The surface clasts are blocky to rounded, and are more rounded down slope. The test pit revealed extremely firm clay with no subsurface clasts and the root filaments terminated immediately below the surface. This terrace has no gravel mantle, only a thin veneer of surface clasts lying directly on the clay bedrock. The vegetation on this terrace is creosote bushes and one ocotillo. Terrace 3.2 has a compass bearing of 355° and has a gradient of one degree or less. The surface clasts are blocky to semi-rounded, ranging from 10 mm to 20 mm. The excavation showed granular silt loam with clasts ranging in size from very fine to coarse and are not sorted. Root filaments extend to 12 cm and are lightly coated with calcium carbonate. This terrace has lechuguilla, dog cholla, and much ocotillo.

Terrace 4.1 has a compass bearing of 350° and a 4° gradient. The surface clasts range in size from 1 mm to 30 mm with one large 30 cm rhyolite clast. Below the surface is prismatic silt loam with unsorted clasts from very fine to very coarse. Root filaments extend to 12 cm and exhibit Stage II calcium carbonate coating. The vegetation consists of one ocotillo, twenty pencil cholla, and four creosote bushes. Terrace 4.2 has a compass bearing of 350° and a 4.5° gradient. The surface clasts are blocky to semi-rounded and range in size from 1 mm to 40 mm. A prismatic silt loam is below the surface and root filaments extend to 10 cm and have a Stage II calcium carbonate coating. The vegetation consists of much ocotillo, many creosote bushes, and much lechuguilla.

Terrace 4.3 has compass bearing of 275°W and a 3.5° gradient that is in direct alignment with breach one. Surface clasts are 1 mm to 30 mm with many large, 30 cm, rhyolite clasts. One clast exhibits a pahoehoe flow structure. The test excavation revealed silt loam and a layer of 2 mm clasts from 7 cm to 9 cm below the surface. Above and below this layer are unsorted coarse clasts. Root filaments extend to 24 cm and have Stage II calcium carbonate coating. The vegetation consists of much ocotillo, much pencil cholla, much dog cholla, and many creosote bushes. The slopes of this terrace are stabilized with much grass and lechuguilla.

Terrace 4.4 is the largest terrace in the study area, has a long axis length of 1280 m, and is the drainage divide between the breach one and breach two drainages. It has a compass bearing of 210° and a 3° gradient. This terrace defines the breach one drainage as it extends from the dike to the pediment flank and has a 16 m elevation change that is lowest near the dike. Surface clasts range in size from 1 mm to 50 mm and this terrace has many more clasts in the 1 mm to 3 mm range than the other terraces. Below the surface is granular to prismatic silt loam with a few 15 mm clasts supported by a 1 mm to 3 mm clast matrix. Root filaments extend to 5 cm and have a calcium carbonate coating. Vegetation consists of much ocotillo, many creosote bushes, and a high concentration of lechuguilla on the eastern half.

The breach two drainage may lose its headwaters to stream piracy in a relatively short time. The breach one drainage is at a lower level and its headward erosion is encroaching upon the southern edge of the breach two drainage. Also encroaching on the northern edge of the breach two drainage is an unnamed tributary to Rough Run Creek that is lower than both the breach one and two drainages. A capture here may result in the entire valley draining into Rough Run upstream of breach three.

Calcium Carbonate Accumulations and Rock Varnish

The extent of calcium carbonate accumulation was examined for the terraces and the pediment gravels. Five of the terraces examined exhibited Stage II calcium carbonate development, which is observed as a thin coating on clasts and root filaments. Terrace 3.1 had no calcium carbonate film, though it did have 1 mm nodules of calcium carbonate and manganese, these were 4 percent by volume. Terrace 4.3 had 10 percent calcium carbonate nodules and terrace 4.3 had 3 percent calcium carbonate and manganese nodules. Test excavations were 30 cm in depth and did not reach the maximum extent of calcium carbonate coating.

The degree of calcium carbonate coating in the pediment gravels was examined at locations where a vertical exposure of the gravels existed. These gravels exhibit a strongly cemented Stage IV accumulation that is 1-2 m deep. This caliche acts as a strong caprock and makes this surface very stable and resistant to erosion. Badland expansion undermines the caliche; the clays below the gravels are removed through erosion until the cemented gravels weaken and fall. The Stage IV calcium carbonate accumulation of the pediment gravels indicates that this surface has been intact for a long period of time. Berry and Williams (2008) stated that old alluvial deposits in BBNP are mid Pleistocene 781,000-126,000 yr, or older. Studies in New Mexico have shown that similar surfaces in the Rio Grande Valley are more than 300,000 years old (Gile et al. 1981).

The Stage II calcium carbonate accumulation or the terrace remnants illustrates the stability of these terraces, although without the cementation of Stage IV it does not act as a strong caprock and these terraces are eroded more easily than the pediment. The low stage of calcium carbonate accumulation indicates that these terraces have existed for a relatively short period of time. The existence of a buried channel in terrace 4.3 that is in direct line with breach one and the higher percentage of calcium carbonate nodules on 4.3 suggest that it may have been near the trunk stream that once existed at the T_4 level.

The gravels on the surface of three levels of the terrace remnants are coated with varnish. Terrace levels T_4 through T_2 have varnish while levels T_1 and T_0 do not. This indicates that the three levels that do have varnish have been stable since the varnish accumulated. The two surfaces without varnish achieved stability after active varnishing ceased. The environment has changed since the T_4-T_2 sequence and the T_1-T_0 sequence. The T_4-T_2 terraces experienced climatic conditions that were moister than the climate in which the T_1-T_0 terraces developed.

CHAPTER VII

CONCLUSION

Figure 9 shows varnish on a cross sectional face of the dike in breach one. Breach two has varnish on all exposed areas of the dike except where concentrated high velocity flows have polished the breach walls at the pouroff and breach three is varnished on all exposed faces. The presence of varnish, which if correlated to a time of wetter climates 11,500 years ago (Wells 1974), indicates that the breaches are pre-Holocene. Varnish on

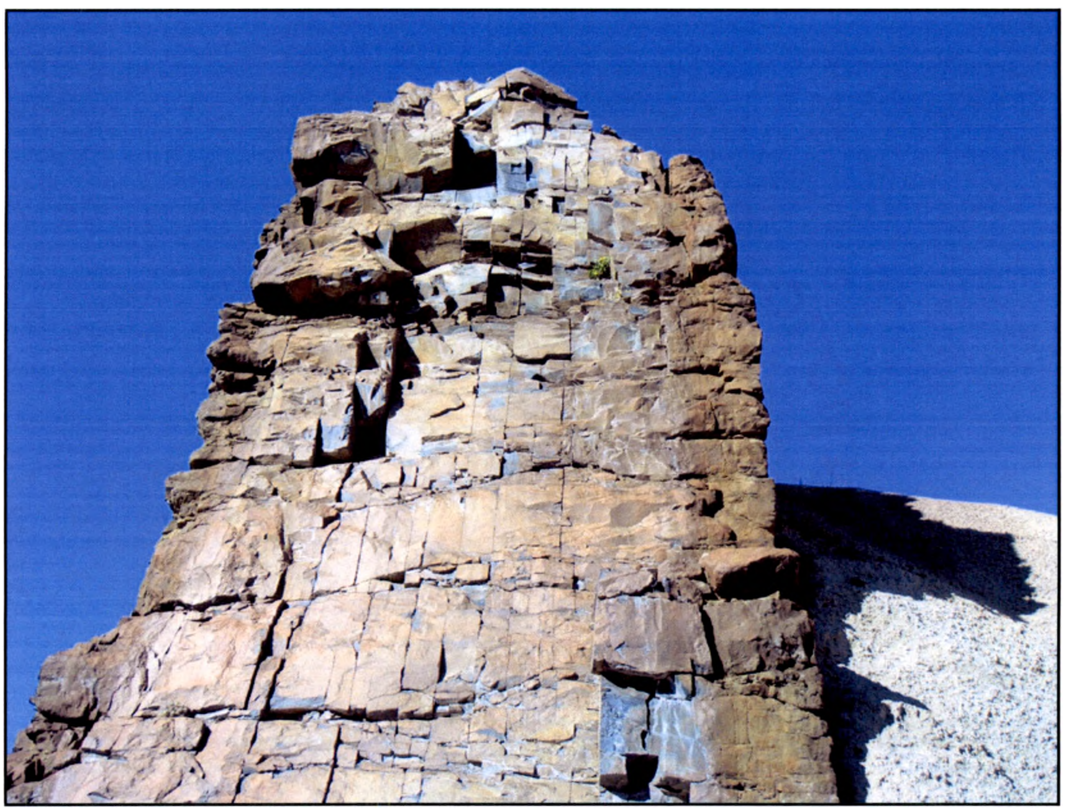

Figure 9. A cross sectional view of the dike showing varnish.

Terrace levels T_4-T_2 illustrate that these terraces were intact during varnish formation during the wetter climate of the Pleistocene.

The terraces in the study area are slowly disappearing due to fluvial erosion. The terrace remnants are long and narrow and channel incisions across the short axes of the terrace dissects it into fragments, which allows more rapid erosional removal of smaller, detached sections. Slope retreat on weak badland forming sediments occurs on all four sides of these smaller sections resulting in a pyramidal shape. A rounded hill results after the gravel veneer on these small terrace sections is removed and the underlying clays are completely exposed to weathering, the soft clays erode easily and the hill is diminished until it is beveled flat.

The USGS (2008) identified six terrace levels adjacent to the Rio Grande near Santa Elena Canyon. The depositional terraces near the river are completely comprised of rounded fluvial gravels rather than the bedrock strath terraces located in the study area. The USGS stated that five of these river terraces correlate to various pediment levels in the park. This suggest that a lowering of the base level of the Rio Grande results in the development of a new pediment at a lower level, leaving remnants of previous pediments at higher elevations. Pediment formation is a slow process indicating that long periods of time existed between base level changes of the river. First a pediment forms and later, when base level lowers, it is dissected by streams.

Each time the river base level was lowered this change translated upstream through the river tributaries by headward erosion. When the river remained at the same level long enough, nickpoint advance would eventually reach the downstream face of the dike and erode the supporting material away. This resulted in expansion of a breach when a collapse occurred, creating a new local base level upstream, which caused renewed down cutting in the study area. The five terrace levels that were examined in the Rough Run drainage are a result of this process. The terraces investigated in this study are not directly related to the terraces at the Rio Grande. These two sets of terraces, upstream of the dike, were graded to two different levels of breach one, and thus were isolated from the base level changes of the Rio Grande.

The study area includes two small drainages, tributaries that dissect a dike, before their confluence with Rough Run Creek, which deeply breaches the dike at a third location. The dike influences drainage, because in the areas where the dike has been exposed by erosion it forms a temporary base level until a breach occurs to form a lower temporary base level. Once a breach occurs, the resistant dike forms a pouroff on the downstream side. Breaching of the dike influences the sequence of terraces that remain upstream of the dike because of stream capture. When a breach occurs or expands by collapse the valley upstream is incised by fluvial erosion to the new level and terraces are left standing at the original height. This was an excellent site to examine drainage system evolution, fluvial processes, and the influence of geologic structures on local drainages. Breaches in the dike resulted from the exposure of its downstream side by headward erosion related to base level changes on the Rio Grande.

Future research at this site with sufficient funding could support efforts to determine an age for the cementation of the pediment gravels and an age for the terrace remnants. Uranium series dating of the calcium carbonate accumulations in these deposits could determine when the calcium carbonate accretion began. This would establish when these surfaces became stable and provide a time interval between the terrace levels. An understanding of when local base level changes occurred would provide important data about the changing level of the Rio Grande, and their impact on the ephemeral drainage, as well as the pediment surfaces, that have graded to the river's level.

Berry and Williams (2008) placed a relative age of mid Pleistocene, 781,000-126,000 yr, or older on the old alluvial deposits in BBNP based on Stage IV cementation of the pediment gravels. The presence of varnish in the breaches and on the exposed areas of the dike indicates that fluvial incision of the pediment occurred before the drier climate of the Holocene. Together this information brackets the time for fluvial dissection because the pediment had to form before it was incised.

Knowing the dates of base level lowering episodes on the Rio Grande may help us to understand why and how the base level dropped. Determining the age of the terraces in the study area would also improve the knowledge of how much time is required for such changes to occur. The five terrace levels have recorded much information about the region. This study focused on the geomorphic information displayed by the terrain. Further research could apply dating methods to acquire the temporal data that is available here.

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