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Geology of the Northern Alto Relex Area, Big Bend National Park, Brewster County, Texas

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Geology of the Northern Alto Relex Area, Big Bend National Park, Brewster
County, Texas

By

Robert Lee Schoen, Bachelor of Science

Presented to the Faculty of the Graduate School of

Stephen F. Austin State University

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Texas

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ABSTRACT

Detailed, 1:12,000-scale geologic field mapping was conducted around Alto Relex in the northern Sierra Del Carmen Mountains in Big Bend National Park. Alto Relex is a prominent, near vertical, ~1000 foot-high fault-line scarp. Cretaceous rocks in the area were folded and faulted by Laramide compression, intruded by Tertiary sills and overprinted by high-angle normal faults from Basin and Range extension. During the Laramide Orogeny and Basin and Range extension, the underlying basement shear zone called, the Texas Lineament, was reactivated creating a transpressional and transtensional regimes. The general geology of this area was outlined by Moustafa (1988) working primarily from aerial data and was partly mapped by Cooper et al. (2011). This study provides more detail in the structurally complex area around Alto Relex. Cretaceous rock units exposed in the study area include the Santa Elena Limestone, Del Rio Clay, Buda Limestone, Boquillas Formation and the Pen Formation. In some areas the thin-bedded, flaggy Boquillas contains small folds that have an average strike of N30°W. Minor thrust faults were found in multiple rock units striking approximately N13°W. A large sinistral strike-slip fault on the east side of Alto Relex was traced for over 3,000 feet, striking N40°W. Distinctive

reddish-brown knobs of fault breccia on the west side of Alto Relex appear to have been silicified or hydrothermally altered. This breccia probably marks the location of a large basin-bounding normal fault. Both map-scale and outcrop scale folding is present. One map-scale monoclinal feature has an orientation similar to the Laramide compression direction and could be a Laramide fault-propagation fold overlying a reverse fault, or a fault-propagation fold that was produced over a Basin and Range normal fault. Some fault planes in the study area have slickensides and chatter marks with different orientations within a short distance, suggesting a complex structural history.

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Stephen F. Austin State University, my grandparents James and Betsy Lidgley and my parents Bryan and Cindi Schoen helped to fund this project. Without them none of this would have been possible.

DEDICATION

This thesis is dedicated to my grandad,
James Hart Lidgey.
You will always be missed.

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CHAPTER I

INTRODUCTION

This is a field-based, geologic mapping study conducted in the Sierra del Carmen Mountain range in eastern Big Bend National Park (BBNP). BBNP is located in west Texas along a large bend of the Rio Grande River (Figure 1.1). It has interesting and diverse geologic features, but some are remote and almost inaccessible. Rock units in BBNP show the effects of multiple tectonic events including Ouachita-Marathon Orogeny, Jurassic rifting, Laramide Orogeny, Paleogene magmatism and Basin and Range extension. In the subsurface, a Precambrian zone of crustal weakness, the Texas Lineament, was reactivated during some of these later tectonic events and influenced fault orientations.

The study area contains Cretaceous carbonate platform rocks that have been subjected to compression, extension and shear stresses. These stresses created deformational features including map and outcrop scale folds, thrust faults, strike-slip faults and normal faults. Some deformation in the study area could also be related to the emplacement of igneous intrusions.

Moustafa (1988) mapped the general geology of the study area and the surrounding Sierra del Carmen Mountains by aerial photographs and spot mapping. A small section of the study area was mapped by Cooper and others (2011), but their mapping essentially ended at Alto Relex. Thus, there are no

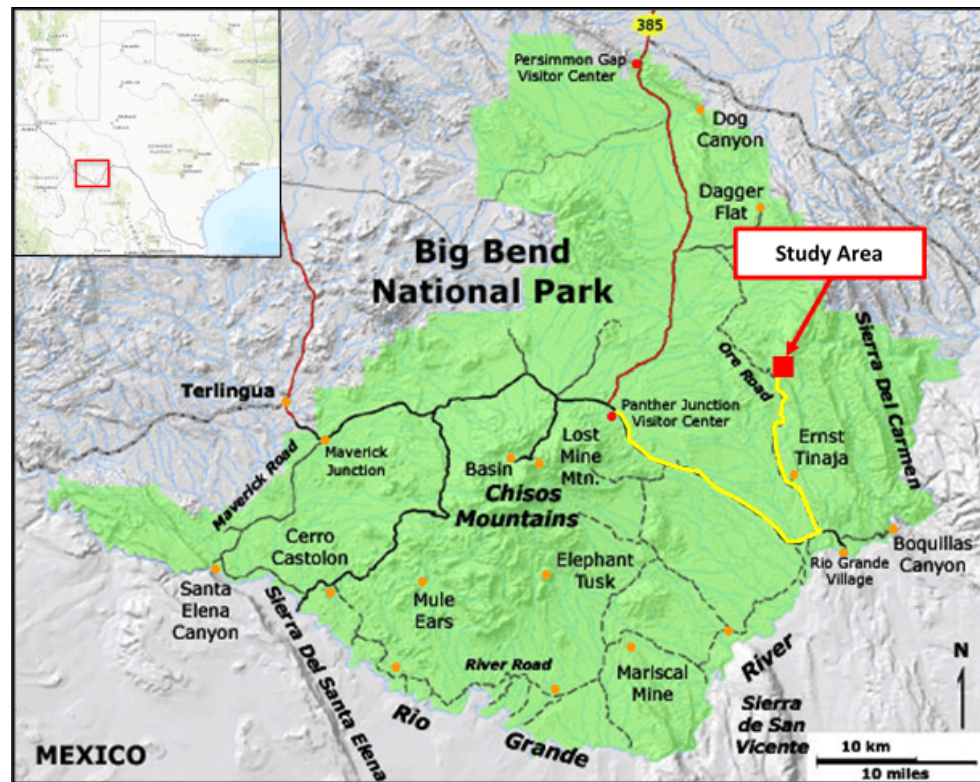


Figure 1.1 - Map of Big Bend National Park highlighting important geographic features. The discussed route to access the study area is shown in yellow and the approximate location of the study area is shown in red (Modified from USGS, 2017).

published, easily accessible large-scale geologic maps of this area where many tectonic events have overlapped. The geologic map, cross-sections and

structural analysis produced in this study should help to unravel the geologic history of this area.

Location

The thesis area is deep in the backcountry of BBNP and is accessible only by driving several miles on a primitive dirt road called Old Ore Road. The study area is 18 miles southeast of Panther Junction (BBNP Headquarters) on Park Route 12, and then 14 miles north on Old Ore Road (Figure 1.1). Approaching the study area on Old Ore Road, the massive cliff face of Alto Relex rises to the east, while to the west is a large symmetrical hill called Roy's Peak (Figure 1.2; Figure 1.3). The latter is part of an extensive igneous intrusion called McKinney Hills (Figure 1.2). Alto Relex (Figure 1.3) is a very prominent, near vertical, approximately 1,000-foot high fault-line scarp that is found within the southwestern portion of the study area. This feature is the westernmost uplifted block of the Sierra del Carmen Mountain range. McKinney Hills is an elongated north trending laccolith that covers an area of approximately 11 square miles (Figure 1.2). A small section of this intrusion is in the northwestern quadrant of the study area. The study area is in the northeastern corner of Roy's Peak quadrangle and the adjacent southeastern corner of the McKinney Springs quadrangle (Figure 1.4; Figure 1.5).

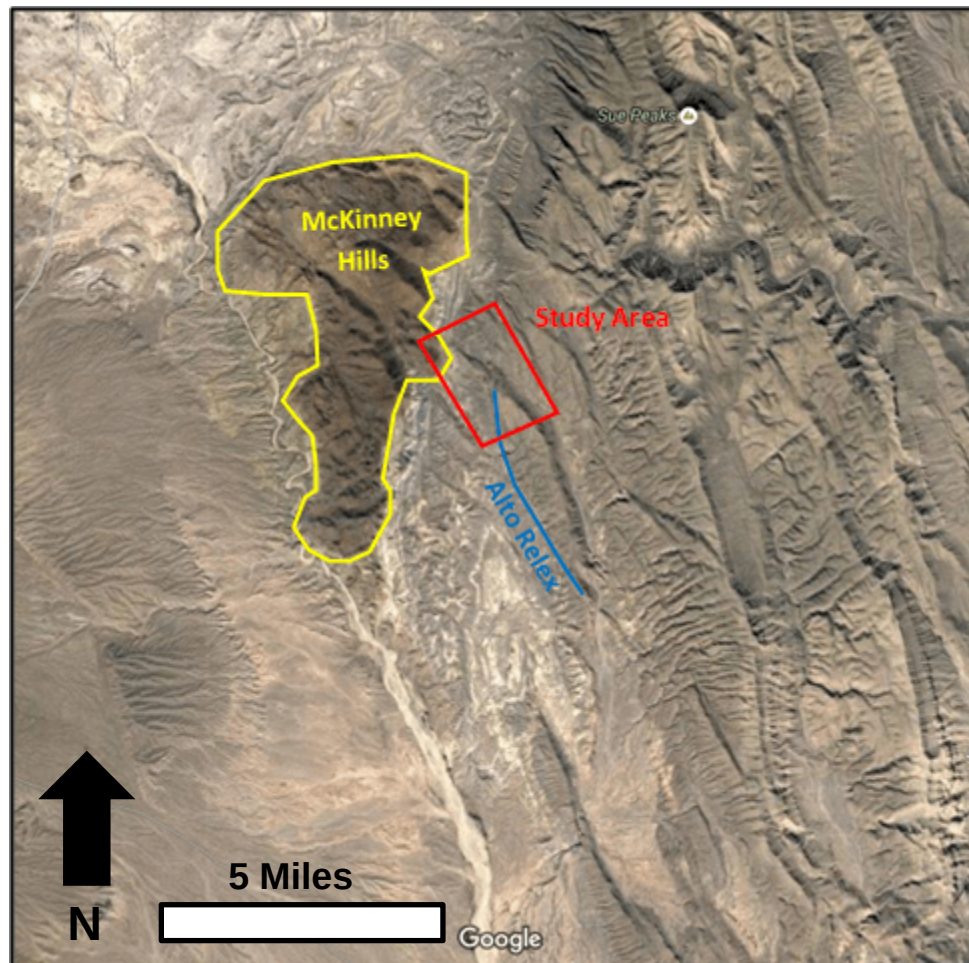


Figure 1.2 - Satellite image of the study area and surround locations with important features labeled (Modified from Google Earth, 2017). Key: McKinney Hills – Yellow, Alto Relex – Blue, Study area – Red.

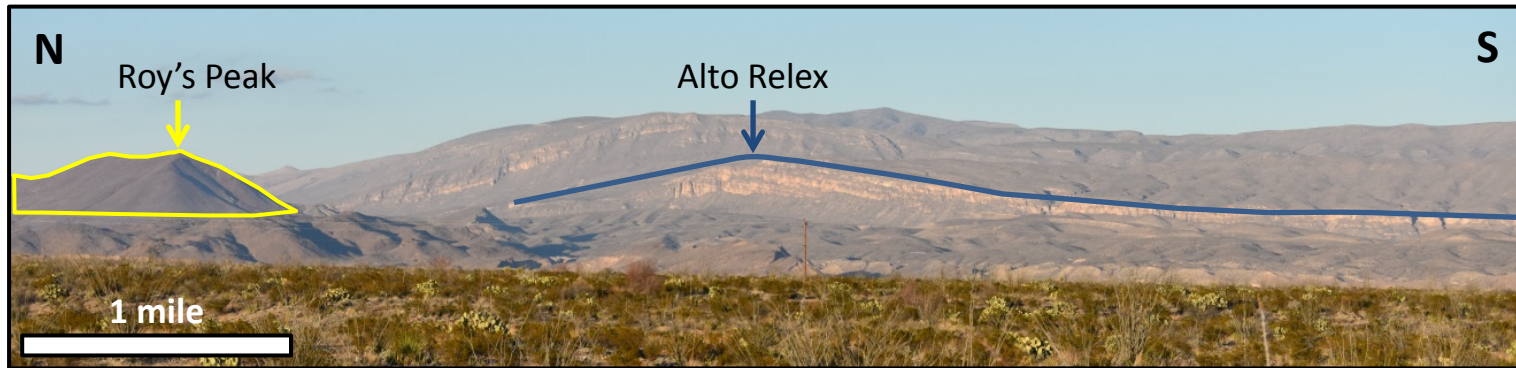


Figure 1.3 – A view of the study area from the west. The fault-line scarp of Alto Relex is shown in blue; this feature represents the westernmost uplifted block of the Sierra del Carmen Mountain range. Roy's Peak, the highest peak of the McKinney Hills Laccolith is shown in yellow. The study area includes a portion of Alto Relex and McKinney Hills laccolith.

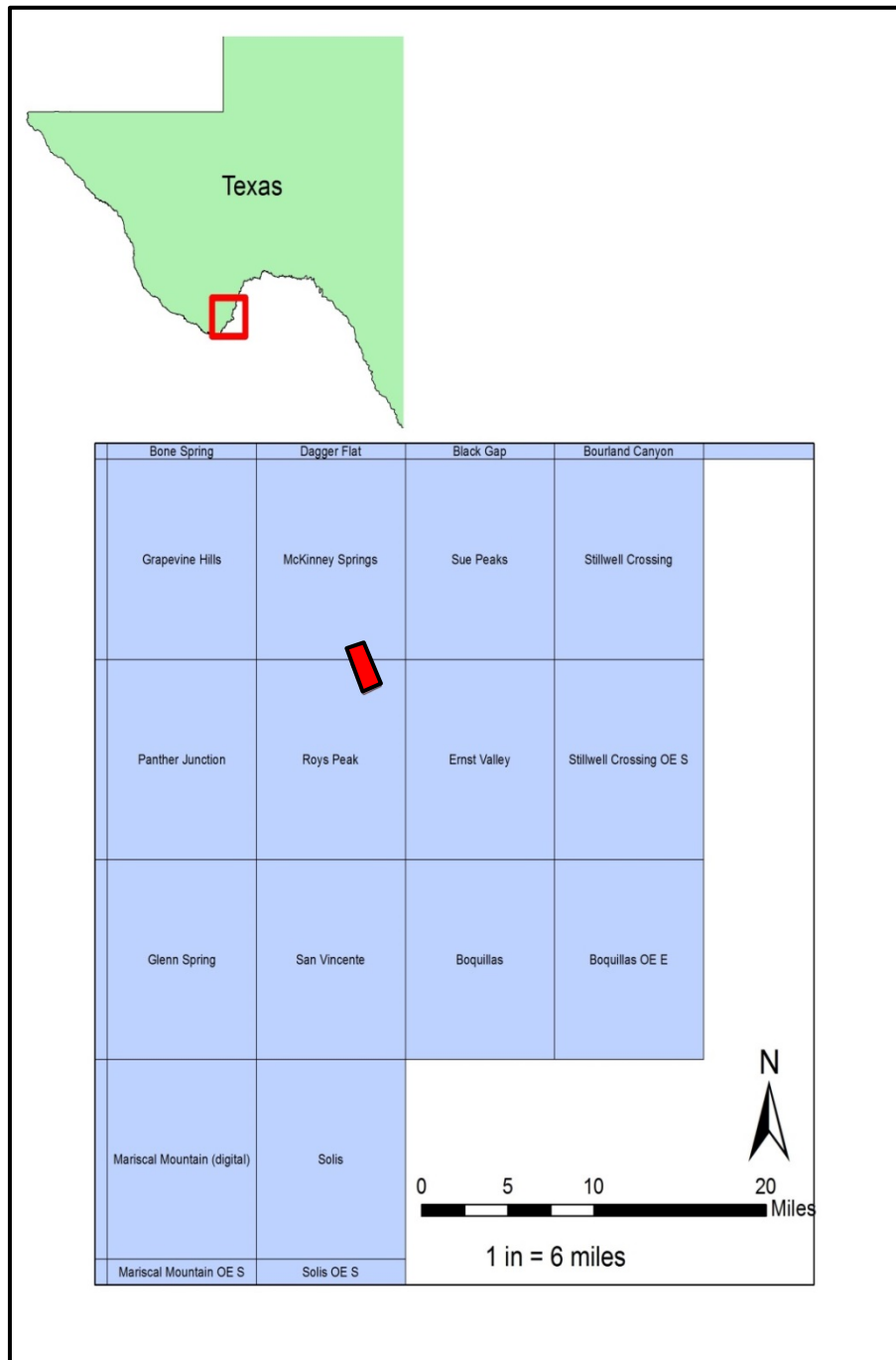


Figure 1.4 - Map showing the location of the study area (red) and the surrounding quadrangle. The study area lies in Roy's Peak and McKinney Springs quadrangles (ArcGIS, 2017).

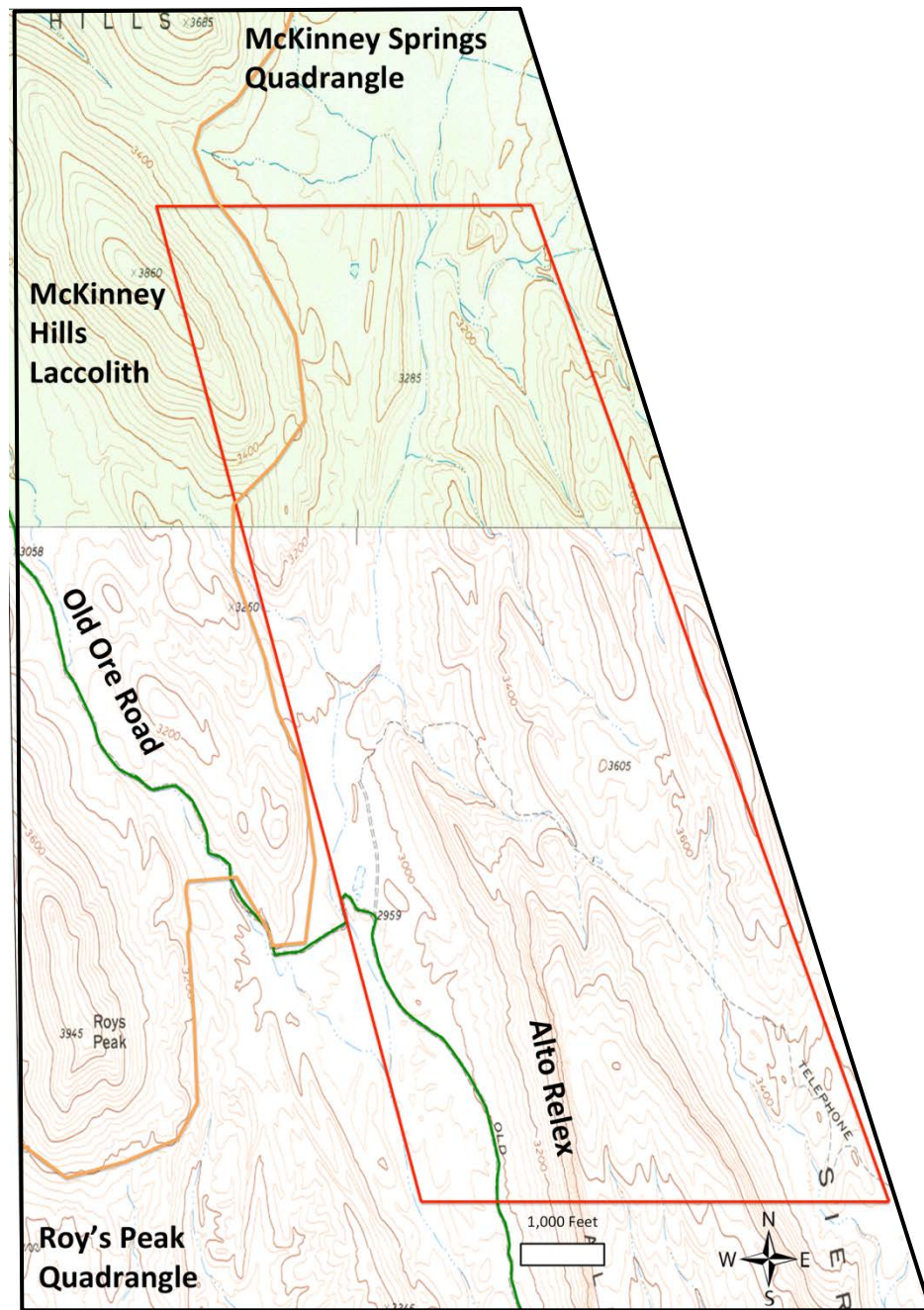


Figure 1.5 - Detailed topographic map of the study location (red) with both quadrangles (Pale Green=McKinney Springs) (White=Roy's Peak) and important structural features, including Alto Relex and McKinney Hills Laccolith (orange), and location of Old Ore Road (green) (Modified from USGS).

Objectives

The primary objective of this study is to delineate the complex tectonic history of the Big Bend area. To accomplish this, secondary objectives were to complete a detailed 1:12,000-scaled geologic map of the area; describe the orientations of thrust, strike-slip and normal faulting; determine the chronological order of the faulting and study map-scale and outcrop-scale folding to reveal the geomechanical process responsible for their creation. Another objective was to determine if sills found in the study area were passively or forcefully injected. Completion of these objectives will provide insight for understanding the structural and tectonic development of the study area. This study contributes to the geologic history of the Sierra del Carmen Mountains, BBNP and West Texas.

Methods

This thesis study used traditional geologic field mapping techniques to create a descriptive structural analysis of the study area. Fieldwork was completed in a total of six weeks during four field sessions, in January 2016, August 2016, November 2016 and January 2017. Roy's Peak quadrangle and McKinney Springs quadrangles were scanned and enlarged (1:12,000) to

produce base maps. A Garmin GPS 64 was used to provide accurate location and elevation data.

A Brunton compass was used for taking field measurements such as strike and dips of bedding planes, fold axial planes, faults and joints, plunge and bearing of slickenlines and the hinge lines of folds. Stereonet 9 by Richard Almendinger was used to plot orientation data on equal-area stereonet. Map units were identified in the field based on rock descriptions, the thickness of beds and topographic expression and compared to descriptions by Turner et al. (2011) and Maxwell et al. (1967). Faults were identified by the juxtaposition of contacts, linear topographic breaks, breccia zones and slickenlines. The direction of transport along faults was determined by chatter mark orientations on the slickenlines of fault planes. In some areas, satellite images acquired from Google Earth were used to trace approximate locations of faults. Margins of sills were studied to help understand how they were emplaced.

Once mapping was completed, geologic maps were created in ArcMap, PowerPoint and Inkscape. Three cross-sections were produced to help to understand the geologic conditions by providing a pseudo three-dimensional view of the study area.

Previous Works

This area has been shown on multiple small-scale regional geologic maps but is not shown in detail on any readily available geologic maps. One of the early geologic maps of BBNP was created by Ross Maxwell in 1968 and is featured in his book, "The Big Bend of the Rio Grande." This book provides a report of major geologic features that define BBNP but the geologic map is not detailed and lacks topography. A regional geologic map of the Sierra del Carmen mountain range based mainly on aerial imagery was produced by Moustafa (1988). More recently, Cooper and others (2011) published maps of the eastern Big Bend area at a scale of 1:24,000. They mapped most of Roy's Peak quadrangle, but not the entire northeast corner, which is where this study is located. Turner and others (2011) with the USGS created a new map of the entire park at a scale of 1:75,000.

CHAPTER II

REGIONAL STRATIGRAPHY

Introduction

The stratigraphy of BBNP consists of mainly Mesozoic marine sedimentary rocks and Cenozoic alluvial and igneous units (Figure 2.1). Paleozoic units can be found at Persimmon Gap, in the northern section of BBNP, but do not extend into the rest of the park. More extensive exposures of Paleozoic Formations can be found around the Solitario and Marathon Uplifts. In Texas, the nearest Precambrian rocks are about 155 miles northwest of BBNP in Van Horn, Texas. Upper and Lower Cretaceous strata make up the majority of rock formations in the study area. The following sections describe the stratigraphy of BBNP.

Paleozoic Stratigraphy

Paleozoic formations underlie most of the west Texas region, but crop out in only a few areas, including El Paso, Van Horn, Shafter – Pinto Canyon,

Marathon Uplift, Solitario Uplift and Persimmon Gap in BBNP (Urbanczyk et al., 2001). The Paleozoic strata that is exposed around Persimmon Gap includes the Ordovician Maravillas Formation, Silurian to Mississippian Caballos Novaculite and the Mississippian to Pennsylvanian Tesnus Formation (Maxwell et al., 1967).

The Maravillas Formation is the oldest unit found in BBNP (Turner et al., 2011). This formation contains mostly black chert with clastic limestone, micrite, marlstone and black shale (McBride, 1975). Caballos Novaculite is a massive, white novaculite to varicolored chert (King, 1937). The Tesnus Formation contains dark gray to black shale, siltstone and sandstone (Maxwell et al., 1967; Turner et al., 2011).

Mesozoic Stratigraphy: Lower Cretaceous

Lower Cretaceous stratigraphic units make up the majority of the formations that were mapped in this study. Most of these sediments were deposited in a carbonate shelf environment that experienced alternating influxes of terrigenous clastic material (Turner et al., 2011). Much of this terrigenous sediment was probably derived from areas associated with the Marathon Uplift, which is just north of BBNP (Smith, 1981). The Lower Cretaceous Formations found in BBNP include the Glen Rose Limestone, Maxon Formation, Telephone

Canyon Formation, Del Carmen Limestone, Sue Peaks Formation, Santa Elena Limestone, Del Rio Clay and Buda Limestone.

Glen Rose Limestone

The Glen Rose Limestone is the oldest Cretaceous unit exposed in BBNP and it unconformably overlies the Tesnus Formation (Turner et al., 2011). The lower contact is marked by a basal conglomeratic unit and the upper contact is marked by an *Orbitolina* zone (Henry and Muehlberger, 1996). The Glen Rose limestone is composed of soft marls and nodular limestones that contain multiple layers of resistant fossiliferous wackestone (Henry and Muehlberger, 1996). This formation is approximately 330 to 500 feet thick in BBNP (Turner et al., 2011). Outcrops of Glen Rose limestone can be observed inside the park at Persimmon Gap, Love ranch, Marufo Vega trail, Telephone Canyon and Santa Elena Canyon (Maxwell et al., 1967).

Maxon Sandstone and Telephone Canyon Formations

These formations are typically mapped as a single unit and tend to form a reddish-colored slope that separates the Glen Rose and Del Carmen limestones (Turner et al., 2011). The Maxon Sandstone is composed of fluvial deposits in the north that grade southward into deltaic and shallow shelf deposits (McBride, 1987). The Maxon Formation is not found everywhere inside the park but crops

out one mile southeast of Persimmon Gap (Turner et al., 2011). At this location, it is composed of silty sandstone that weathers reddish and is around 10 feet thick (Maxwell et al., 1967). The Maxon Sandstone grades upward into the Telephone Canyon Formation, which is composed of thin nodular limestone and marl beds (Turner et al., 2011; Maxwell et al., 1967). The limestone is yellow to brownish gray and the marl is yellowish gray (Turner et al., 2011). These formations represent the first influx of terrigenous clastic material during the Cretaceous (Turner et al., 2011; Smith, 1981). Combined, these units range from 65 to 150 feet thick (Turner et al., 2011).

Del Carmen Limestone

The Del Carmen Formation unconformably overlies the Telephone Canyon Formation (Turner et al., 2011). It contains alternating beds of limestone and marl but is characterized by a resistant ridge-forming limestone (Henry and Muehlberger, 1996). The limestone in this formation is massively-bedded, gray, weathers to shades of brown and contains abundant chert nodules (Corry et al., 1990). The Del Carmen Formation ranges from 300 to 470 feet thick and is well known for its prominent exposures in the Sierra del Carmen Mountains and Mesa de Anguila inside of BBNP (Corry et al., 1990; Maxwell et al., 1967). Fossils identified in this formation include rudists, gastropods, echinoids and foraminifera (Turner et al., 2011).

Sue Peaks Formation

Maxwell and others (1967) subdivided the Sue Peak Formation into three members; these three members include a lower yellowish-gray marly shale member, a middle massive gray limestone ledge and an upper, thin-bedded gray limestone member. This unit is approximately 250 to 260 feet thick and forms a slope between the Del Carmen Limestone and the Santa Elena limestone (Turner et al., 2011; Wylie, 1987). Fossils discovered in this formation include gastropods, echinoids and ammonites (Maxwell et al., 1967).

Santa Elena Limestone

The Santa Elena Limestone (Figure 2.1) is an important unit in this study. It is the oldest Lower Cretaceous unit that is mapped in the study area (Figure 2.2) and is commonly seen throughout the Sierra del Carmen Mountain range. This rock unit is light gray to whitish, massive limestone that weathers to light or dark shades of reddish brown (Maxwell et al., 1967). It is dominantly a finely crystalline limestone that contains bountiful rudists and some rounded chert nodules (Maxwell et al., 1967; Tuner et al., 2011; John, 1966). Other fossils that have been identified in this formation include gastropods, echinoids and foraminifera (Maxwell et al., 1967; Turner et al., 2011). This formation ranges from 655 to 800 feet thick and often forms steep cliff faces (Corry et al., 1990). In

some locations it contains marly beds towards the upper contact (Corry et al., 1990; Turner et al., 2011). It has been interpreted that this unit was deposited in a carbonate-shelf environment (Turner et al., 2011).



Figure 2.2 – A view to the east of a massive cliff composed of Santa Elena Limestone (Kse) located along the western side of Alto Relex.

Del Rio Clay

The Del Rio Clay (Figure 2.1) also crops out in the study area. This unit is bounded by unconformities and is mostly composed of thin beds of reddish-brown to rust-colored clay (Lock et al., 2013; Maxwell et al., 1967). In some

areas, it contains interbeds of flaggy, siliceous limestone and fragile sandstone (Figure 2.3) (Maxwell et al., 1967). Limestone beds in this formation can be described as an oyster packstone, which locally displays megaripples (Lock et al., 2009). The sandstone units in the Del Rio Clay have been described by Lock and others (2007) as very fine-grained, well-sorted, cross-laminated and bioturbated sandstone. The bioturbation that is present in this sandstone is mostly fossil burrows including *Ophiomorpha*, *Thalassinoides* and *Spongeliomorpha* (Lock et al., 2007). In some localized areas it contains distinctive liesegang oxidation/reduction banding, which displays concentric red and tan bands (Figure 2.4) (Lock et al., 2013; Silberstorf, 2017). This formation thins southeastward across BBNP; it measures 65 to 100 feet thick in the northern Sierra del Carmen Mountains and less than one foot thick to absent in the southern Sierra del Carmen Mountains (Turner et al., 2011; Silberstorf, 2017). In some areas, this formation creates slopes that are made up of red to orange rock fragments of fine-grained sandstone, which contain the foraminifer *Cribratina texana* (Cullen et al., 2013). This formation represents another influx of terrigenous clastic material that was deposited in a near-shore environment (Lock et al., 2013). Across West Texas, this formation varies in thickness which is likely due to the basal onlap against the irregular surfaces of Cretaceous limestone beds combined with differential sedimentation rates (Lock et al., 2007; Hover et al., 2008).

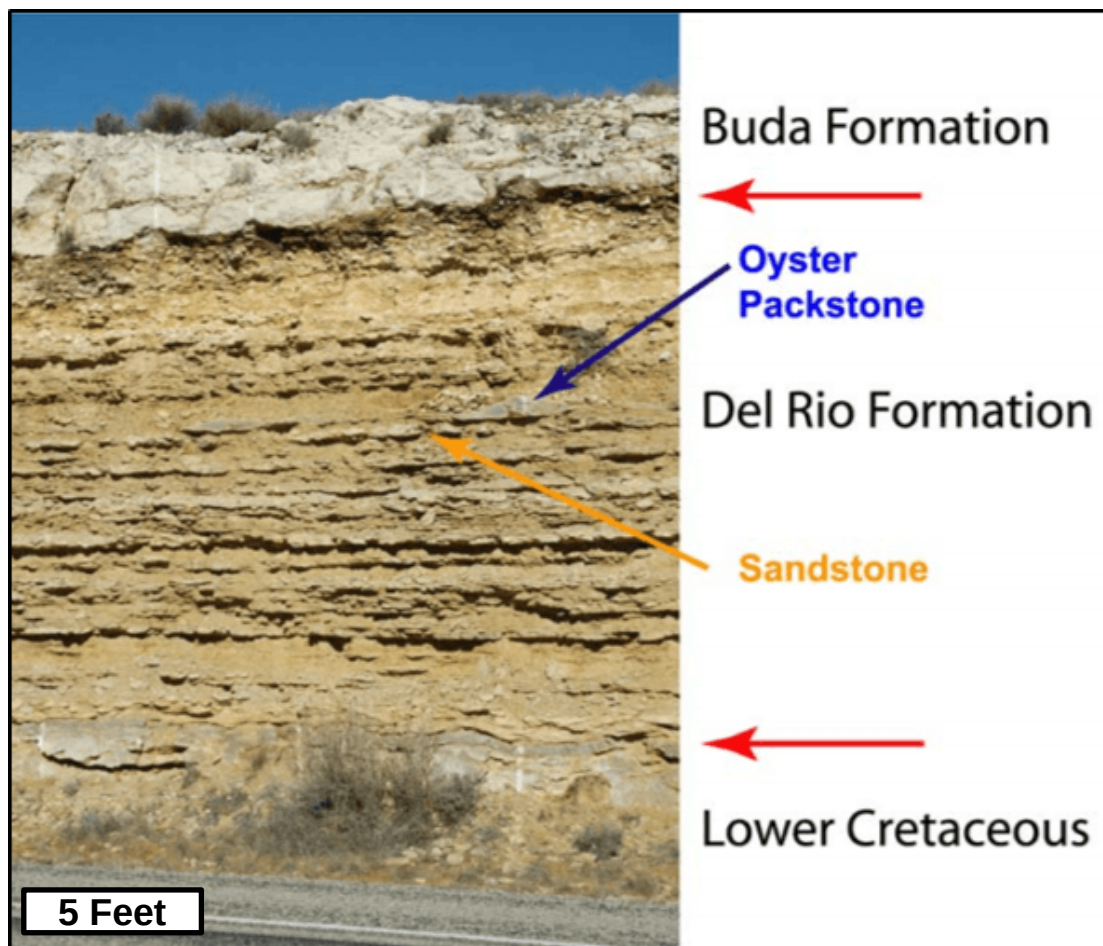


Figure 2.3 - A typical outcrop of the Del Rio Clay (Kdr) located at Seminole Canyon along U.S Highway 90. This unit is bounded by unconformities (red arrows) and is composed of mostly light-orange clay that contains thin sandstone (orange arrow) and oyster packstone beds (blue arrow) (From Hover et al., 2008).

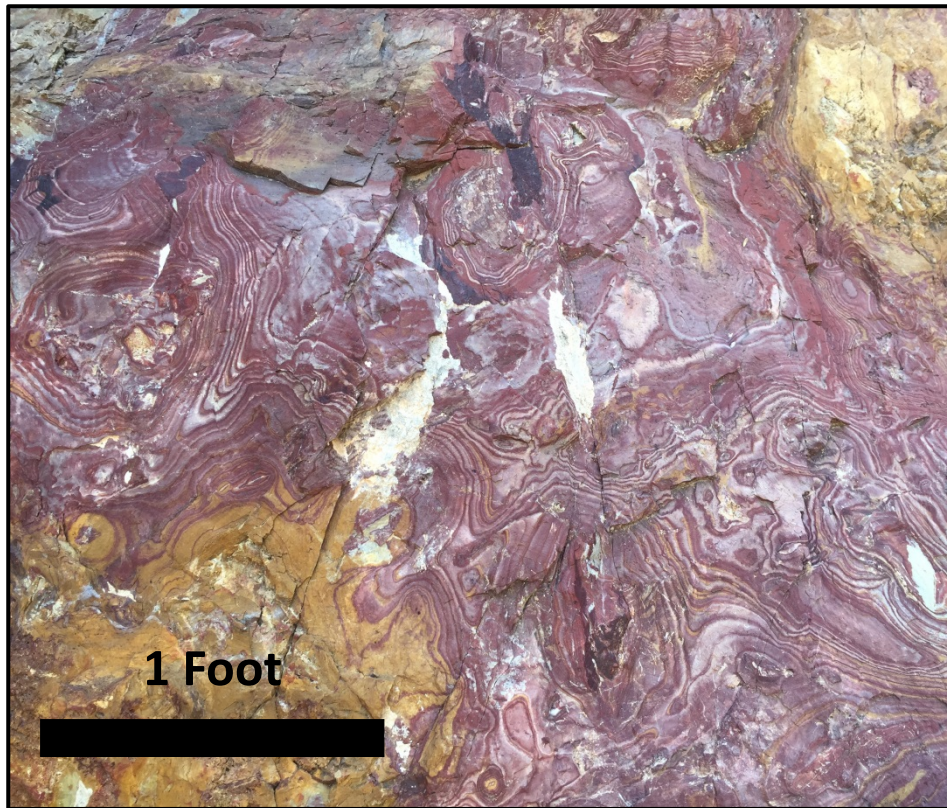


Figure 2.4 – In Ernst Tinaja Canyon seven miles south of the study area liesegang banding is pervasive in the Del Rio Clay. This banding could have been produced by the movement of iron rich, hydrothermal fluids related to an underlying igneous body.

Buda Limestone

The Buda Limestone (Figure 2.1) crops out in the study area. It contains upper and lower cliff-forming members that are separated by a slope-forming, light gray, nodular and marly limestone (Turner et al., 2011). The cliff-forming members are described as ivory to white (Figure 2.5), finely crystalline, thick-bedded wackestones with lime mudstone (Cullen et al., 2013; Turner et al.,

2011). Both of these members display conchoidal fracture and a hackly-weathered surface (Freeman, 1968). This formation varies from 65 to 100 feet thick and contains fossils including ammonites, solitary coral, hemiasters and exogyra (Freeman, 1968; Turner et al., 2011).

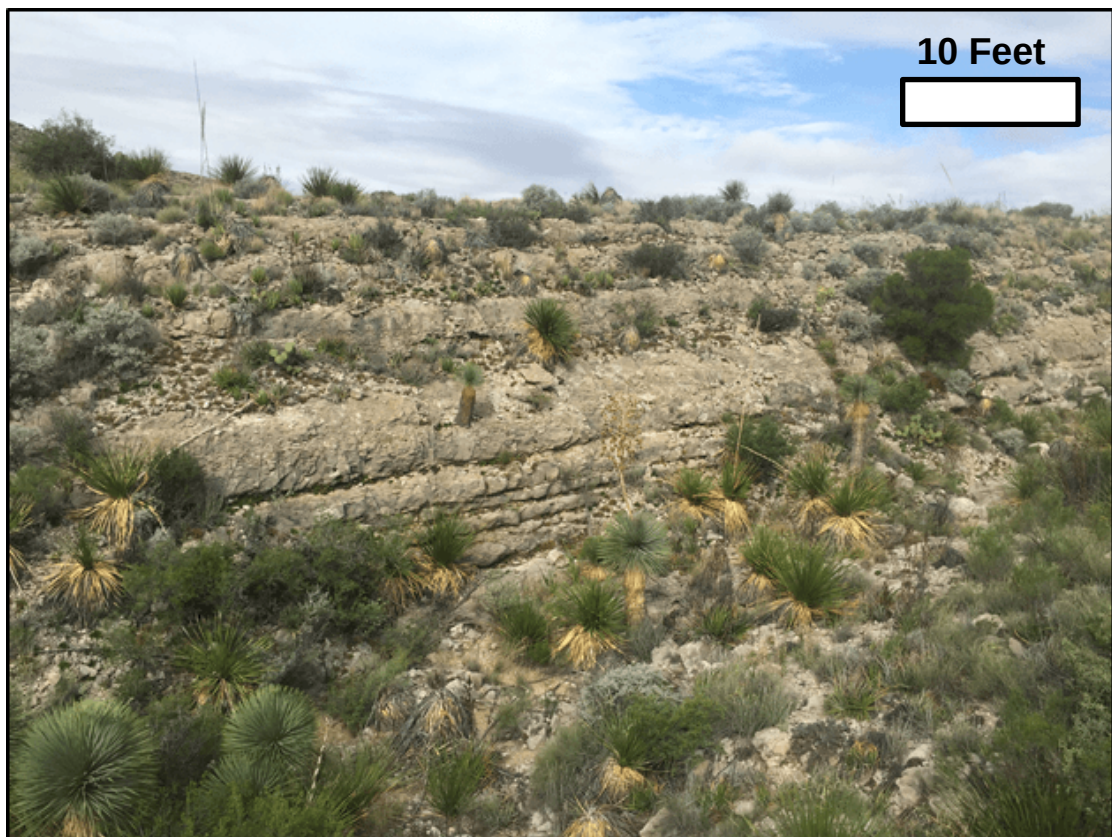


Figure 2.5 – Cliff forming member of the Buda Limestone (Kbu) exposed in the study area, a view to the west at location S70.

Mesozoic Stratigraphy: Upper Cretaceous

Upper Cretaceous formations in the Trans-Pecos region comprise a northeastwardly thinning wedge of terrigenous marine, paralic (transitional) and continental strata (Lehman, 1986). The Upper Cretaceous Formations present in BBNP include the Boquillas Formation, Pen Formation, Aguja Formation and the Javelina Formation.

Boquillas Formation

The Boquillas Formation (Figure 2.1) crops out in the study area and unconformably overlies the Buda Limestone (Turner et al., 2011). It was first described by Udden (1907) as a light tan-grayish to ferruginous, thin-bedded flaggy limestone (Figure 2.6). It is subdivided into two units, the lower Ernst Member and upper San Vicente Member (Maxwell et al., 1967). There is a relative increase in shale and marl beds from the bottom to the top of this Formation (Maxwell et al., 1967).

The Ernst Member of the Boquillas Formation consists of light yellowish, gray to buff, silty, finely crystalline limestone flags, with siltstone and calcareous clay (Maxwell et al., 1967). This member is around 330 feet thick in the Big Bend region (Maxwell et al., 1967; Turner et al., 2011). The limestone beds range from

a few inches to three feet and are separated by a thin-bedded, flaggy clay material (Henry and Muehlberger, 1996).

The contact between the San Vicente and Ernst Members is marked by an *Allocrioceras hazzardi* zone (Cooper et al., 2005; Cooper, 2007; Turner et al., 2011). This zone is five feet thick and stratigraphically located in the Upper Ernst Member (Cooper and Cooper, 2014; Turner et al., 2011). *Allocrioceras hazzardi*

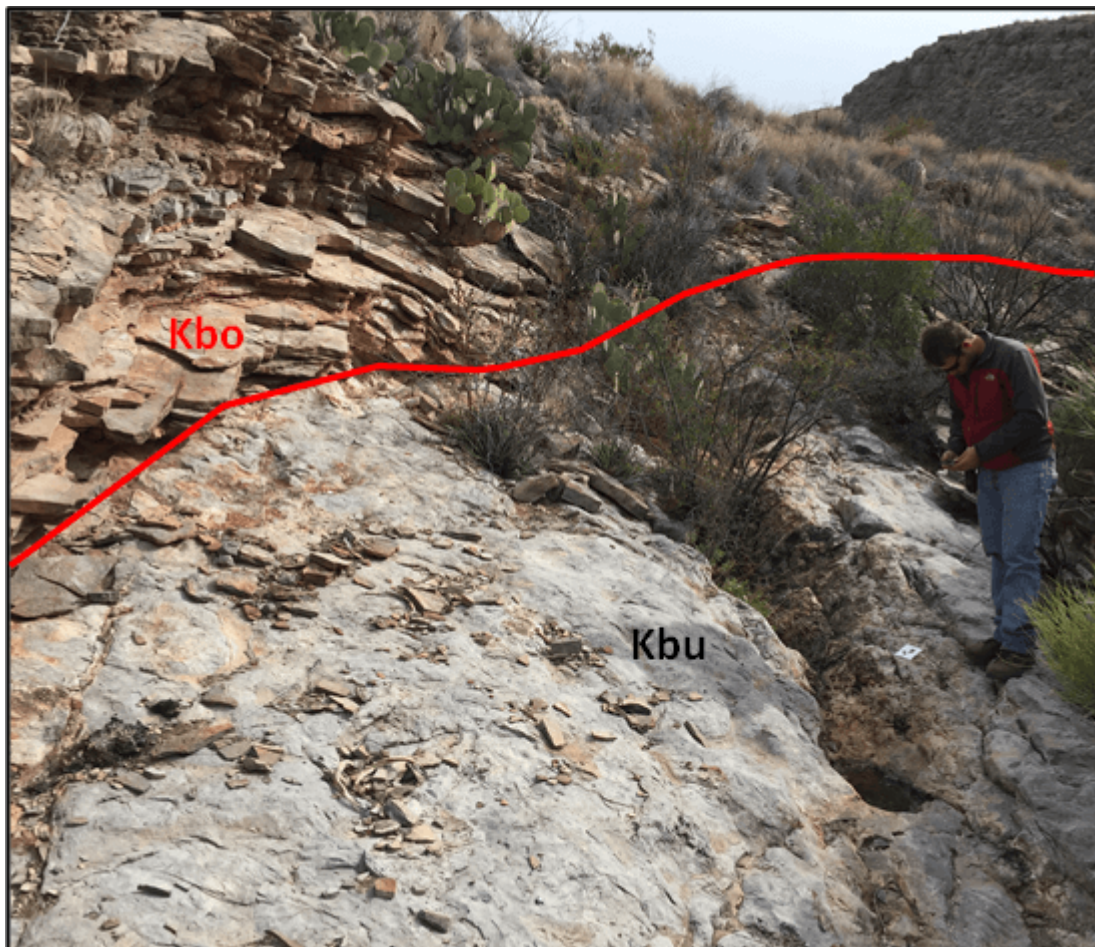


Figure 2.6 - Outcrop of the Boquillas Formation (Kbo) at location S9. This formation unconformably overlies the Buda Limestone (Kbu) and is composed of thin, alternating limestone and shale beds.

is a nektonic, heteromorphic ammonite that is typically replaced by calcite in BBNP (Cooper and Cooper, 2014).

The San Vicente Member can be described as a gray, thin- to medium-bedded, chalky and argillaceous limestone that is interbedded with gray to yellowish-gray, platy to soft marl (Maxwell et al., 1967). There have been reports of bentonitic clay and minor tuff beds in this member (Maxwell et al., 1967; Turner et al., 2011). This unit is estimated to be around 475 feet thick (Turner et al., 2011). An index fossil *Inoceramus undulatopticatus* can be found in the upper 15 to 20 feet of this member (Barnes, 2012). *Inoceramus undulatopticatus* is a bivalve macrofossil that can measure up to 30 inches wide and three inches thick (Barnes, 2012).

Pen Formation

The Pen Formation is the youngest Cretaceous unit that crops out in the study area. Maxwell and others (1967) described the Pen Formation (Figure 2.1), as a slope-forming claystone deposit that has poor expression due to rapid weathering (Figure 2.7). The formation is mostly light gray shale that weathers to yellow and has interbedded limestone layers ranging from one to 15 feet thick (Martin, 2007). Fossils present in this formation include ammonites, pelecypods and gastropods (Turner et al., 2011). It generally forms a slope that ranges from

330 to 750 feet thick (Turner et al., 2011). The Pen Formation shares a gradational contact with the overlying Aguja Formation (Turner et al., 2011).

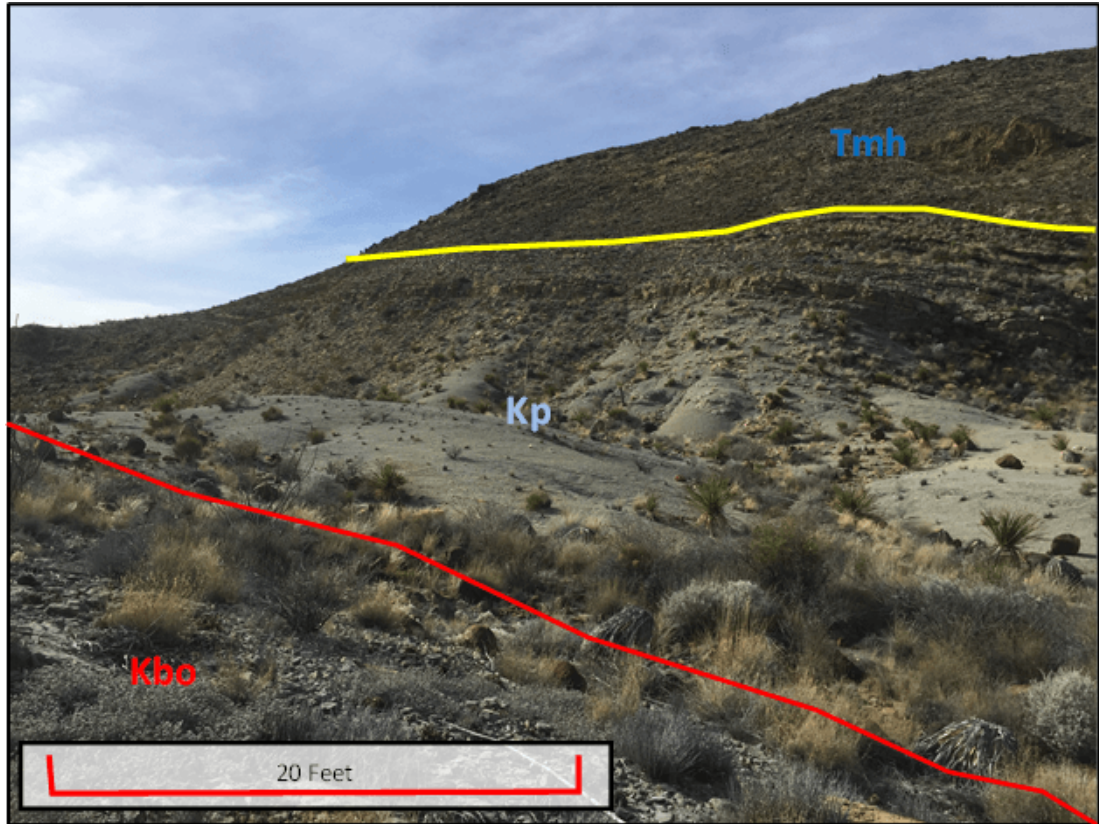


Figure 2.7 - The Pen Formation (Kp) was found in direct contact with the igneous rock of McKinney Hills (Tmh) at location S185.

Aguja Formation

The lower contact of the Aguja Formation displays a yellow marine sandstone unit that contains ripple marks, marine fossils and other tidal flat

characteristics (Hopkins, 1965, Maxwell et al., 1967). Lignitic shale and coal beds can be found in the middle of this formation (Hopkins, 1965). Towards the upper contact, it contains mottled maroon and green claystone, limestone conglomerates and sandstone beds (Hopkins, 1965). This unit varies from 330 to 915 feet thick (Turner et al., 2011).

Javelina Formation

The Javelina Formation mostly represents a clay unit with lenticular masses of yellow-gray, yellow-brown and dark-brown, crossbedded sandstone (Maxwell et al., 1967). This unit ranges from 100 to 2,000 feet thick and contains abundant vertebrate fossils and petrified wood (Turner et al., 2011).

Cenozoic Stratigraphy

Cenozoic units in BBNP are dominated by volcanic clastic sedimentation and lava flows found in the Chisos Group and South Rim Formations and igneous intrusions such as the McKinney Hills Laccolith. Cenozoic formations found in BBNP include the Black Peaks, Hannold Hill, Canoe, Chisos Group, South Rim and the Burro Mesa formations. No Cenozoic volcanic units are exposed in the study area.

CHAPTER III

REGIONAL GEOLOGY

Introduction

At least three orogenic belts intersect in Trans-Pecos, Texas, including the Precambrian Van Horn mobile belt, Paleozoic Marathon-Ouachita thrust belt and the Cretaceous Laramide tectonic belt (Shepard and Walper, 1982). BBNP has undergone multiple deformational events including rifting cycles, mountain building events, basin development, faulting, folding, volcanism and plutonism. These occurrences took place from the Precambrian to Cenozoic and shaped the unique landscape observed today.

Precambrian Deformational and Accretionary History

During the Precambrian, the Laurentian craton grew by multiple accretionary events. Provinces that were accreted to the southern margin of Laurentia include the Yavapai province (1.8 to 1.7 Ga), Mazatzal province (1.7 to 1.6 Ga) and the Grenville province (1.3 to 0.9 Ga) (Figure 3.1) (Mako, 2014;

Bickford, 2000; Amato et al., 2007). The addition of these provinces onto the Laurentian craton created the basement material that underlies the southwestern United States and parts of the Trans-Pecos region.

Yavapai Province

The Yavapai province is a northeast-trending zone of juvenile arc crust that is exposed from Arizona to southern Colorado. It extends northeastward in the subsurface to the mid-continental region (Whitmyer and Karlstrom, 2007; Bowring and Karlstrom, 1990; Karlstrom and Humphreys, 1998). This province was welded to the Laurentia craton during the Yavapai Orogeny that occurred from 1.71 to 1.68 Ga (Whitmyer and Karlstrom, 2007). The rocks that characterize this province include primarily mafic metavolcanic rocks with a substantial amount of felsic and intermediate metavolcanic rocks (Whitmyer and Karlstrom, 2007). The Yavapai province arcs could have been created over a north-dipping subduction zone (Karlstrom and Humphreys, 1998).

The boundary between the Yavapai and Mazatzal provinces is characterized by a series of steeply dipping shear zones (Shaw and Karlstrom, 1999). There is a transition zone between these two provinces that is estimated to be approximately 190 miles wide (Shaw and Karlstrom, 1999). Alkali rhyolites and mature quartzites are common along this boundary and have been

interpreted to be fluvial and shallow marine deposits that were produced from the southern edge of the Yavapai province (Karlstrom and Humphreys, 1998).

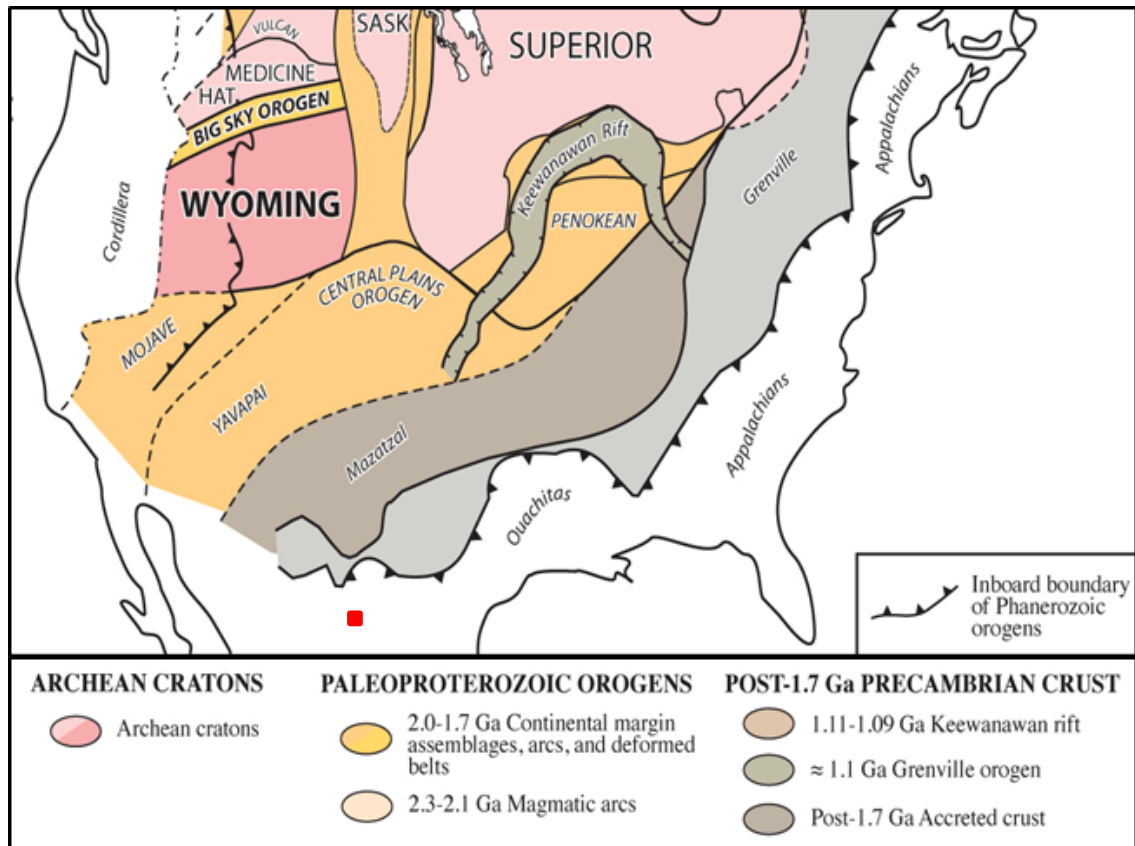


Figure 3.1 - Precambrian basement terranes of North America. Light orange represents the Yavapai province; dark gray represents the Mazatzal province; light gray represents the Grenville province (from Keck Geology Consortium, 2014). The red box is the approximate locations of BBNP.

Mazatzal Province

The Mazatzal province is thought to have been assembled off-shore from 1.70-1.60 Ga and then added to the Laurentia craton from 1.65 to 1.60 Ga, during the Mazatzal Orogeny (Whitmyer and Karlstrom, 2007). Whitmyer and Karlstrom (2007) proposed that the rocks of the province were created in a continental margin volcanic arc and back-arc system that was related to the supra-crustal succession found throughout the southwestern United States to the Canadian Maritime Provinces. The rocks associated with this province include 1.68 to 1.65 Ga volcanogenic greenstone complexes which generally include basalt and basaltic andesites, dacitic tuff and rhyolites (Whitmyer and Karlstrom, 2007; Karlstrom et al., 2004).

Grenville Orogeny

The next accretionary event was the Grenville Orogeny, which occurred from 1.3 to 0.9 Ga and represents a continent-to-continent collision that created the final assembly of Rodinia during the Proterozoic (Tollo et al., 2004; Whitmyer and Karlstrom, 2007). The Grenville domain is found in northeastern North America from the coast of Labrador to eastern Michigan, and southward through the Appalachians into northern Alabama. It continues in the subsurface to Texas where it crops out in the Llano Uplift and around Van Horn, Texas (Whitmyer and

Karlstrom, 2007). The beginning stage of this orogenic event was termed the Elzevirian Orogeny; this event sutured multiple cratonic blocks to the eastern margin of Laurentia from 1.3 to 1.2 Ga (Whitmeyer and Karlstrom, 2007). The Ottawa Orogeny followed this episode (1.09 – 0.98 Ga) and induced northwest thrusting and imbrication of terranes in southeast Canada (Moore and Thompson, 1980; Whitmeyer and Karlstrom, 2007).

In Texas, the Grenville Orogeny (Figure 3.2) was caused by arc-continent and continent-continent collisions (Mosher, 1998; Wilkerson et al., 1988). Precambrian outcrops in the Llano area present a glimpse of Grenville deformation. These outcrops have all been polydeformed and metamorphosed to amphibolite – granulite facies (Whitmeyer and Karlstrom, 2007). Precambrian rocks can also be observed in the Trans-Pecos region; these areas include the Franklin Mountains, Eagle Mountains, Pump Station Hills, Wylie Mountains, and near Van Horn (Brooker, 1985; Mosher, 1998). In the Van Horn area, the deformed and metamorphosed Carrizo Mountain Group was thrust northward over the Allamoore and Hazel sedimentary successions (Ewing, 1991; Reynolds, 1989; King and Flawn, 1953). The Carrizo Mountain Group rocks have been dated at 1.2 Ga old and were described by Brooker (1985) and Davidson (1980) as a complex mixture of metaigneous and metasedimentary rocks. The metamorphic grade of the Carrizo Mountain Group increases from greenschist facies in the north to amphibolite facies in the south (Henry and Price, 1985).

Within this group, there are at least two phases of tight, inclined, northwest vergent folds and a single phase of kink folds (Ewing, 1991; Fayon and Nielsen, 1988).

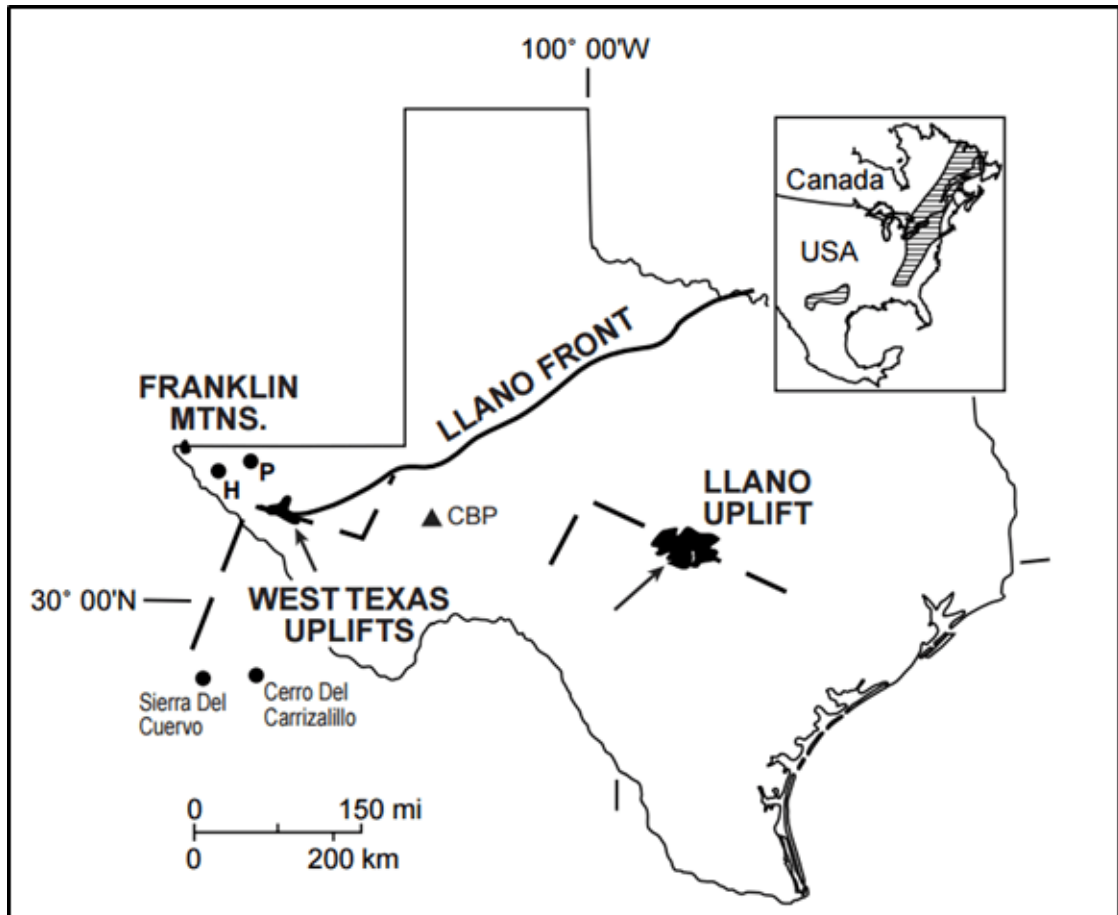


Figure 3.2 - Map showing areas where Precambrian rocks are exposed in Texas. Including the Llano Uplift, and west Texas uplifts found at the Hueco Mountains (H), Pump Station Hills (P) and the Franklin Mountains (from Mosher, 1998).

The Allamoore Formation is a sedimentary-volcanic rock succession and the Hazel Formation is a sequence of sandstones and conglomerates (Brooker, 1985). These formations have been folded and thrust creating dominantly east-trending folds; these were probably related to the northward movement of the Carrizo Mountain Group (Henry and Price, 1985).

The oldest tectonic event that is directly expressed in BBNP is the Marathon-Ouachita Orogeny, but it is possible that Proterozoic rifting (800-550 Ma) of Rodinia helped created a northwestward structural trend (Page et al., 2008). The rifting of Rodinia created northwest-striking continental transform faults that laterally offset the southern continental margin (Page et al., 2008; Thomas, 1991; Poole et al., 2005). This early faulting could have influenced the deformation caused by the Ouachita-Marathon Orogeny in the Trans-Pecos area (Page et al., 2008; Poole et al., 2005). These transform faults are sub-parallel with the Texas Lineament, which is described by Muehlberger (1980) as a wrench faulted zone that divides more stable crust on the north from less stable crust to the south.

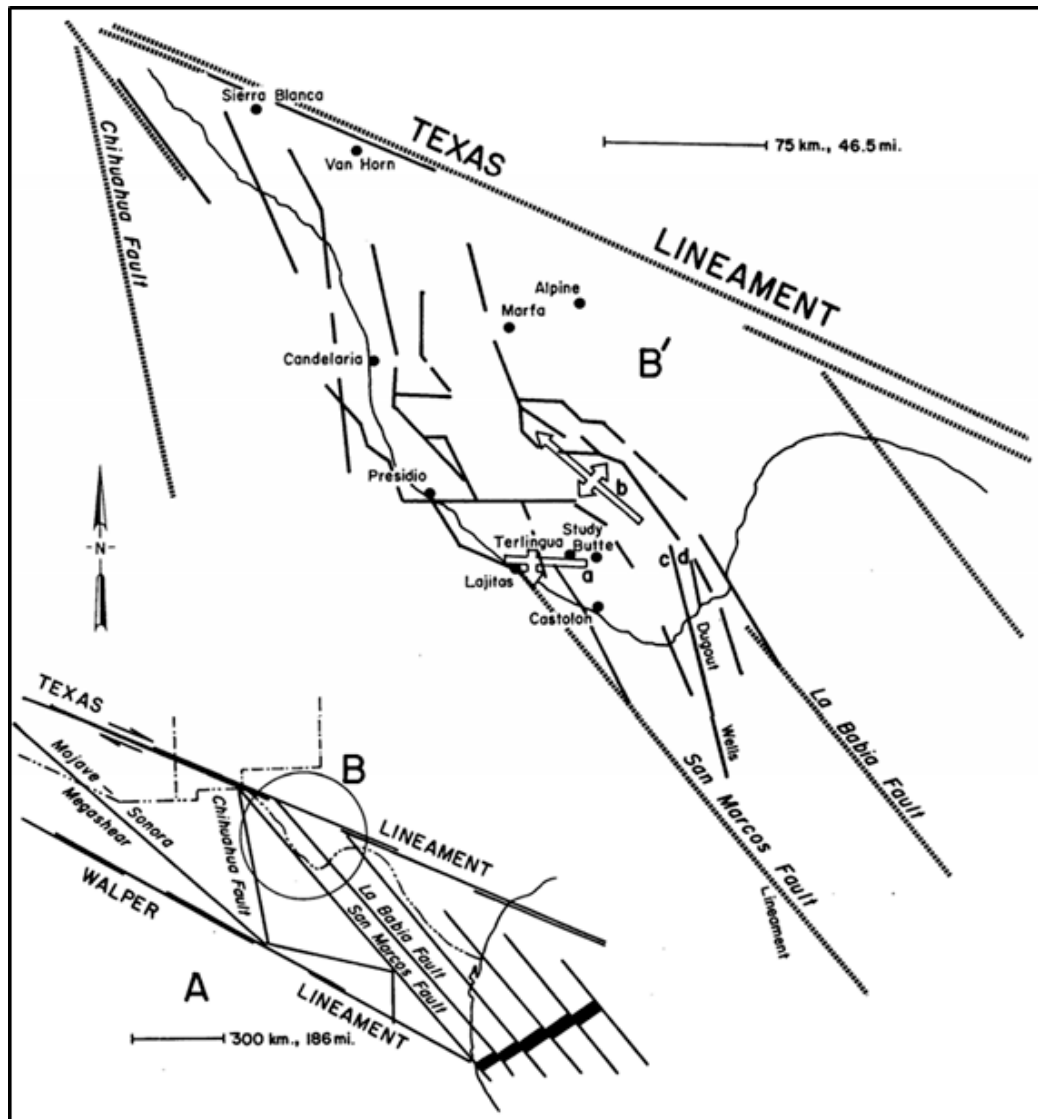


Figure 3.3 - The Texas Lineament in Trans-Pecos Texas, with faults that are obliquely related (from Stevens et al., 1986).

Texas Lineament

The Texas Lineament (Figure 3.3) is a northwest-trending zone, that is approximately 50 mile wide and can be traced from Presidio, Texas southward into BBNP (Page et al., 2008; Muehlberger, 1980). Regionally, it extends west-northwest from the Gulf of Mexico to an area just southwest of Las Vegas, Nevada (Hildebrand, 2015). The faulting of the Texas Lineament is deeply buried and could have formed during Proterozoic rifting, around 1.5 to 1.0 Ga (Page et al., 2008; Muehlberger, 1980). This rifting event could have broken off a piece of the western and southern North American craton (Muehlberger, 1980; Sears and Price, 1978). The Texas Lineament could be a Precambrian analog of modern-day oceanic fracture zones (Hildebrand, 2015). In Stockton Pass, Arizona there is a minimum of 4 miles of left-lateral displacement observed along the lineament (Dickerson, 1980; Swan, 1975). This feature could be related to the sinistral, parallel trending Lewis and Clark transverse zone, which is located 800 miles north (Hildebrand, 2015). The Texas Lineament was reactivated during later tectonic episodes, including the Ouachita-Marathon Orogeny, Laramide Orogeny and the Basin and Range faulting (Page et al., 2008; Cobb and Poth, 1980).

Ouachita – Marathon Orogeny

The Ouachita–Marathon Orogeny created a belt of deformed Paleozoic rocks along the southern edge of the North American craton that is approximately 2,000 miles long (Figure 3.4) (Poole, 2005). This zone extends from Mississippi through Arkansas and Oklahoma, southwestward through Texas and continues westward through Chihuahua and Sonora, Mexico (Poole, 2005; Flawn, 1959). Along most of its length in the United States, the deformed rocks are in the subsurface, but they crop out in the Ouachita Mountains in Arkansas and Oklahoma and in the Marathon and Solitario uplifts in West Texas.

The rifting of the supercontinent Rodinia, which ended in the early Cambrian, influenced the structural trend for this orogeny (Arbenz, 1989). The onset of this event began in the Middle Mississippian when Africa collided with Laurentia's eastern margin (Oldani, 1986; Thomas, 1991). This collision was followed by the diachronous convergence between South America and the southern margin of Laurentia during the Pennsylvanian (Oldani, 1986; Hickman et al., 2008; Thomas, 1991; Muehlberger and Dickerson, 1989). This series of events eventually led to the assembly of Pangaea and created the Appalachian and Ouachita mountains (Oldani, 1986). This report focuses on the southern convergent margin.

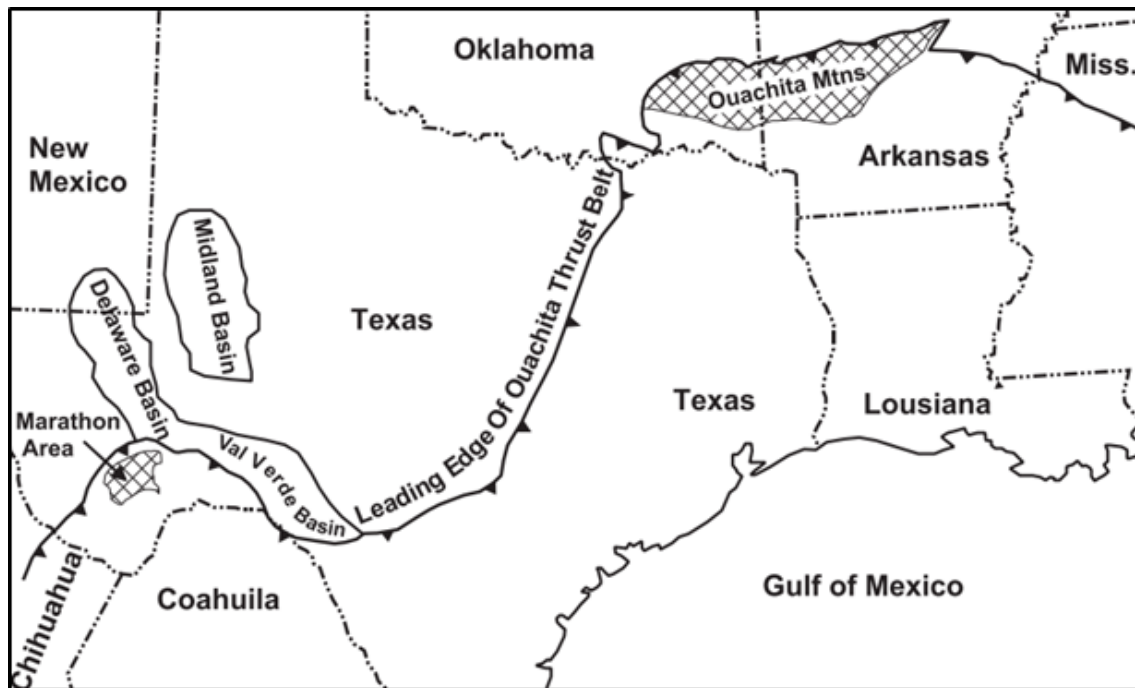


Figure 3.4 - Map showing the location of the Ouachita-Marathon thrust belt in the southern United States, and where the thrust belt outcrops in the Marathon area and the Ouachita Mountains (Oklahoma and Arkansas) (from Hickman et al., 2008).

Folding and faulting created by the Ouachita-Marathon Orogeny is exposed near BBNP in both the Marathon and Solitario uplifts (Figure 3.5, Figure 3.6) (Hickman et al., 2008; Urbanczyk, Rohr and White, 2001). The Marathon Uplift (Figure 3.5) contains a strongly-deformed, allochthonous wedge of Cambrian to Pennsylvanian stratum that was thrust northwestward and placed over Pennsylvanian fore-deep sediments (Hickman et al., 2008). The trend of folds and faults in the Marathon and Solitario regions is dominantly northeast-southwest and thrusting was most likely from southeast to northwest (King, 1937;

Henry and Price, 1985). The thrusting that is present within these areas is complex due to the abundance of thick shale sequences that acted as detachment levels and accommodated compression (Ewing, 1991). Paleozoic rocks in the Solitario area display thrust faulting on both large and small scale (Corry et al., 1990). Folding types include S-folding, chevron folds, isoclinal folds, boudinage structures and anticlinal-synclinal folding, all of which are trending northeastward (Corry et al., 1990).

In the north part of BBNP, the southernmost vestiges of the Marathon Orogeny can be observed at Persimmon Gap. At this location, two phases of thrusting can be observed (Hazzard et al., 1958). The Marathon Orogeny thrust the Paleozoic Maravillas and Tesnus formations from southeast to northwest and then those rocks were overlain by Cretaceous rocks (Hazzard et al., 1958; White et al., 2002). The Paleozoic and Cretaceous units were later thrust from northeast to southwest by the Late Cretaceous Laramide Orogeny (Hazzard et al., 1958).

Mesozoic Rifting

From the Late Triassic to Late Cretaceous, rifting between North and South America created the Gulf of Mexico (Muehlberger, 1980; Muehlberger and Dickerson, 1989; Page et al., 2008). During this time BBNP, was located on

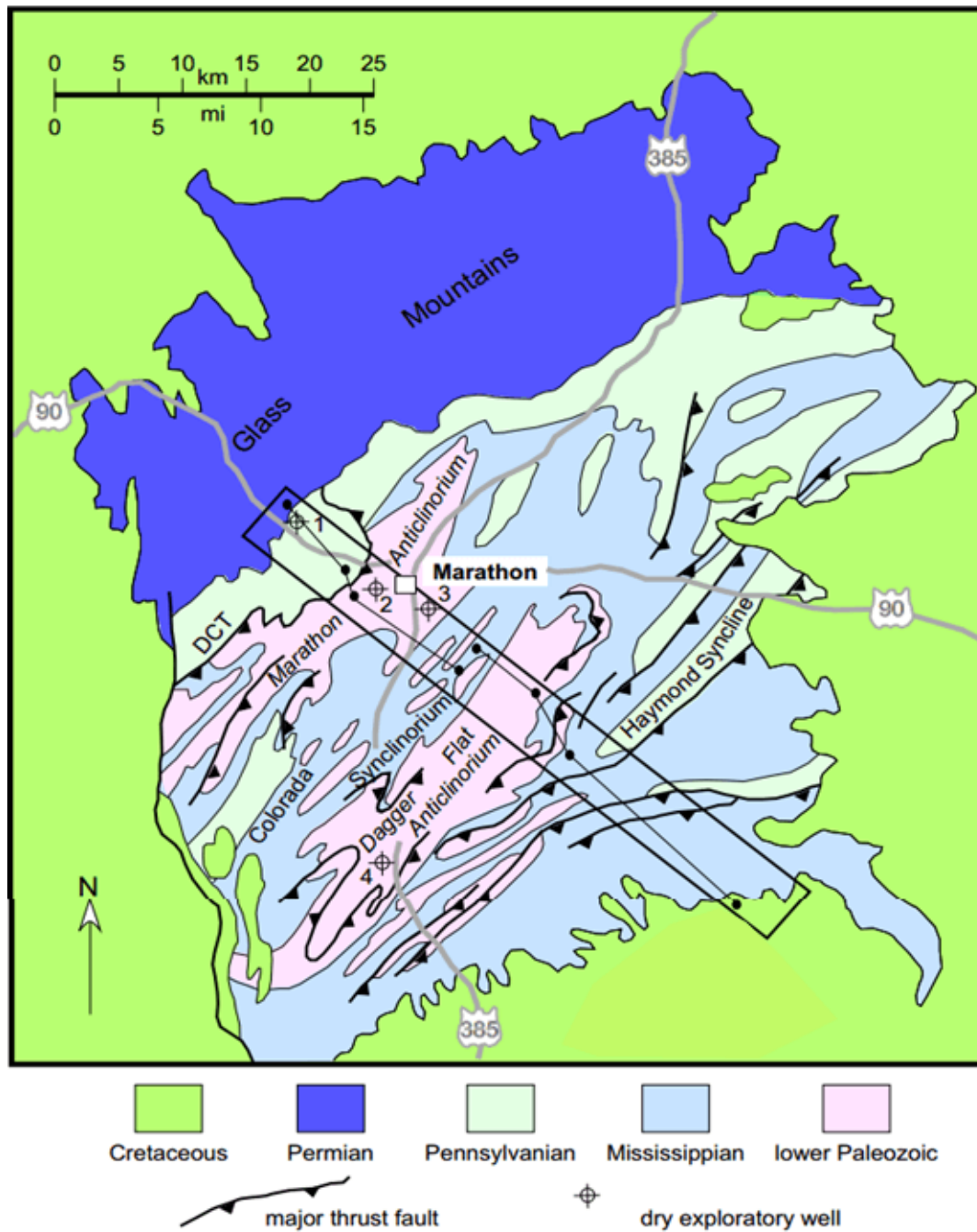


Figure 3.5 – Generalized geologic map of the Marathon Uplift and the northeast trending thrust faults that are associated with the Ouachita-Marathon Orogeny (from Hickman et al., 2009).

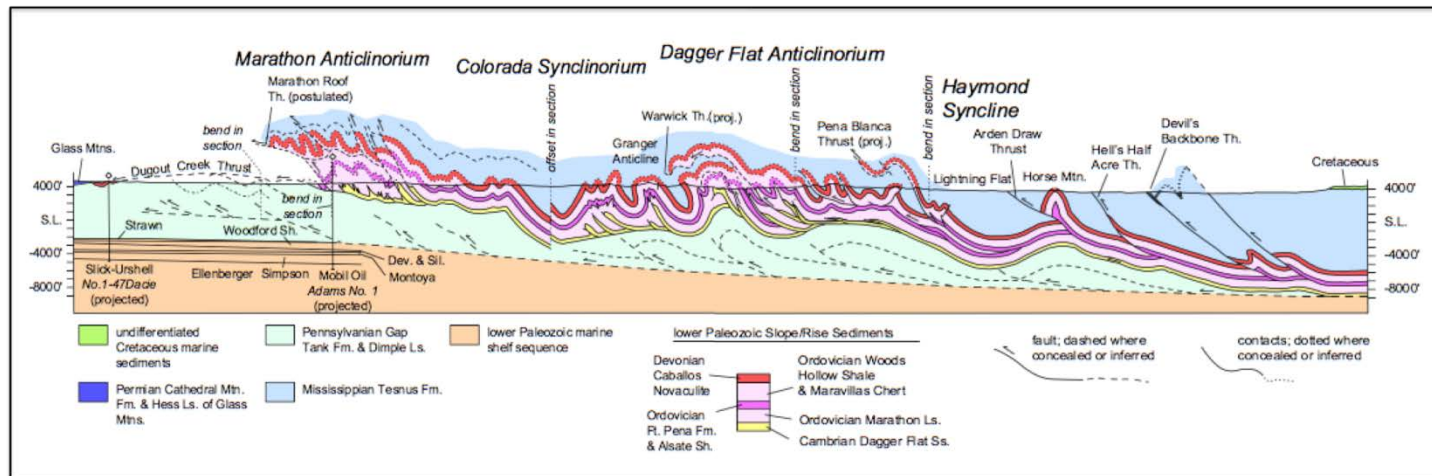


Figure 3.6 - Cross-section of the Marathon Uplift (from Hickman et al., 2009)

the Diablo Platform (Figure 3.7), which was a structurally positive region where multiple north-dipping, west-northwest trending monoclines were formed due to transtension (Henry, 1998; Goldhammer and Johnson, 1999, Page et al., 2008; Playton and Kerans, 2006). On this platform, Upper and Lower Cretaceous limestone and shales were deposited, including the Glen Rose Limestone, Del Carmen Limestone, Sue Peaks Formation, Santa Elena Limestone, Del Rio Clay, Buda Limestone and the Boquillas Formation (Page et al., 2008; Henry, 1998).

During this rifting, a deep ocean basin was formed just southwest of the Diablo Platform called the Chihuahua Trough (Figure 3.7) (Page et al., 2008). The Chihuahua Trough was located in present-day Texas, New Mexico and northeastern Chihuahua, Mexico (Henry and Price, 1985; Muehlberger, 1980; Muehlberger and Dickerson, 1989; Haenggi, 2007). Haenggi (2007) has suggested that the faults responsible for the opening of this trough have been intermittently active from the Middle Proterozoic to present day. Upper and Lower Cretaceous rock units are much thicker in the Chihuahua Trough than those found on the Diablo Platform (Page et al., 2008). The opening of the Gulf of Mexico may be related to the same extensional stresses that created the Chihuahua Trough (Muehlberger, 1980; Muehlberger and Dickerson, 1989; Page, et al., 2008).

There are no Triassic and Jurassic rocks exposed in the Trans-Pecos area; it is possible that during this time the region was sub-aerially exposed and

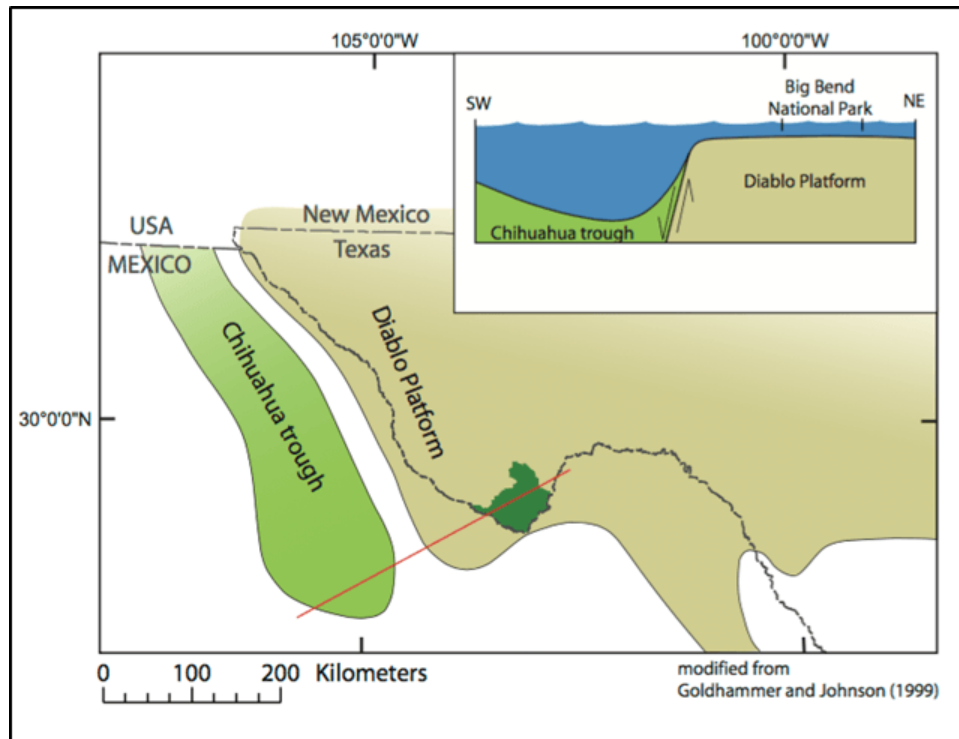


Figure 3.7- Map showing the locations of the Chihuahua trough and the Diablo Platform, both features that were created during the rifting event in the Mesozoic (from Page et al., 2008).

experienced no active deposition or tectonism (McCormick, 1996; Urbanczyk et al., 2001).

Laramide Orogeny

The Laramide Orogeny created an extensive zone of deformation during the Late Cretaceous to Early Paleogene that extends from Canada to Mexico

(Page et al., 2008; Muehlberger and Dickerson, 1989). The exact driving mechanism that produced the Laramide Orogeny is still debated within the geologic community. Proposed mechanisms (Figure 3.8) include retroarc thrusting, “orogenic float” tectonics, flat-slab subduction and Cordilleran transpressional collision (English and Johnston, 2004).

Effects related to flat-slab subduction of the Farallon plate under the western margin of the North American plate is the most accepted theory (Urbanczyk et al., 2001; Page et al., 2008; Dickerson, 1981; Henry and Price, 1985). This subduction generated east to northeast compressive stress, which created high-angle reverse faults, strike-slip faults, monoclines, anticlines and synclines in the Trans-Pecos region (Ewing, 1991; Urbanczyk et al., 2001; Henry and Price, 1985; Muehlberger, 1980).

Basement-involved (thick-skinned) Laramide compressional tectonics resulted in high-angle reverse faults in the Franklin Mountains near El Paso and the Santiago Mountains in the Big Bend area (Ewing, 1991; Muehlberger, 1980). Strike-slip faulting patterns of the Laramide Orogeny have a similar trend to those created by left-lateral transpression of the Texas Lineament (Ewing, 1991; Muehlberger, 1980). The Laramide Orogeny created major structural features in BBNP (Figure 3.9) including the Mesa de Anguila, an uplifted monocline on the western side of the park, and the Sierra del Camen-Santiago Mountains, part of which is an uplifted and thrust faulted monocline found on the east side of the

park (Page et al., 2008; Muehlberger, 1980). The Tornillo Basin developed between these two uplifted structures.

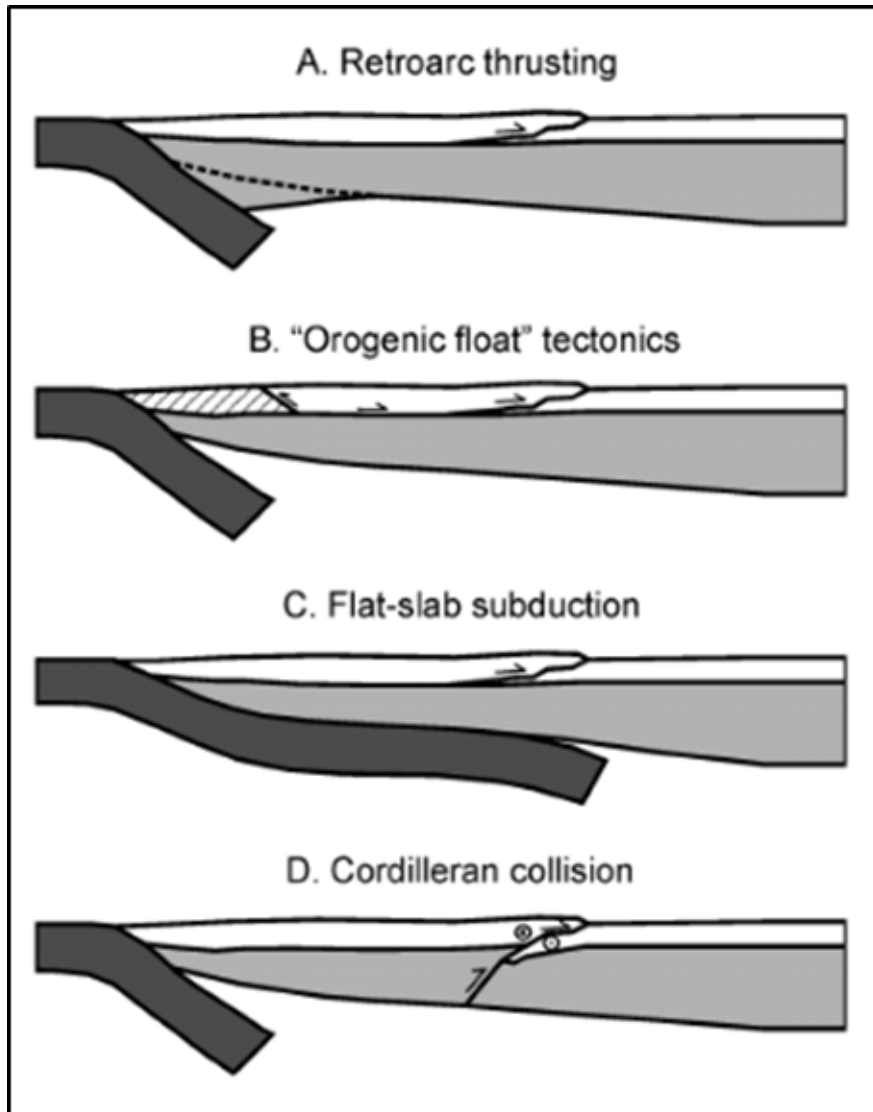


Figure 3.8 - Schematic diagram illustrating the different mechanisms that could have produced the inland fold and thrust belts of the Laramide Orogeny (from English and Johnston, 2004). Flat-slab subduction (C) is considered to be the most likely cause of Laramide deformation.

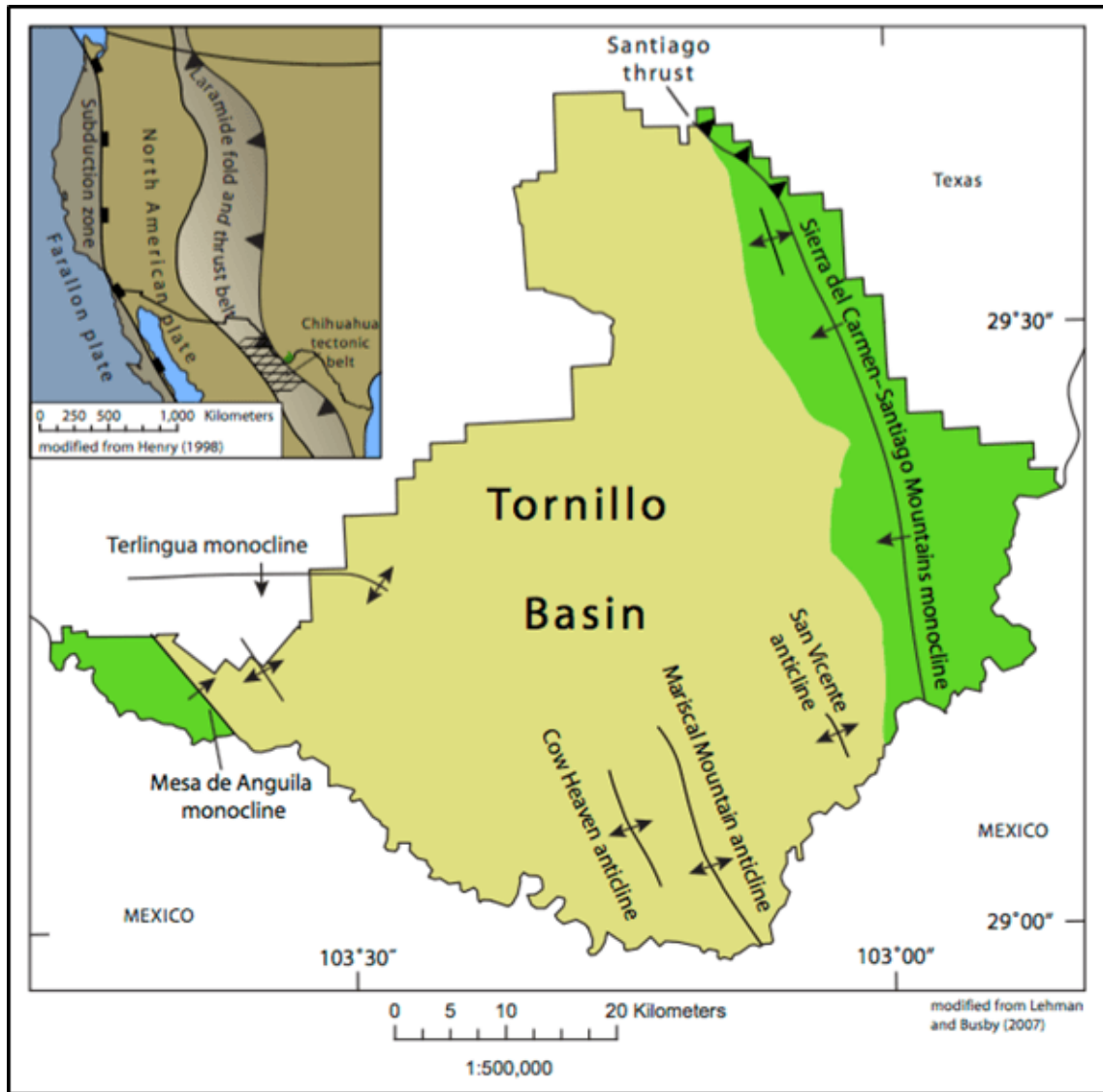


Figure 3.9 - Map of BBNP displaying Laramide features. The most prominent Laramide features include the Mesa de Anguila monocline, Terlingua monocline, Cow Heaven anticline, Mariscal Mountain anticline, San Vicente anticline, Santiago thrust and the Sierra del Carmen Mountains monocline. The inset map shows the extent of the Laramide fold and thrust belt (from Page et al., 2008).

The Santiago-Sierra del Carmen Mountains are a range of long, straight uplifted fault blocks that trend northwest in eastern BBNP (Cobb and Poth, 1980; King, 1937). The study area lies on the western edge of the Sierra del Carmen Mountains. The Sierra del Carmen Mountains are part of a west-dipping uplift that is broken by numerous Basin and Range high-angle normal faults that generally trend northwest (Cobb and Poth, 1980; Maxwell et al., 1967). This uplift could be part of the north-south trending basement ridge uplift that exhumed the Marathon region approximately 20 miles to the north (Dickerson, 1980).

The initial stage of Laramide deformation in this area was characterized by the development of en echelon folds (Cobb and Poth, 1980). As compression continued, northwest trending thrust faults developed with left-lateral strike-slip components (Moustafa, 1988).

Other Laramide features found in and around the Trans-Pecos region include the Terlingua-Fresno Monocline, Mariscal Mountain, the Chihuahua Tectonic Belt and Persimmon Gap (Muehlberger and Dickerson, 1989; Urbanczyk et al., 2001; Page et al., 2008).

Stratigraphic evidence for the Laramide Orogeny is indicated by erosional unconformities due to uplift and a resultant influx of coarse-grained sediment (Muehlberger and Dickerson, 1989).

Paleogene Volcanism and Plutonism

BBNP experienced extensive volcanism from mid-Eocene to late Oligocene (Page et al., 2008). It is suggested that this magmatic activity was produced by shallow subduction of the Farallon plate along the western margin of North America (Page et al., 2008; Maxwell et al., 1967). As this subducting plate descended, the increase in temperature beneath the crust of western Laurentia produced magma that ascended into the overlying continental crust to either erupt at the surface or be injected at depth (Page et al., 2008). This event can be traced from Mexico to Canada (Page et al., 2008).

The Trans-Pecos region displays numerous outcrops of volcanic and igneous material. This area has been termed the Trans-Pecos Magmatic Province (TPMP) (Figure 3.10) (White et al., 2006). Volcanic features of the TPMP include the Chisos Mountains, Davis Mountains Volcanic field, Chinati Mountains, Leyva Mountains and the Paisano Volcano (White, 2006; Henry and McDowell, 1989).

During the Early Oligocene, BBNP was not only experiencing widespread volcanism, but plutons were also being emplaced in multiple regions (Page et al., 2008). Due to uplift and erosion, some of these large igneous bodies can now be observed on the surface (Figure 3.11). In BBNP some plutons have created positive topographic expressions; these plutons include the Rosillos Mountains,

McKinney Hills and Grapevine Hills (Turner et al., 2011). There are more intrusions within BBNP, but this study will focus only on features near or in the study area. These plutons were all emplaced from approximately 32.1 to 31.9 Ma

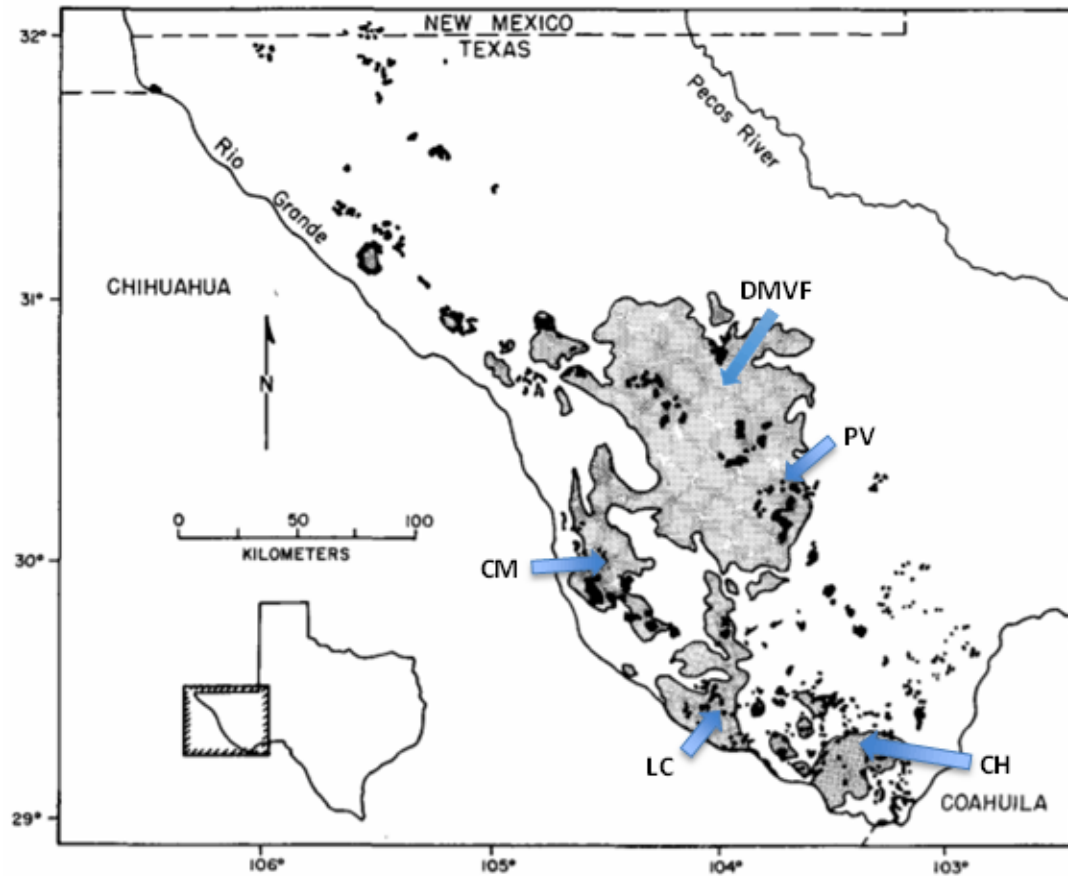


Figure 3.10 - Distribution of volcanic and plutonic rocks that make up the Trans-Pecos Magmatic Province; plutonic rocks are shown in black; lavas and pyroclastic material are shown in gray. Volcanic sub-provinces are labeled, including (CH) Chisos Mountains, (LC) Leyva Canyon Volcano, (CM) Chinati Mountain, (PV) Paisano Volcano, and the (DMVF) Davis Mountain volcanic field (modified from Barker, 1977).

(Turner et al., 2011). The rocks associated with these intrusions will be discussed below. This intrusive activity is important for this project because the mapping area includes a portion of the McKinney Hills laccolith.

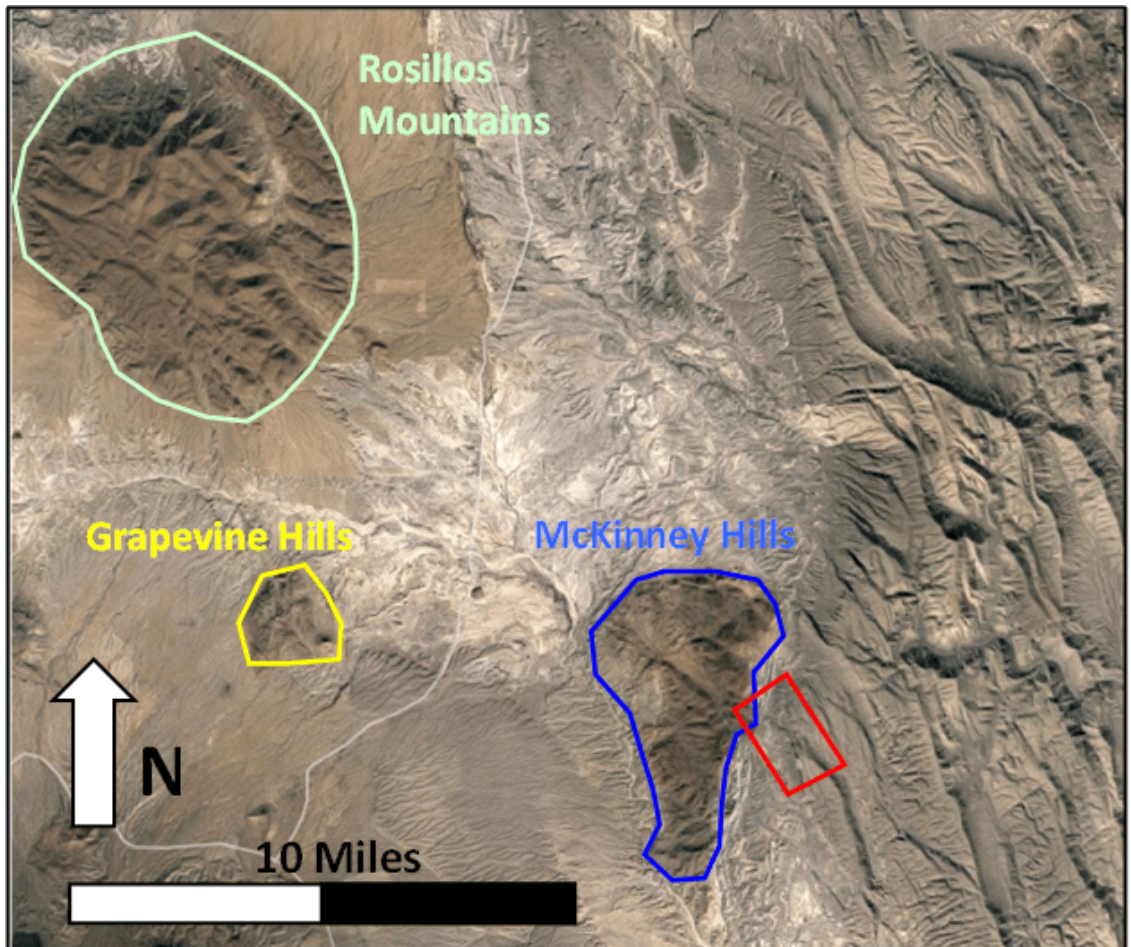


Figure 3.11 - Satellite image of eastern BBNP with significant intrusive features labeled including McKinney Hills, Grapevine Hills and the Rosillos Mountains (modified from Google Earth, 2017). Note the location of the study area near McKinney Hills laccolith.

McKinney Hills Fayalite Syenite

The McKinney Hills laccolith is an elongated north-trending intrusion that covers an area of approximately 11 square miles. This laccolith was intruded into the Upper Boquillas and Lower Pen formations (Martin, 2007). Part of this igneous complex is included in the mapping area. It has been described as a blue to bluish-green, fine-grained syenite that contains euhedral to subhedral phenocrysts of alkali feldspar, augite, fayalite and quartz (Turner et al., 2011). The thickness of this intrusion ranges from 650 to 1,300 feet thick, and it has been age dated to 32.2 ± 0.2 Ma (Martin, 2007; Turner et al., 2011).

Rosillos Mountains Syenite

The Rosillos Mountains represent the weathered interior of a large (7 miles wide) circular laccolith that is located 12 miles northwest of the study area. This pluton was intruded into the lower Aguja Formation and is around 2,000 feet thick (Anderson, 2007). It is dominantly composed of blue to green, fayalite-bearing, syenite that contains fine- to medium-grained, euhedral to subhedral phenocrysts (Anderson, 2007; Turner et al., 2011). This intrusion has been age dated to approximately 32.1 ± 0.2 Ma (Turner et al., 2011).

Grapevine Hills Fayalite Syenite

Grapevine Hills is a smaller (2 mile wide), near-circular laccolith that is located 9 miles due west of the study area. This laccolith is composed of gray, fine- to medium-grained syenite that contains euhedral phenocrysts of alkali feldspar, quartz, fayalite and pyroxenes (Turner et al., 2011). The thickness of this intrusion is approximately 650 feet and has been age dated to 31.9 +/- 0.2 Ma (Shields and Plymate, 2012; Turner et al., 2011).

Basin and Range

The final tectonic episode to affect BBNP was widespread high-angle normal faulting produced during Basin and Range extension, which occurred from the late Oligocene to the late Pliocene (Page et al., 2008). Basin and Range tectonism extends from the Delaware Basin of West Texas across the southwestern United States into California (Figure 3.12) (Horak, 1985). This event may have been the result of a change in the stress orientation off the west coast of North America coinciding with a change from a convergent to a transform boundary during the mid-Cenozoic (Oldani, 1986). The onset of extensional deformation in the Trans-Pecos region was oriented northeastward, similar to the rest of the Basin and Range province (Ewing, 1991; Zoback, 1981;

Henry, 1983). Approximately 10 Ma, the extensional direction shifted to a more northwestern orientation (Ewing, 1991). This rifting episode produced lithosphere stretching, which formed a series of uplifted ranges and down-dropped basins (Page et al., 2008; Ewing, 1991).

BBNP is located within the Rio Grande Rift, which is a sub-province of the Basin and Range. The Rio Grande Rift can be traced from the most southern point of BBNP northward up to the San Luis Valley in southern Colorado (Dickerson and Muehlberger, 1994; Baker, 1934). The Rio Grande rift affected BBNP around 23 Ma during the early Miocene (Dickerson and Muehlberger, 1994).

North to northwest striking, high-angle normal faults found in BBNP can be attributed to Basin and Range extension (Turner et al., 2011). These faults were formed perpendicular to the east to east-northeast extensional direction (Cobb and Poth, 1980). This extensive normal faulting interacted with previous structural trends created during the Ouachita-Marathon and Laramide orogenies (Page et al., 2008). Of particular importance for this study, is the Sierra del Carmen fault zone in BBNP. This fault zone is made up of abundant northwest striking normal faults and will be described in more detail later in this paper.

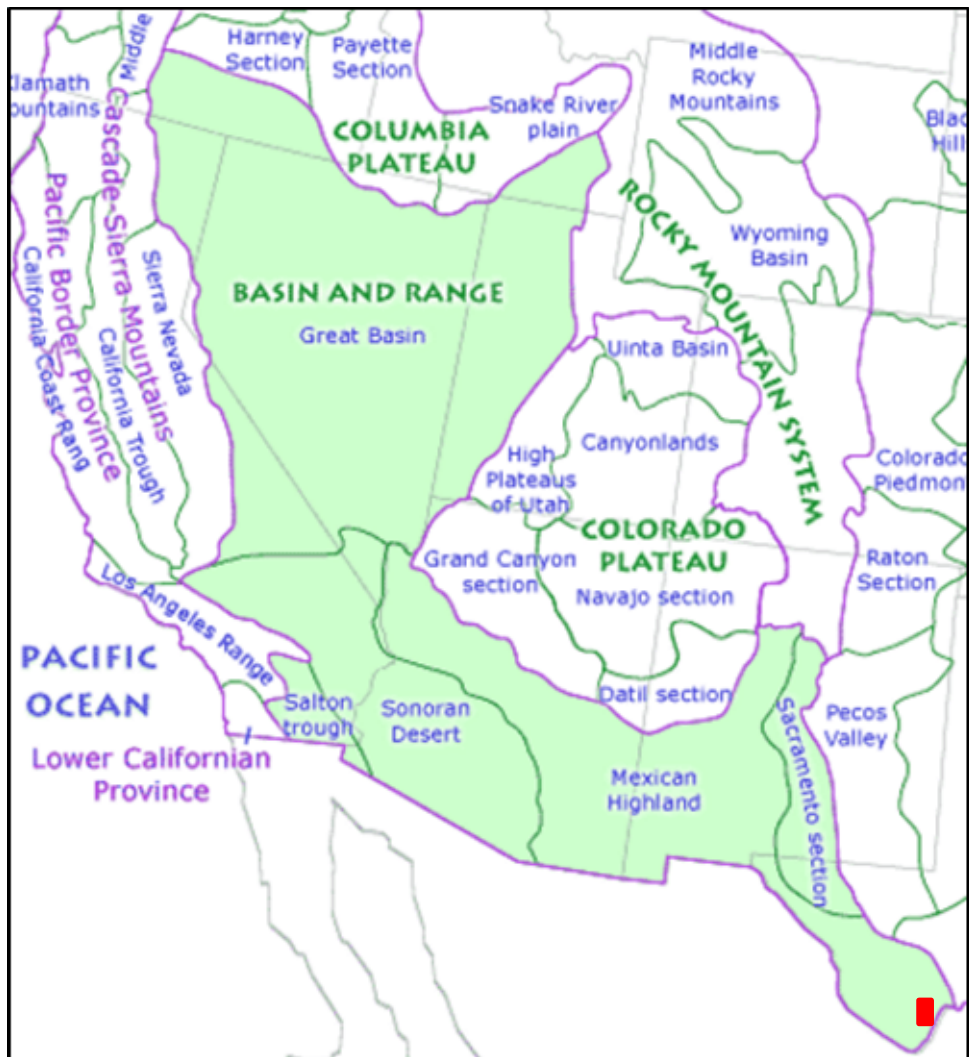


Figure 3.12- Map showing the extent of the Basin and Range Province in the southwestern United States. Approximate location of the study area highlighted in red (from USGS, 2014).

CHAPTER IV

FIELD RESULTS

Field Description of Map Units

This section presents detailed rock descriptions of each rock unit in the study area, based on observations made during field mapping. The majority of these units were Upper and Lower Cretaceous formations, including the Santa Elena Limestone, Del Rio Clay, Buda Formation, Boquillas Formation and the Pen Formation. There were also two types of igneous intrusions observed, syenite in the McKinney Hills laccolith and mafic sills.

Pictures and descriptions of fossils found during this study are in Appendix A.

Santa Elena Limestone

This formation is particularly important because it is one of the main map units found in the study area. The prominent cliff face, Alto Relex (Figure 1.3)

is composed of approximately 800 feet of resistant Santa Elena Limestone. Throughout the study area, the Santa Elena Limestone is a massive bedded (5 – 50 feet thick), light gray, crystalline limestone that weathers dark-gray to slightly reddish, light brown. Bedding plane surfaces often display karstic features, such as rill and karrens. Rudist bioherms that are regionally widespread in this formation were only found at select locations in the study area (Appendix A). *Trochosmilia* fossils were found near the upper contact in one location (S122) (Appendix A). In the study area the lower contact is not observed, and the upper contact is usually covered by outcrops of the overlying Del Rio Clay and Buda Limestone.

Del Rio Clay

The Del Rio Clay crops out in the interior of the study area (Figure 4.1) and is dominantly a light-gray clay unit that also contains minor sandstone and limestone beds. Clay beds are light gray to red ranging from one to ten feet thick and typically outcrop as friable, crumbly clay. Sandstone beds range from two to eight inches thick and are typically light-brown to dark-red; these beds weather to a light-brown to dark-orange color. Sand grains are well rounded, well-sorted and very fine-grained. Bioturbation including *Thalassinoides* and *Spongeliomorpha* is commonly found in these sandstone beds (Appendix A).

Limestone beds in the Del Rio are found towards the upper contact and look similar to those of the Santa Elena limestone; however, these beds only range from two to five feet thick. This limestone is a light-gray wackestone that weathers to light and dark shades of brown. The Del Rio Clay outcrops as a steep slope that locally contains copious amounts of fossils including *Turritellas*, *Holaster simplex*, *Tylostoma tumidum*, *Mariella (Wintonia) brazoensis* and *Paracymatoceras hilli* (Appendix A). The upper contact is marked by a one to two-foot packstone layer that contains abundant bivalves (Appendix A). This formation ranged from 75 to 110 feet thick in the study area.



Figure 4.1 - A typical outcrop of the Del Rio Clay (Kdr) in the study area (S80).

Buda Limestone

The Buda Limestone (Figure 2.5) in the study area is a cliff-forming unit that is usually found on the top of cuestas. In some locations, the Buda was so extremely weathered that most of the outcrop was composed of large piles of float. In less weathered outcrops, it is a massive-bedded, light-gray to white, crystalline limestone that weathers to dark-gray. This formation is heavily fractured, displays iron staining and lacks significant fossils. The thickness of this formation in the study area ranges from 40 to 60 feet. The Buda shares a sharp overlying contact with the Boquillas Formation.

Boquillas Formation

The Boquillas Formation (Figure 4.2) was found in the north and southeast portions of the study area. This formation is commonly separated into two members, the Ernst and San Vicente. The index fossil, *Allocrioceras hazzardi* (Appendix A) that marks the contact between these two members was not found in the study area. Due to the lack of this stratigraphic indicator the Ernst and San Vicente members were mapped as a single unit. Overall, this formation is composed of light-tan to gray mudstones and wackestones separated by alternating light-gray, friable shale (Figure 4.2). Limestone beds range from two inches to two feet thick and commonly display laminations. Shale layers range

from one to four feet thick and in some localities two to four foot layers of black to dark gray shale are present. These beds weather to a light-tan color and have a slight hydrocarbon odor when fractured. Some beds display undulations (Figure 4.2) that generally have a wavelength of five to ten feet. Dark red to orange, two to four-inch thick ash beds can be found in locations S284 and S285 (Appendix C). Due to faulting, a full stratigraphic section of the Boquillas Formation is not exposed in the study area but this unit does form cuestras that can range from 200 to 400 feet tall. A large ten inch mold of an ammonite was also found in this formation at location S292 (Appendix A; Appendix C). The Boquillas Formation shares a gradational contact with the overlying Pen Formation.



Figure 4.2 - Alternating limestone and shales of the Boquillas Formation (Kbo). Note the undulations in this outcrop (S39).

Pen Formation

The Pen Formation (Figure 2.7) is exposed in the northwestern edge of the study area in direct contact with the McKinney Hills laccolith. The lower 50 feet of this formation contains no distinct bedding and is a light-gray to white, clay unit that weathers into large, spherical mounds. The upper section of this unit contains light gray, clay beds that weather to light yellow. This formation is approximately 150 feet thick and no fossils were identified.



Figure 4.3 – Looking northwest from location S185, you can observe the large, spherical maroon boulders of McKinney Hills syenite.

McKinney Hills Laccolith

Intrusive igneous rocks of the McKinney Hills laccolith are found in the northwestern portion of the study area. This rock unit is a felsic, phaneritic, alkali-feldspar syenite; fresh surfaces are whitish but weather dark red to maroon. Phenocrysts ranged from 0.04 to 0.08 inches and are dominantly euhedral to subhedral crystals of alkali feldspar, hornblende and quartz. This unit typically weathers into one to three foot spherical boulders (Figure 4.3).

Sills

Igneous sills are found in the northern portion of the study area. The thickness of these intrusions ranges from three to 15 feet; they are black, mafic and phaneritic. Specific minerals were hard to distinguish in hand samples but it is probably composed of amphibole and Ca-plagioclase. These sills are commonly heavily fractured and display spherical weathering (Figure 4.4). They are found in the Boquillas Formation and have sharp upper and lower contacts. In some areas, chill margins can be observed. In the chill margin, crystal sizes vary from 0.04 inches near the contact to 0.1 inches towards the sill's interior.



Figure 4.4 - Ten foot sill intruding into the Boquillas Formation at location S266. Note the heavily fractured areas and spherical weathering.

Quaternary Alluvium

Consolidated and unconsolidated alluviums are typically found in topographic lows in the study area. Most of this material is located in or along dry creek beds and composed of poorly-bedded gravels, sands and silts. There are abundant subangular to subrounded, cobble to small boulder sized clasts. In some locations, where the alluvium was consolidated (Figure 4.5), it crops out as a five to ten-foot vertical ridge. In these ridges, different flow regimes are apparent in the bedding. Bedding ranges from three inches to one foot thick and is near horizontal.



Figure 4.5 - Consolidated Quaternary alluvium found at location S5. Bedding shows evidence of fluctuating stream energy.

Structures

The main objectives of this thesis study were to map the extent of the different geologic units, delineate structures such as faults and folds, (Figure 4.6) and derive a structural evolutionary model for the study area. To complete this task, geologic structures were thoroughly investigated. These structures include thrust faults, normal faults, strike-slip faults and sills, along with outcrop and map scale folds. A total of 397 measurements were obtained during this study: 113 strike and dip attitudes on faults planes; 77 plunge and bearing attitudes on slickensides; 12 strike and dip measurements on fold axial planes; 12 plunge and bearing attitudes on fold hinge lines; and 183 strike and dip readings on bedding planes. All of these measurements and their corresponding locations are listed in table form in Appendix B.

Orientation of Bedding Planes

Numerous strike and dips were taken on bedding planes (Figure 4.7) throughout the field study. Taking multiple measurements helped to identify large-scale structural features. Two regions were identified (R-1 and R-2) in the study area that had dissimilar bedding plane orientations. In each of these regions, bedding is homoclinal but is dipping in different directions. In region R-1,

bedding is dominantly dipping to the SW or NW. This dip direction is commonly encountered throughout the Sierra del Carmen Mountain range. The bedding in R-2 is consistently dipping to the SE. The average strike and dip of bedding planes in region R-1 is N19°W, 25°SW, and in region R-2 is N60°E, 25°SE (Figure 4.8).

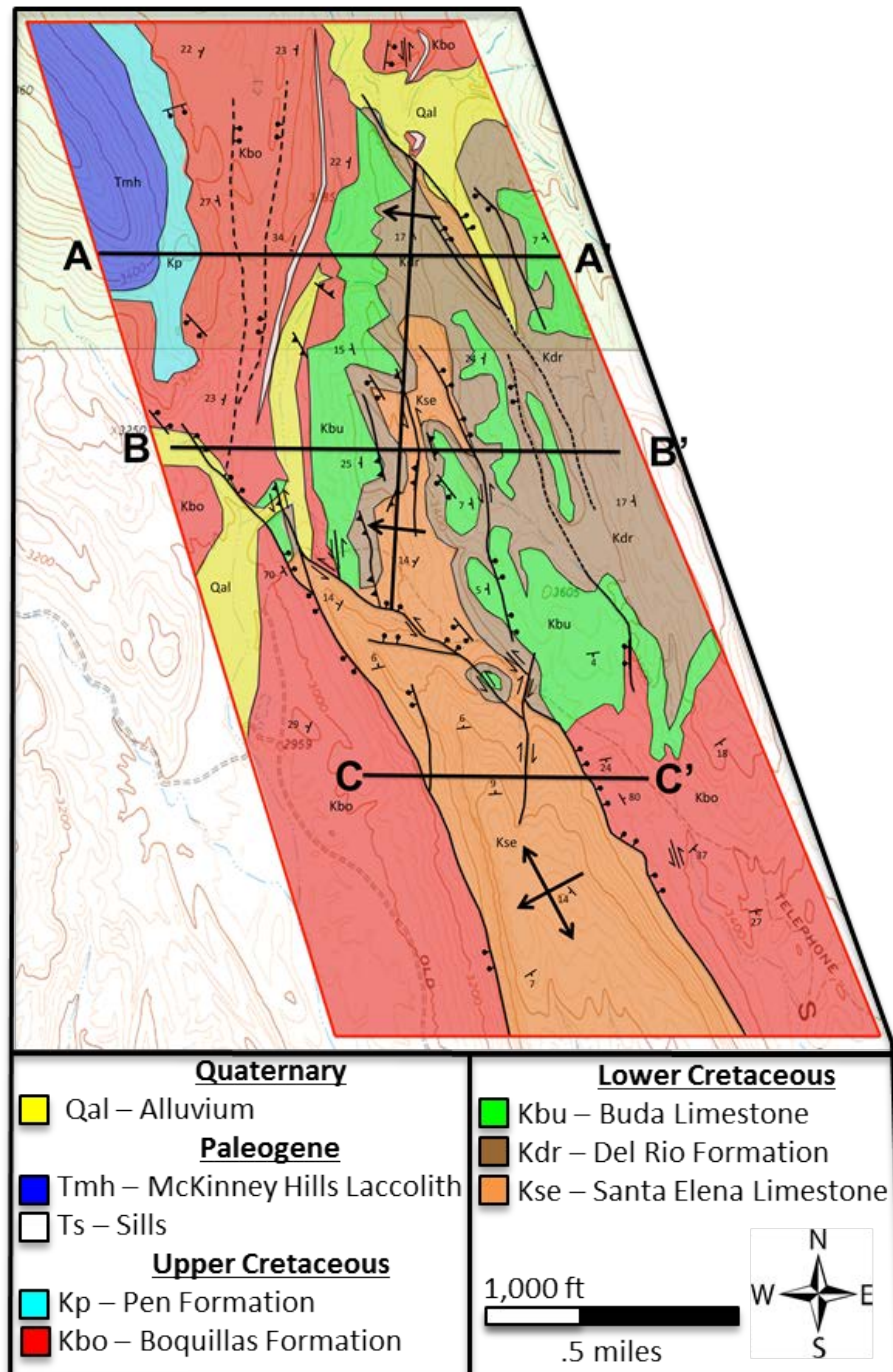


Figure 4.6 - Geologic map created during the study (Enlarged in Plate 1). This map has similarities to previous regional maps, but shows more detail, particularly in the distribution of outcrops and the location and type of faults.

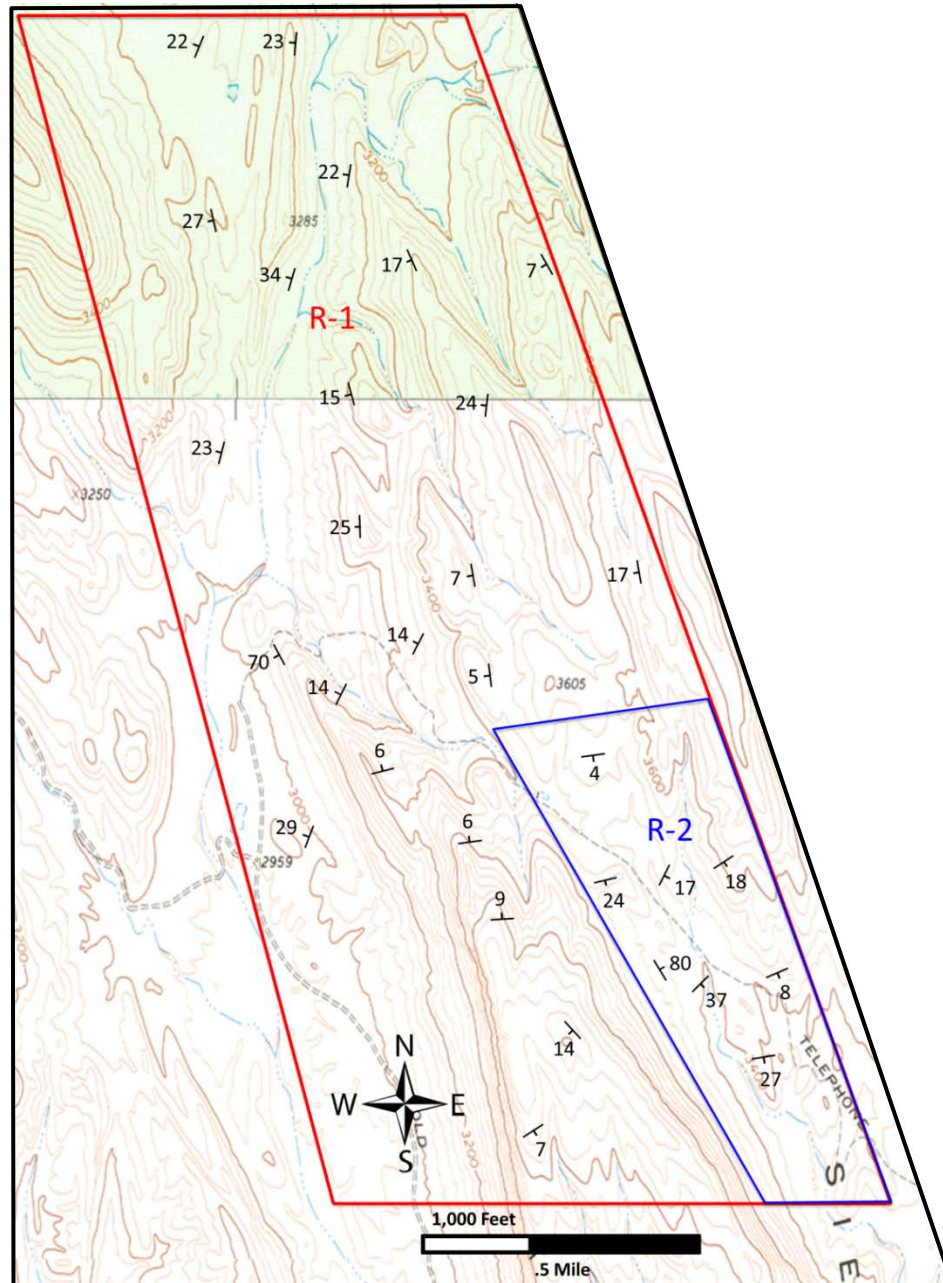
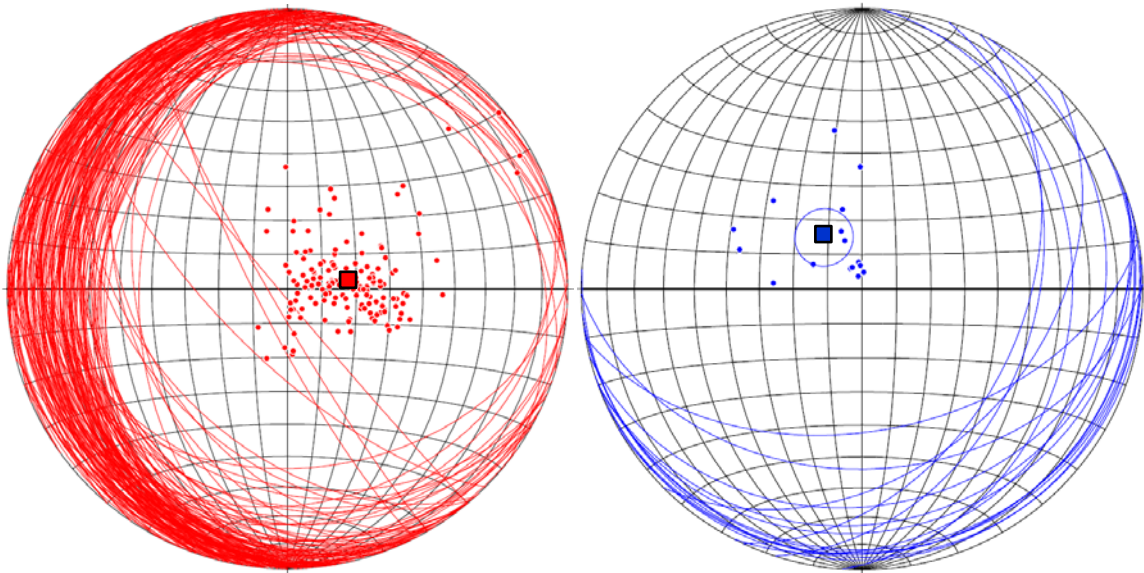


Figure 4.7- Topographic map of the study area showing the regions (R-1 and R-2) where beds have different orientations. In region R-1 the average strike and dip of bedding is N5°W, 22°SW. In region R-2 the average strike and dip of bedding is N60°E, 21°SE. A larger map displaying the locations of all strike and dip measurements obtained during this study can be found on Plate 4.

Stereonet Diagrams Displaying the Strike and Dips found in
Regions **R-1** and **R-2**



Average Strike and Dip of Regions			
Region	Color	Avg. Strike and Dip	n
R-1	Red	N5°W, 22° SW	164
R-2	Blue	N60°E, 21° SE	16

Figure 4.8 - Equal area stereonet showing all strike and dip of bedding found in R-1 (Red) and R-2 (Blue). The mean vectors of the poles are plotted as a square, and the average strike and dip and the number of measurements taken in each region is located in the table above.

Folds

Map and outcrop scale folds were discovered in the study area. Map scale folding refers to large, first order flexures that can be easily seen at a distance.

Two of these folds were found in the study area, a monocline and anticline.

Outcrop scale folding refers to small-scale folds that only locally affect a rock formation. Six locations in the Boquillas Formation displayed outcrop scale folding. Each fold will be discussed in further detail in the following sections.

Map Scale Folding

The first map scale fold (MSF-1) was identified at the northern end of the Alto Relex escarpment. At this location, there is a very broad, long wavelength, gently dipping, anticlinal structure that folds beds exposed in Alto Relex (Figure 4.9). The northern limb has an average strike and dip of N75°E, 6° NW (Figure 4.10). The southern limb has an average strike and dip of N65°E, 6° SE (Figure 4.10). The strike and dip of the axial plane of this very large fold was impossible to measure directly but was calculated to be approximately N63°E, 90°. The interlimb angle was 165° and the wavelength was approximately one mile long.

Another map scale fold (MSF-2) is located in the interior of the study area (Figure 4.9). This structure is a monocline (Figure 4.11) that has a steeply dipping west limb and a gently dipping eastern limb. The west limb of this feature

has an average strike and dip of N4°W, 25° SW, and the east limb has an average strike and dip of N5°W, 7° SW (Figure 4.12). The axial plane of this structure is inferred to strike N5°W and dip 50° to the northeast.

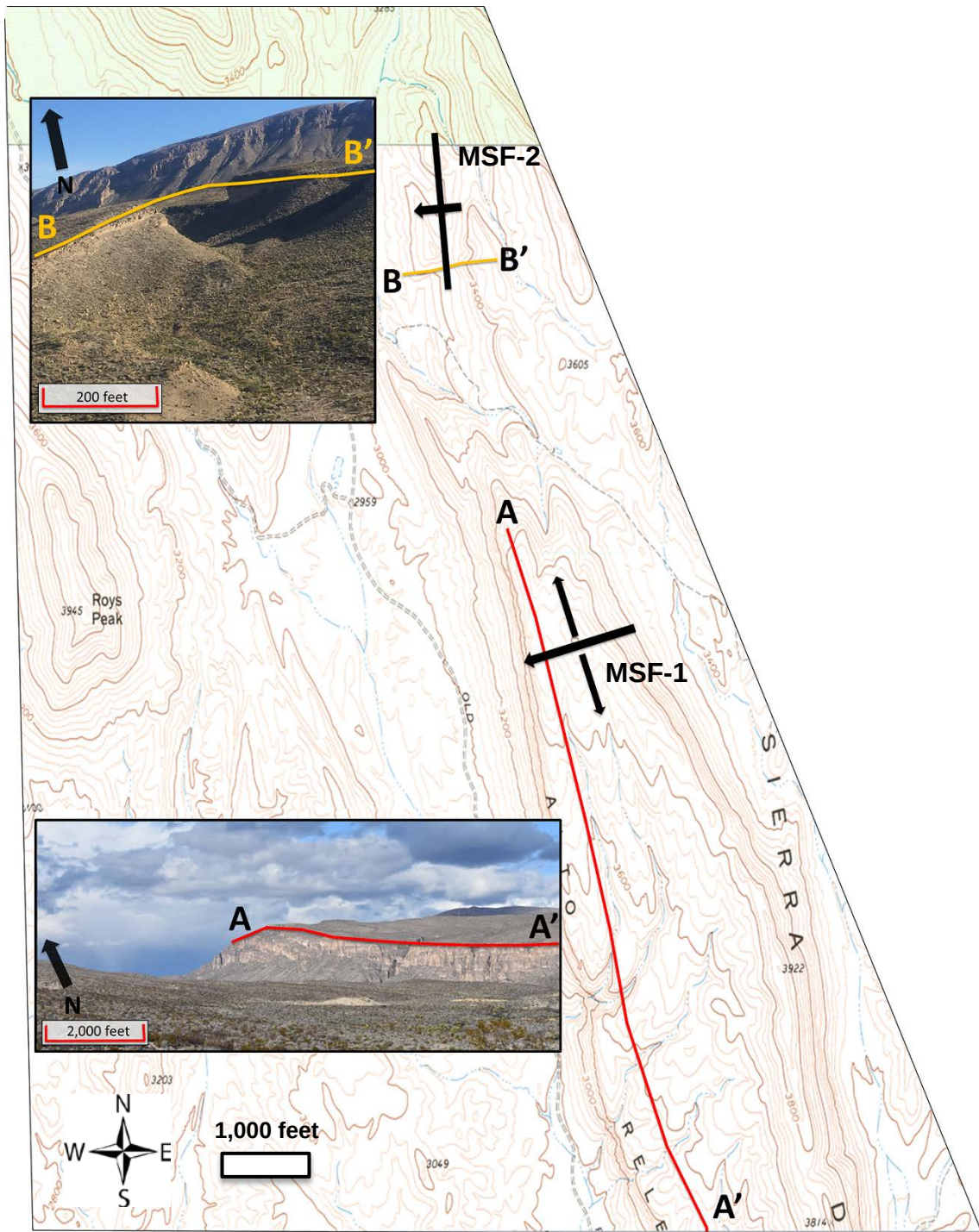
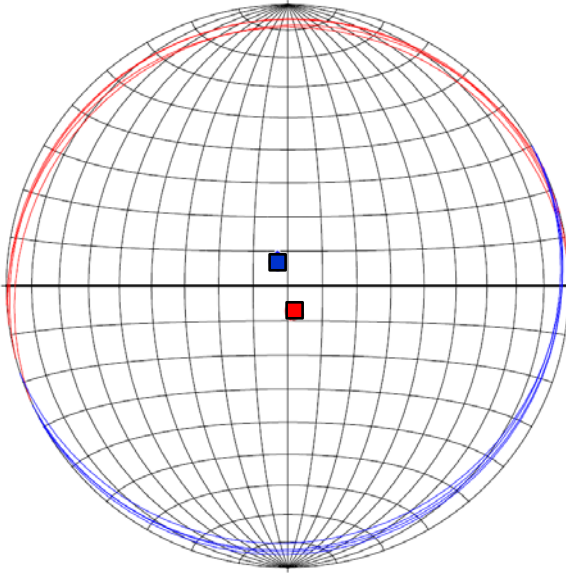


Figure 4.9 - Topographic map displaying the locations of MSF-1 and MSF-2, with pictures of each structure.

Stereonet Diagrams Displaying the Strike and Dip
Measurements taken on each limb of MSF-1



Average Strike and Dip of Limbs			
Limbs	Color	Avg. Strike and Dip	n
North	Red	N77°E, 8° NW	4
South	Blue	N64°E, 8° SE	4

Figure 4.10 - Equal area stereonet displaying the orientations of the north (Red) and south (Green) limbs of MSF-1. Mean vectors of the poles are plotted on the stereonet as squares. The average strike and dip of each limb is shown in the table above.

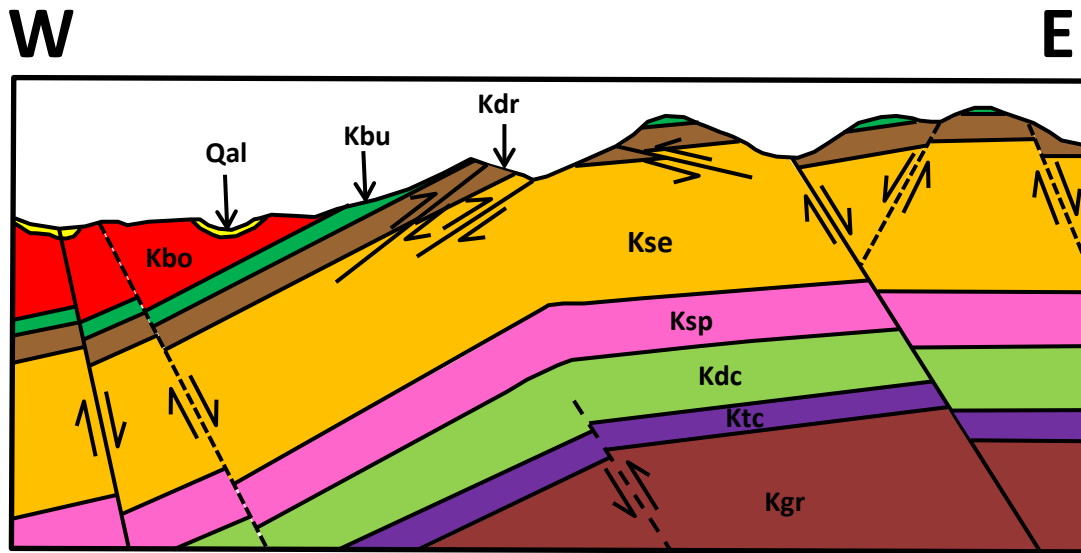
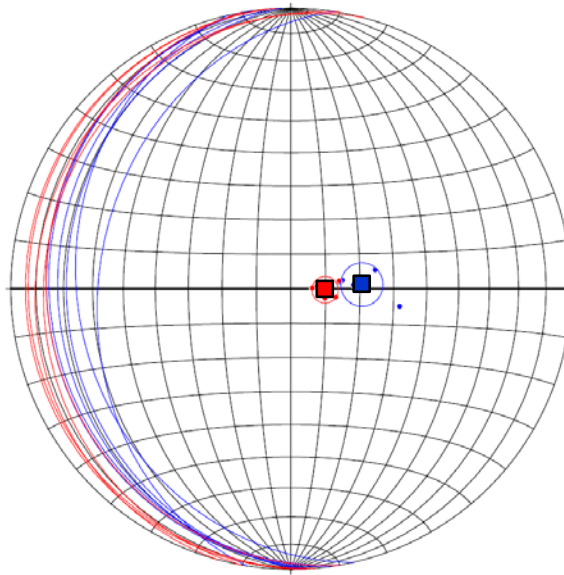


Figure 4.11 – Cross-section of the monocline (MSF-2) in the study area. This inferred axial plane of this monocline has a strike and dip of N5°W, 50° NE. This feature has a steeply dipping west limb (~25°) and a gently dipping east limb (~5°).

Stereonet Diagram Displaying the Strike and Dips taken on the Limbs of MSF-2



Average Strike and Dip of Limbs			
Limbs	Color	Avg. Strike and Dip	n
East	Red	N2°W, 10° SW	6
West	Blue	N5°W, 21° SW	5

Figure 4.12 - Equal area stereonet displaying the orientations of the east (Red) and west (Green) limbs of the monocline (MSF-2). Mean vectors of the poles are plotted on the stereonet as squares. The average strike and dip of each limb is shown in the table above.

Outcrop Scale Folding

In the southern portion of the study area, there were six locations (Fo-1 to Fo-6) where outcrop scale (smaller) folding was observed (Figure 4.13). These are all parallel type folds that are found only in the Boquillas Formation. The strike of the axial planes range from N8°W to N47°W and the dips vary from 70° SW to 73° NE (Figure 4.14). Each area is described in further detail below. Folds were classified using the Fleuty's Fold Classification chart (Figure 4.15).

The folds at Fo-1 (Figure 4.13) are anticlines and synclines that verge slightly to the northeast. They are asymmetrical folds with an average interlimb angle of 155° and wavelengths ranging from ten to 15 feet. The average strike and dip of fold axial planes is N47°W, 85°SW (Figure 4.14, red arcs) and the average plunge and bearing of fold hinge lines is 16°, S40°E. These folds can be classified as upright and sub-horizontal using the Fleuty system (Figure 4.15).

The fold found at Fo-2 (Figure 4.13) is a symmetric anticline that has a wavelength of five feet and a vertical axial plane (Figure 4.16). The strike and dip of the fold axial plane is N18°W, 90° (Figure 4.14, blue arcs), the plunge and bearing of the fold hinge line is 22°, S18°E, and the interlimb angle is 145°. This fold can be classified as upright and gently plunging (Figure 4.15).

Folds at Fo-3 (Figure 4.13) are asymmetric anticlines and synclines that have wavelengths ranging from six to ten feet (Figure 4.16). The average strike

and dip of the fold axial planes is N8°W, 78° SW (Figure 4.14, green arcs), the average plunge and bearing of fold hinge lines was 8°, S3°E and the average interlimb angle was 100°. These folds are classified as steeply inclined and sub-horizontal (Figure 4.15).

A single symmetric, anticlinal fold (Figure 4.16) with a wavelength of four feet was found at Fo-4 (Figure 4.13). The strike and dip of the fold axial plane is N27°W, 83°SW (Figure 4.14, orange arcs), the plunge and bearing of fold hinge line was 25°, S20°E, and the interlimb angle was 85°. This fold is classified as upright and gently plunging (Figure 4.15).

The two anticlines (Figure 4.16) found at Fo-5 have wavelengths ranging from four to six feet. The average strike and dip of the fold axial planes is N18°W, 73°NE (Figure 4.14, purple arcs), the average plunge and bearing of the fold hinges is 10°, S28°E and the average interlimb angle is 100°. These folds are classified as steeply inclined and gently plunging (Figure 4.15).

One asymmetrical, near chevron fold (Figure 4.16) with a wavelength of eight feet was found at Fo-6 (Figure 4.13). The strike and dip of the fold axial plane is N25°W, 70° SW (Figure 4.14, black arcs), the plunge and bearing of the fold hinge is 29°, S20°E, and the interlimb angle is 90°. This fold can be classified as steeply inclined and gently plunging (Figure 4.15).

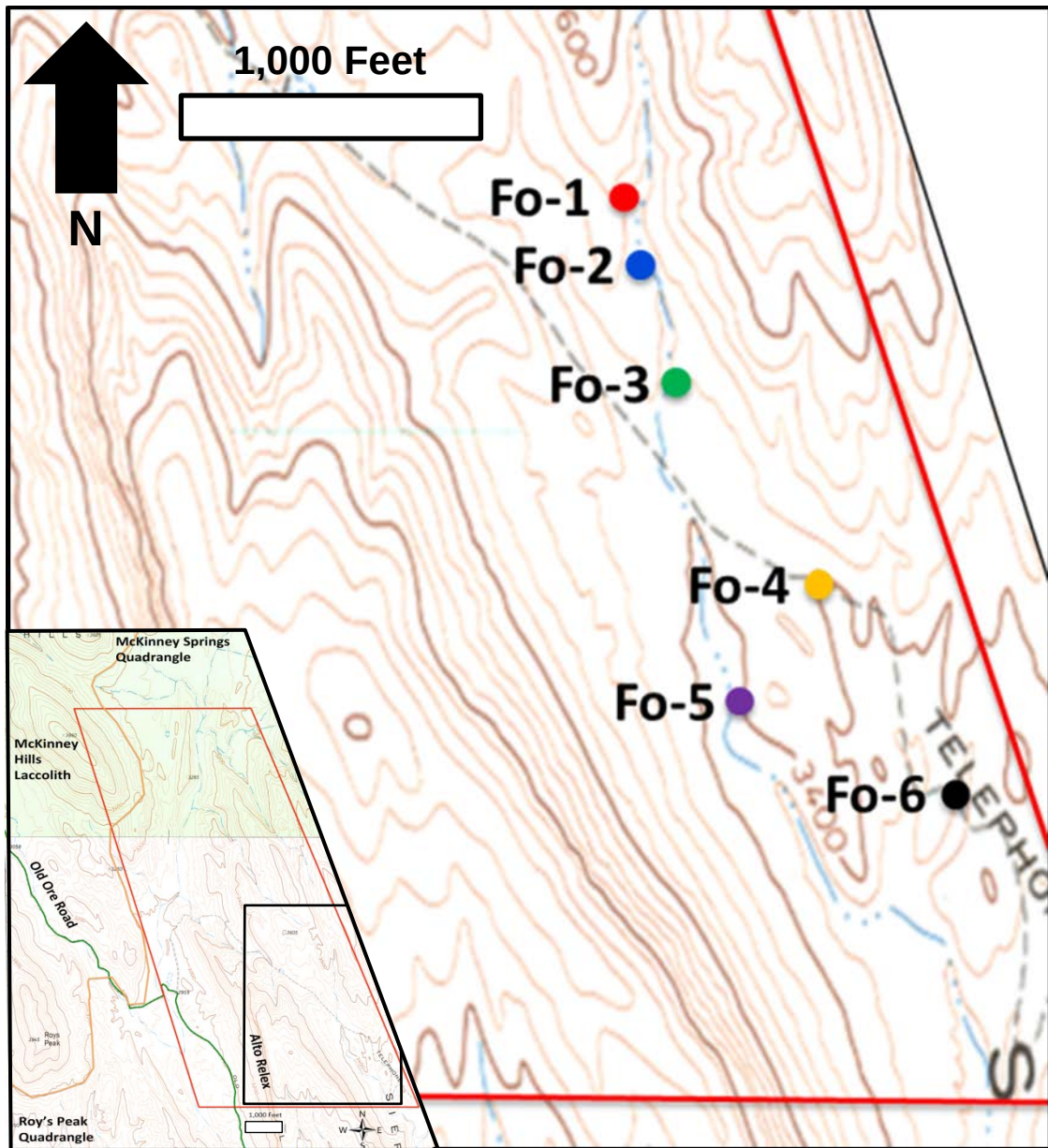
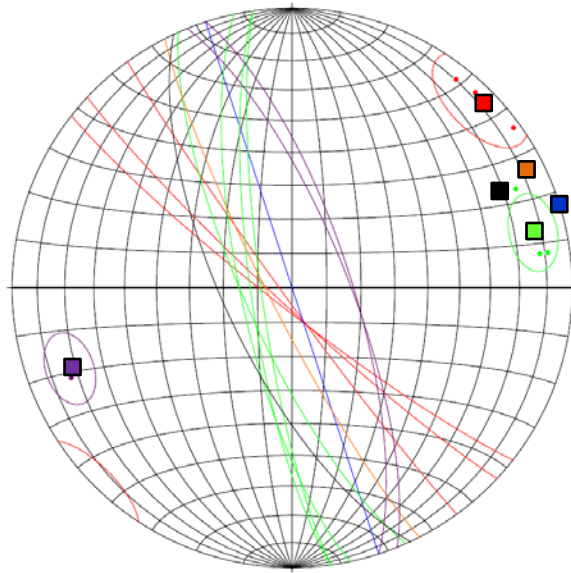


Figure 4.13 - Locations of outcrop scale folding that is found in the Boquillas Formation. All of these folds were found in the southeastern portion of the study area.

Stereonet Diagram Displaying the Strike and Dip of Axial
Planes in Outcrop Scale Folding



Average Strike and Dip of Fold Axial Planes			
Folds	Color	Avg. Strike and Dip	n
Fo-1	Red	N45°W, 85° SW	3
Fo-2	Blue	N18°W, 90°	1
Fo-3	Green	N13°W, 78° SW	4
Fo-4	Orange	N27°W, 83° SW	1
Fo-5	Purple	N20°W, 74° NE	2
Fo-6	Black	N25°W, 70° SW	1

Figure 4.14 - Equal area stereonet displaying the orientations outcrop scale folds discovered in the study area. Mean vectors of the poles are plotted on the stereonet as squares and the average strike and dip is found in the table.

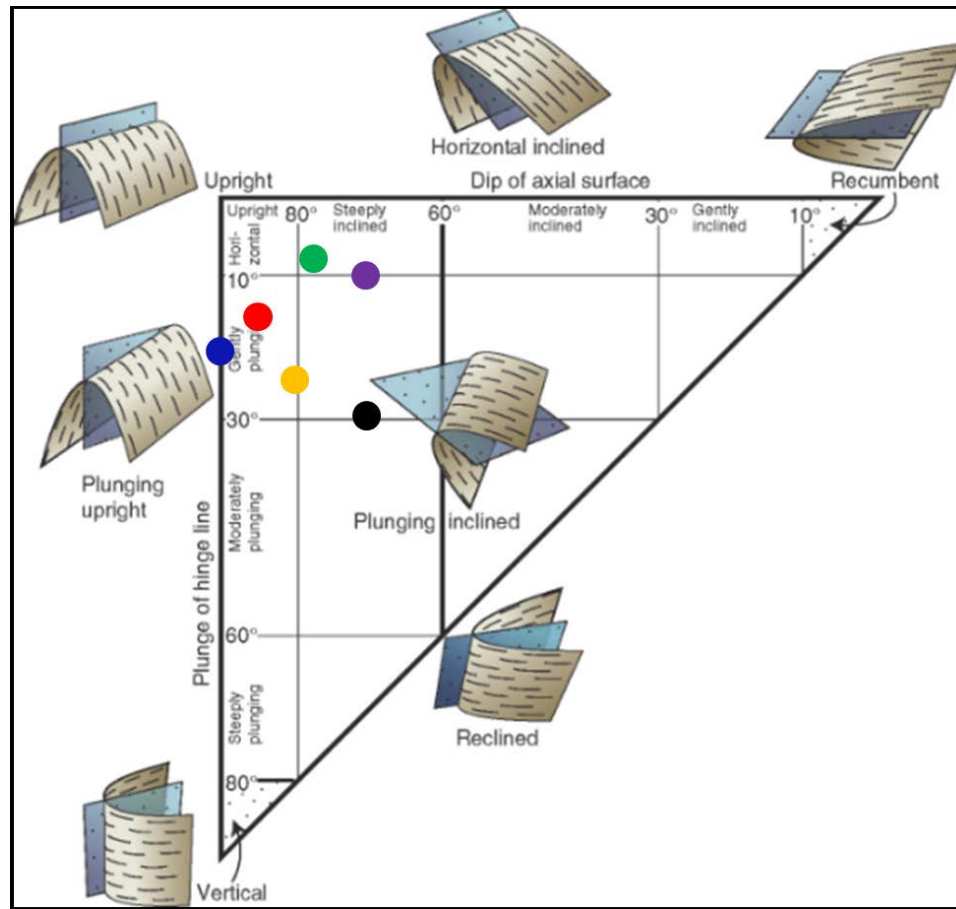


Figure 4.15 – Folding discovered during this study plotted on a Fleuty's (1964) fold classification chart. Key: Fo-1=Red, Fo-2=Blue, Fo-3=Green, Fo-4=Orange, Fo-5=Purple and Fo-6=Black.

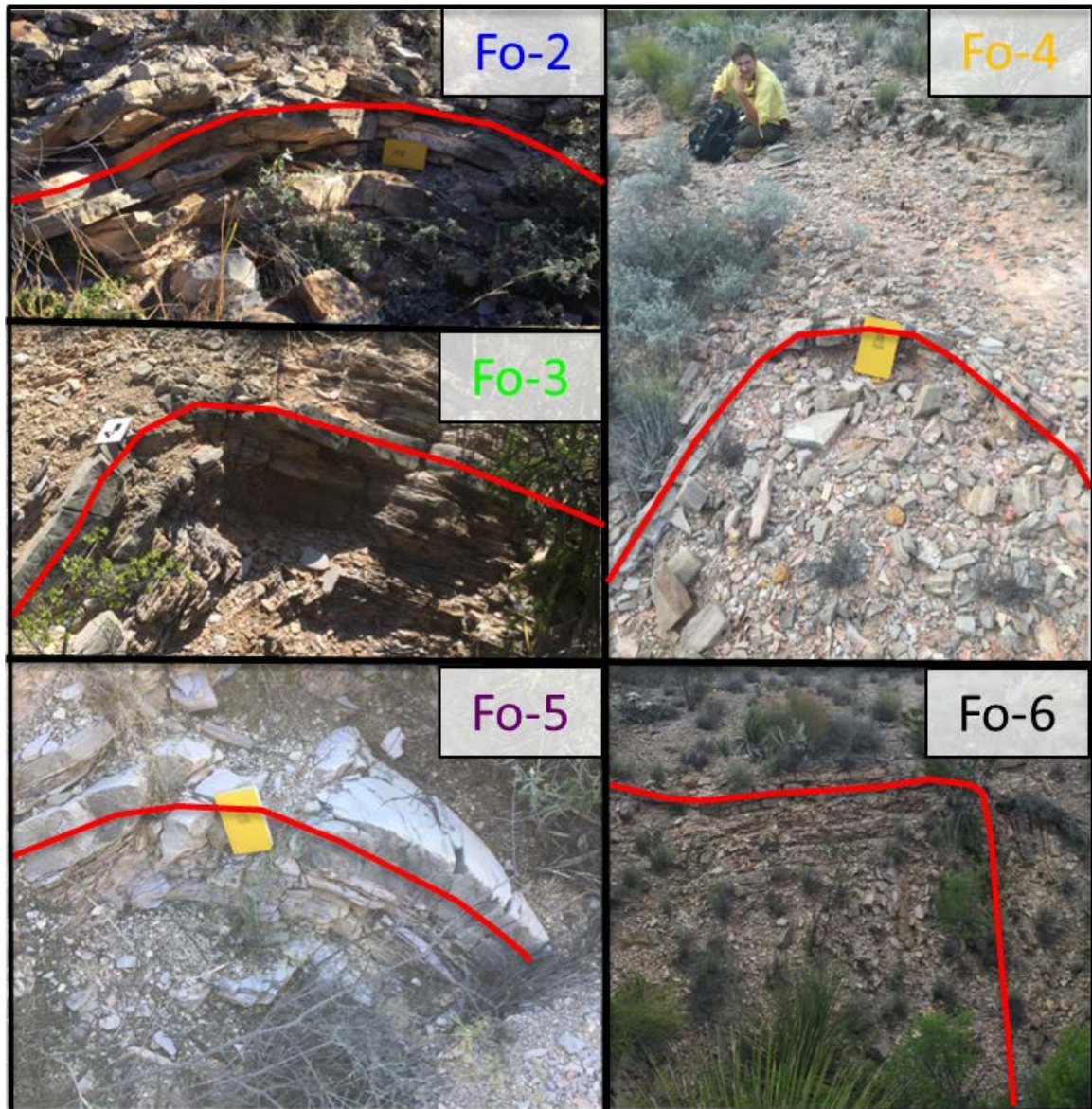


Figure 4.16 - Pictures of folding at different locations in the study area. Fo-2=Blue, Fo-3=Green, Fo-4=Orange, Fo-5=Purple and Fo-6=Black.

Faults

A total of 38 faults were found during this study; eight minor thrust faults; two major strike-slip faults; six minor strike-slip faults; eight major normal faults and 14 minor normal faults. Each fault is discussed in the following sections.

Minor Thrust Faults

Evidence of minor thrust faulting was found in eight locations in the study area (Figure 4.17). The amount of displacement was difficult to determine due to a lack of offset indicators. These faults are characterized as minor because no significant breccia zones were discovered. Therefore, fault movement may have been relatively minimal. Thrust fault planes are located in multiple map units including the Santa Elena Limestone, Buda Limestone, Del Rio Clay and the Boquillas Formation. Most of these fault planes have patches of calcite mineralization, slickensides and slickenfibers. Many also have stepped chatter marks which allowed the determination of relative movement. The orientation data that was collected from these thrust faults have been plotted in Figure 4.18.

Half of the thrust faults (T-1 to T-4) in the study area strike around N20°W and dip approximately 35° to the southwest (Figure 4.18, red arcs). The longest thrust fault (T-1) was found in the Upper Del Rio Clay trending N17°W. In this area, the Del Rio Clay forms a 1,000-foot long cuesta that is cut by a 10-foot

wide, east to west trending valley (Figure 4.19). In this valley, Quaternary gravel covers any evidence of the thrust. T-1 was first identified at location S46 striking N14°W and dipping 48° SW (Figure 4.18, red arcs). The plunge and bearing of slickenlines on T-1 are 46°, S73°W. This fault was traced approximately 900 feet to the north (S76) where it is striking N20°W and dipping 41°SW (Figure 4.18). The plunge and bearing of slickenlines at this location are 41°, S59°W. This fault plane could be related to a thrust fault that was found further north (T-2), in the Boquillas Formation (Figure 4.17). The average strike and dip of the axial plane at T-2 is N30°W, 60°SW (Figure 4.18, red arcs) and the slickenlines have a plunge and bearing of 55°, S82°W.

T-3 and T-4 (Figure 4.17) are located 300 to 400 feet east of T-1 and have similar fault plane orientations. The fault plane at T-3 is located in the Upper Del Rio Clay and has a strike and dip of N16°W, 43°SW (Figure 4.18, red arcs). The plunge and bearing of the slickenlines on T-3 are 42°, S75°W. T-4 was found above a clay layer within the Del Rio Clay, approximately one foot above the Santa Elena Limestone contact (Figure 4.20). The fault plane at T-4 has an average strike and dip of N20°W, 38°SW (Figure 4.18, red arcs), with slickenlines that have an average plunge and bearing of 35°, S68°W. Thrust faults T-1 to T-4 display en-echelon thrust faulting pattern and are possibly all related. In other locations (T-5 to T-8), thrust fault planes do not match the N20°W trend.

The thrust fault, T-5 (Figure 4.17) has a fault plane that protrudes from a dip slope of Santa Elena Limestone (Figure 4.21). This fault has a strike and dip of N23°W, 12°NE (Figure 4.18, blue arcs). Slickenfibers on the fault plane have a plunge and bearing of 8°, N82°E. At this location the slickenlines were very faint and there was only two to eight inches of the fault plane exposed (Figure 4.21). This fault displayed no obvious vertical displacement.

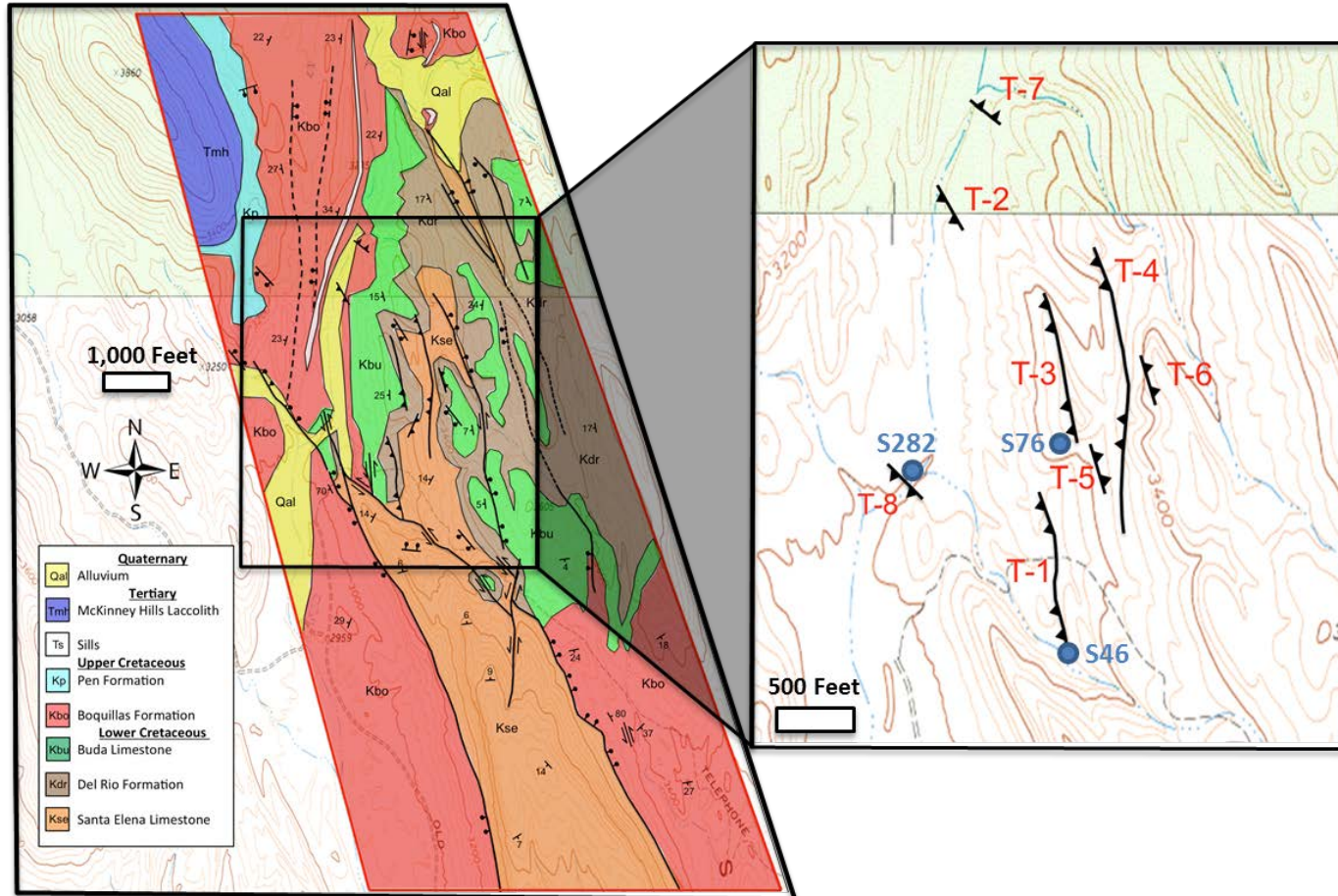
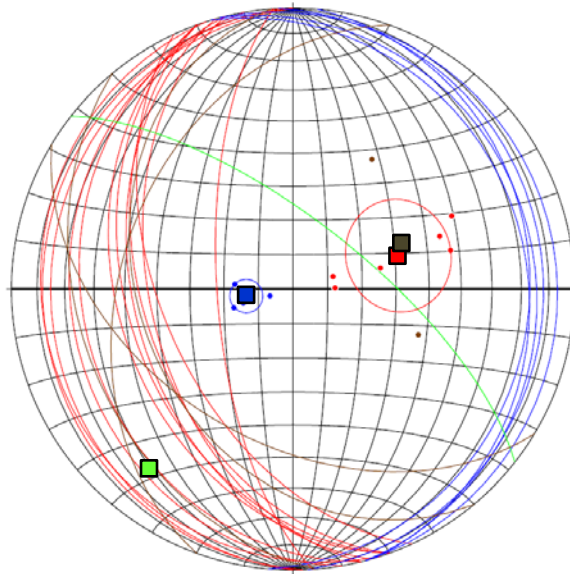


Figure 4.17 - Topographic map of the study area displaying the locations of each thrust fault that was found in the study area. The majority of these faults trend north-northwest and dip to the southwest (T-1, T-2, T-3, T-4 and T-8). However, some of these faults (T-5, T-6, T-7) have an opposite dip direction (northeast).

Stereonet Diagram Displaying the Strike and Dip of Thrust Faults



Average Strike and Dip of Thrust Fault			
Thrusts	Color	Avg. Strike and Dip	n
T-1 – T-4	Red	N14°W, 35° SW	12
T-5 – T-6	Blue	N13°W, 14°NE	5
T-7	Green	N52°W, 70° SW	1
T-8	Brown	N20°W, 42° SW	2

Figure 4.18 – Equal area stereonet displaying orientations of thrust faults found in location T-1 to T-8. Mean vectors of the poles are plotted on the stereonet as squares and the average strike and dips of the thrusts can be found in the table.

The fault plane at T-6 has a strike and dip of N17°W, 18°NE (Figure 4.18, blue arcs) and slickenlines with a plunge and bearing of 14°, N74°E. This fault was found in the Upper Del Rio Clay and had well-developed slickenlines and chatter marks. T-5 and T-6 have similar fault plane orientations.

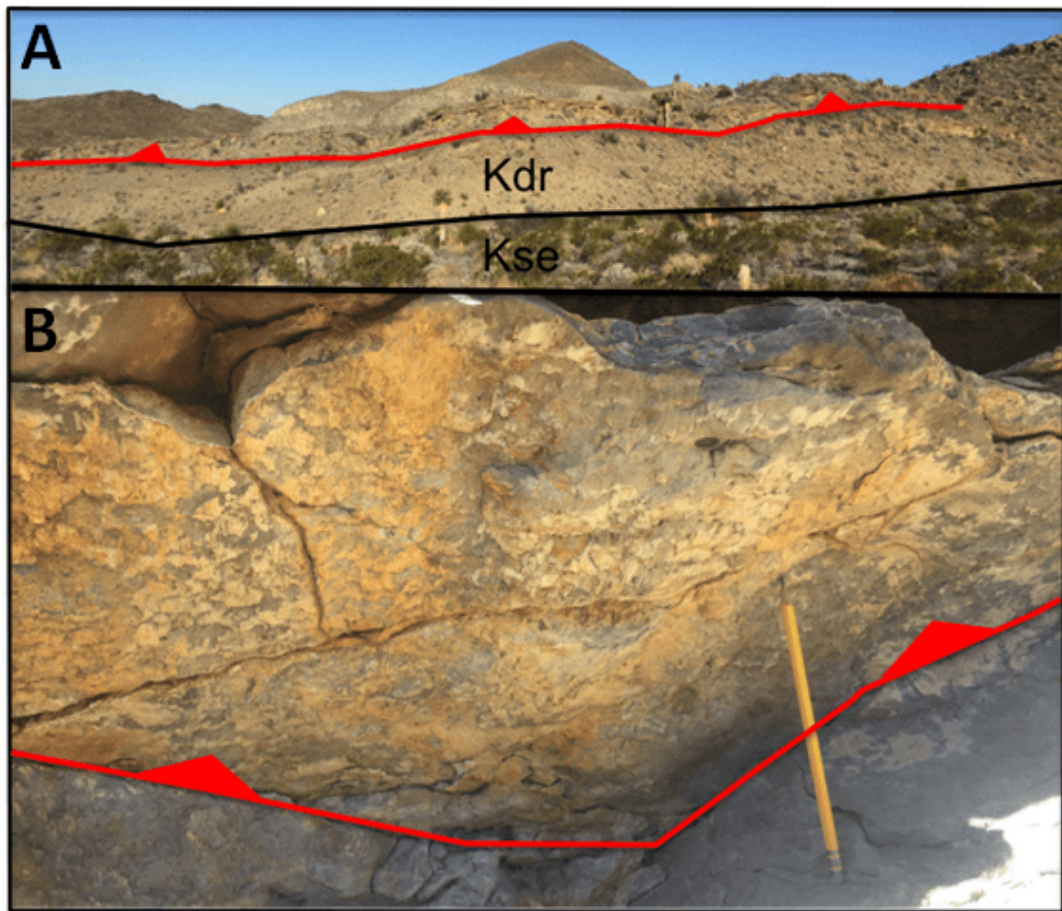


Figure 4.19 - A) A cuesta made up of Del Rio Clay with the approximate location of thrust fault T-1 shown with a red line. B) Fault plane and slickenlines found along thrust fault T-1 (S36). Note the pencil for scale.

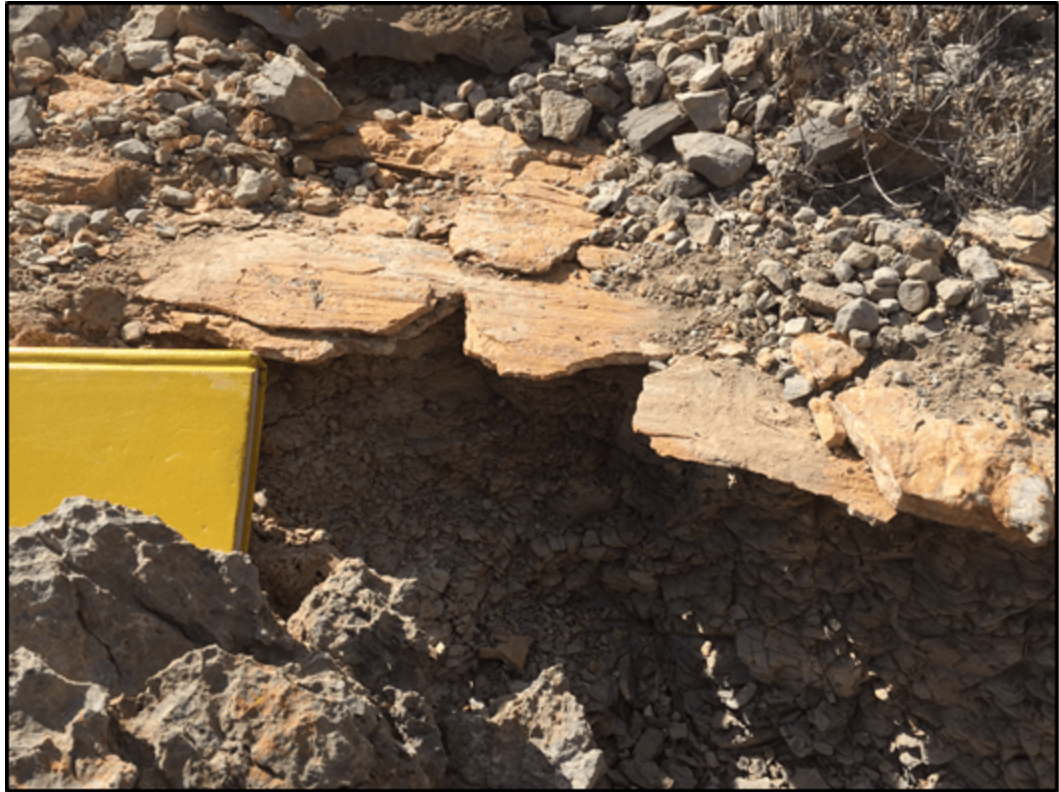


Figure 4.20 - Slickenlines found at T-4 lying on a clay layer in the Del Rio at location S52/81.

Fault T-7 (Figure 4.17) is a possible reverse fault that was discovered in the Boquillas Formation (Figure 4.22). The fault plane has a strike and dip of N52°W, 70° NE (Figure 4.18); no slickenlines were found. An offset ash bed suggests that there is approximately two feet of vertical displacement. This fault

is in close proximity to a ten-foot thick mafic sill that was intruded into the Boquillas Formation.

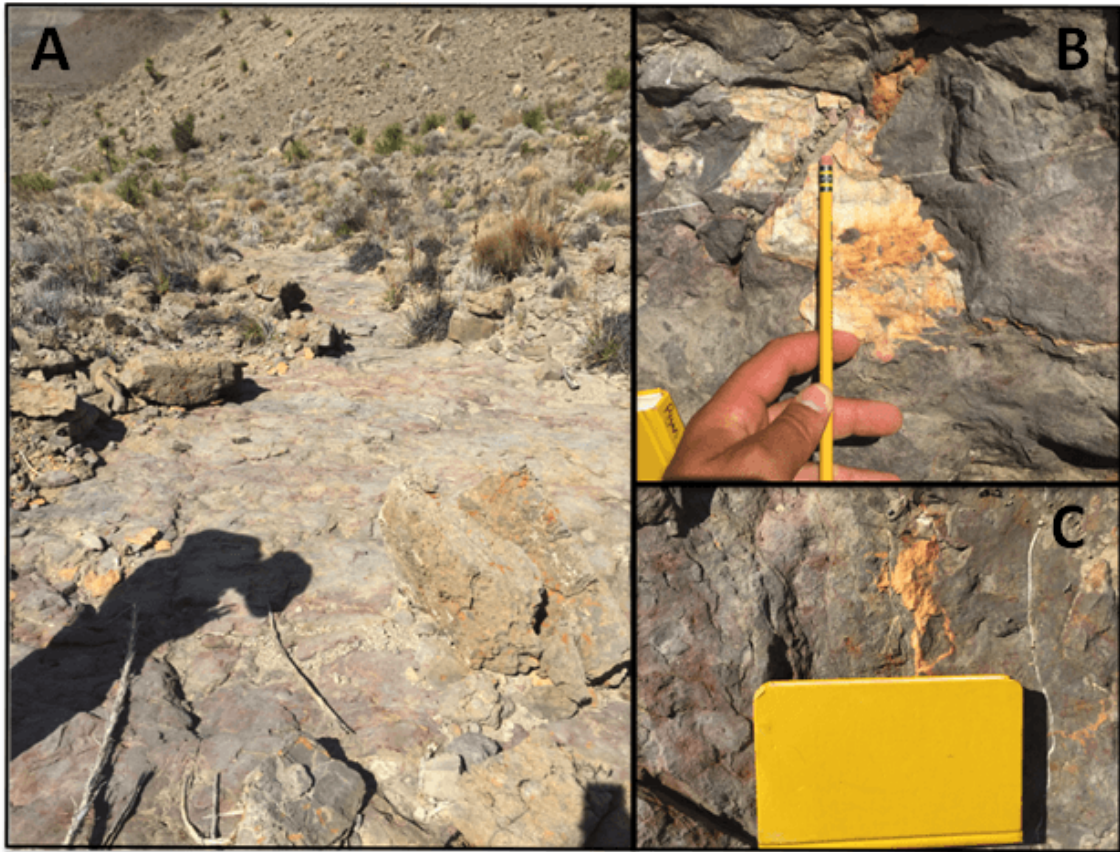


Figure 4.21 - A) Dip-slope of the Santa Elena where the slickenlines for T-5 were discovered (S80). Slickenlines found at locations S80 (B) and S53/79 (C) along this dip-slope.

At location S282, fault T-8 (Figure 4.17) has multiple fault planes with different thrust orientations. One plane has an average strike and dip of N59°W, 45° SW (Figure 4.18) and has slickenlines with an average plunge and bearing of 37°, S5°W. Over two feet of vertical displacement was measured along this fault

plane. The other plane has an average strike and dip of N20°E, 39° NW (Figure 4.18) and has slickenlines with an average plunge and bearing of 24°, S72°W. Some chatter marks in this location suggest evidence of both normal and strike-slip movement.

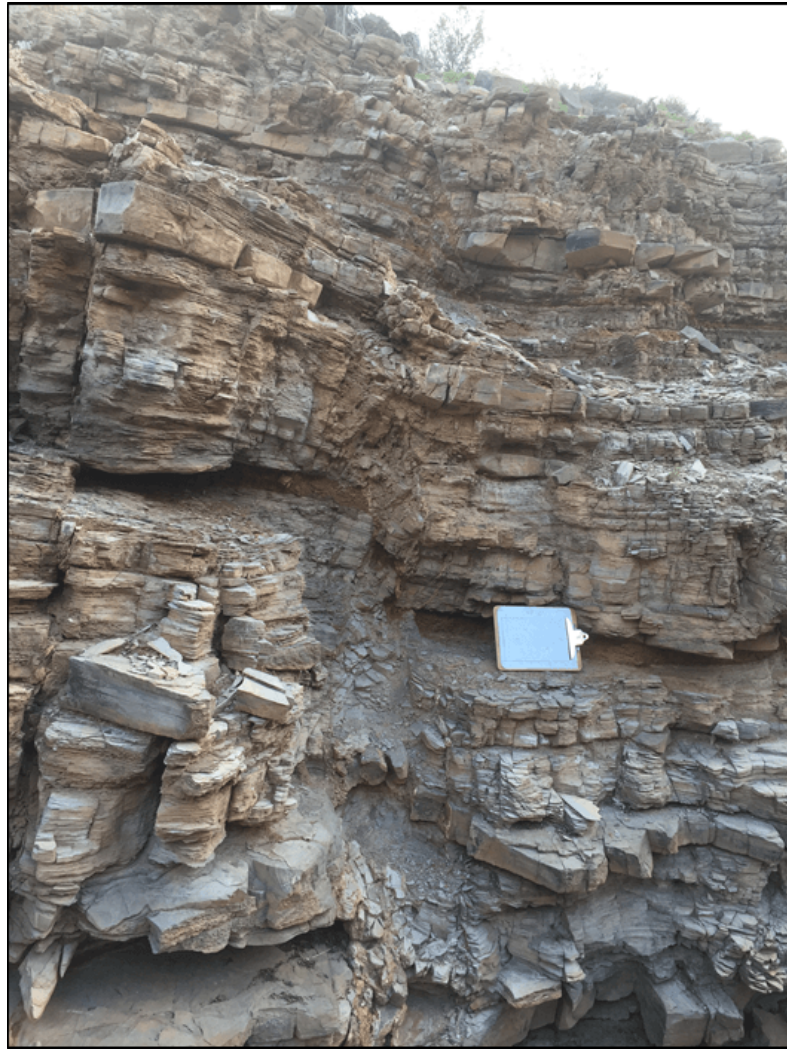


Figure 4.22 - Possible reverse fault (T-7) found at location S282. Note the distinctive red to orange ash beds that has been displaced approximately two feet.

Major Strike-Slip Faults

Major strike-slip (MSS) faults were found in the study area that have extensive outcrops of horizontal slickenlines, breccia zones, calcite deposits, vertically-dissected bedding and adjacent zones of sigmoidal, tension gashes that have become mineralized veins. These faults are geographically extensive and cut across large portions of the study area (Figure 4.23). Two major (MSS-1 and MSS-2) strike-slip faults were found displacing the Santa Elena Limestone (Figure 4.23).

MSS-1 is a major strike-slip fault that trends around N52°W and can be traced for over 3,000 feet. This fault was observed at locations S115 – S136, S281 and S282 (Figure 4.23). It is best exposed in a narrow, 75 to 100-foot deep slot canyon (Figure 4.24) that trends N45°W. At S116, the fault plane strikes N41°W and dips 85°NE (Figure 4.25) and has slickenlines with a plunge and bearing of 9°, N38°W. The majority of the chatter marks found on the fault plane suggest that this was a sinistral strike-slip fault. However, a few chatter marks in some areas showed evidence of both dextral and sinistral movements. Tension gashes indicating sinistral shear, mineralized veins and zones of fault breccia are found along this fault. At location S136 (Figure 4.23) this fault zone (Figure 4.26) is approximately 20-foot wide and contains multiple one to two-foot thick calcite veins and associated breccia that trend N50°W. In this location, one calcite vein

appears to have been sheared into a five-foot-long sigmoidal shape (Figure 4.26). If this represents a large tension gash, then it may indicate dextral shear that is trending N42°W. In this location, the strike and dip of the fault plane averages N63°W, 86°NE (Figure 4.25) and the plunge and bearing of slickenlines averages 30°, S60°E. Vertical stylolites (Figure 4.27) were also found in this location trending N45°E. They have tapered and pointed teeth that ranged from ¼ to one inch tall.

The strike-slip fault zone associated with MSS-1 was discovered again at location S128 (Figure 4.23) but the associated breccia zone was only ten feet thick. At this location, it contains abundant light orange fault breccia with cobble to coarse gravel size clasts. This breccia is dissected by multiple sinistral strike-slip faults that have an average strike and dip of N63°W, 90° with slickenlines that have an average plunge and bearing of 15°, N63°W.

This strike-slip fault zone was not found beyond location S282 (Figure 4.23). At this location, the fault plane has a strike and dip of N14°W, 90° (Figure 4.25) and the slickenlines have a plunge and bearing of 22°, S14°E. This area has multiple sets of eight- to ten-inch tension gashes that have a general trend of N5°W.

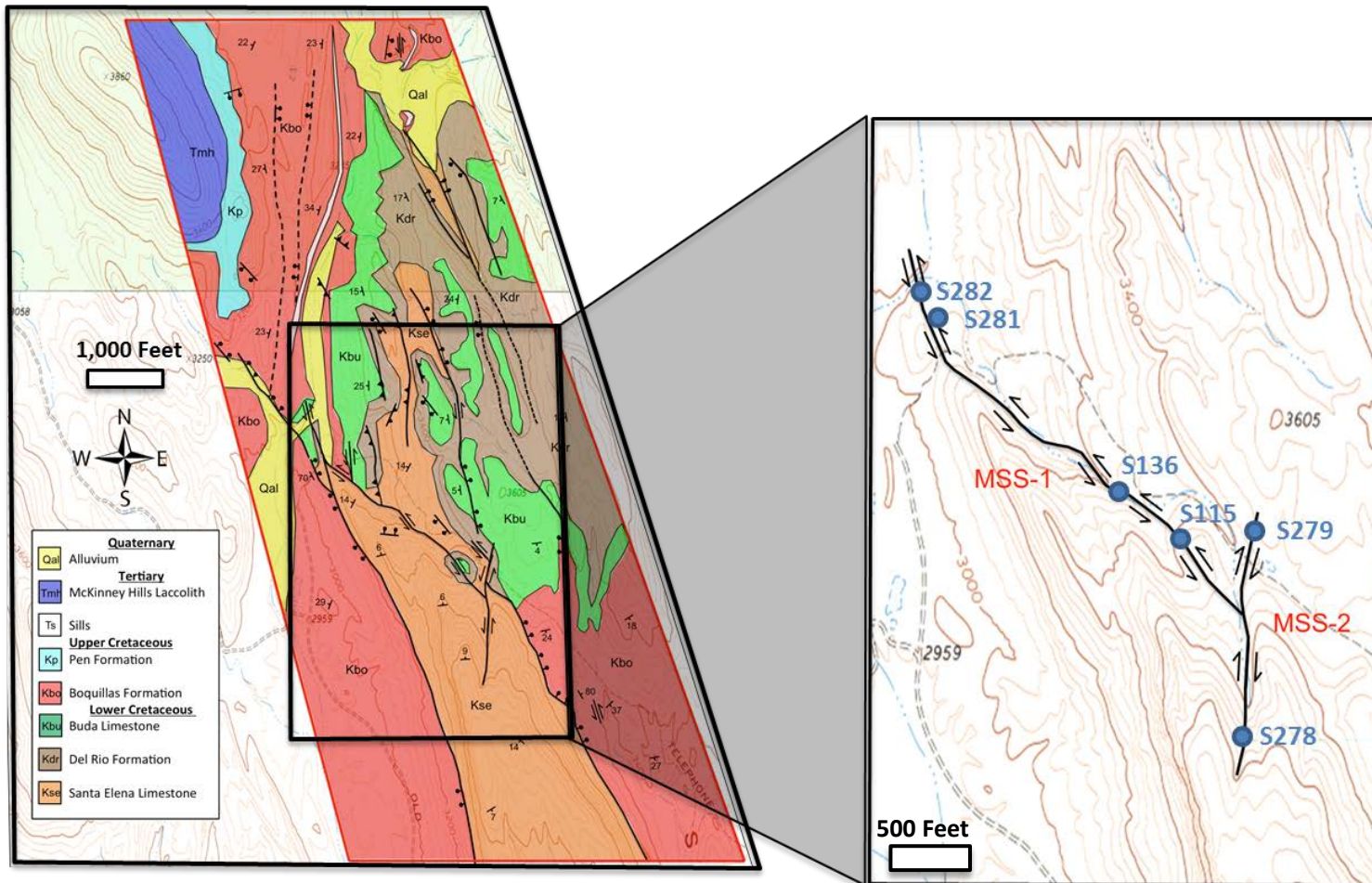
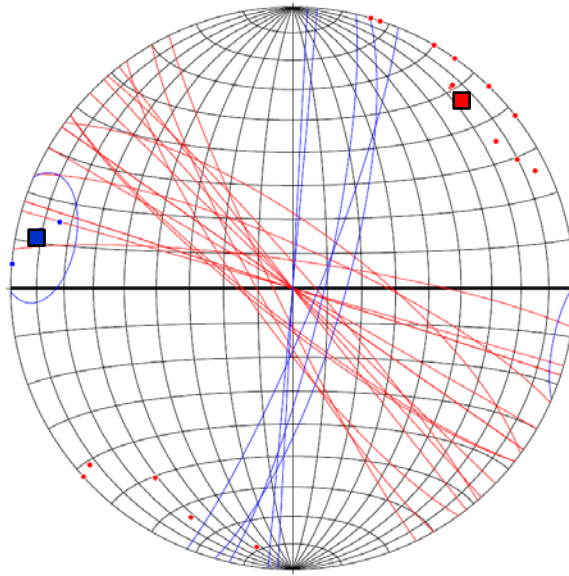


Figure 4.23 - Topographic map displaying the locations of each major strike-slip fault that was found in the study area. Important locations that were discussed have been labeled and plotted with a blue dot.



Figure 4.24 - Slot canyon with the approximate location of MSS-1 shown in red. Bedding on the east side of the canyon is near horizontal. However, on the western side of the canyon bedding is dipping and deformed. This photo was taken from location S124.

Stereonet Diagram Displaying the Strike and Dip of Major
Strike-Slip Faults (MSS)



Average Strike and Dip of Major Strike Slip Faults			
MSS	Color	Avg. Strike and Dip	n
MSS-1	Red	N60°W, 85° SW	20
MSS-2	Blue	N12°E, 84 SE°	5

Figure 4.25 - Equal area stereonet displaying the strike and dip of fault planes measured along two major strike-slip faults in the study area. Mean vectors of the poles are plotted on the stereonet as squares and the average strike and dip of the faults are located in the table.

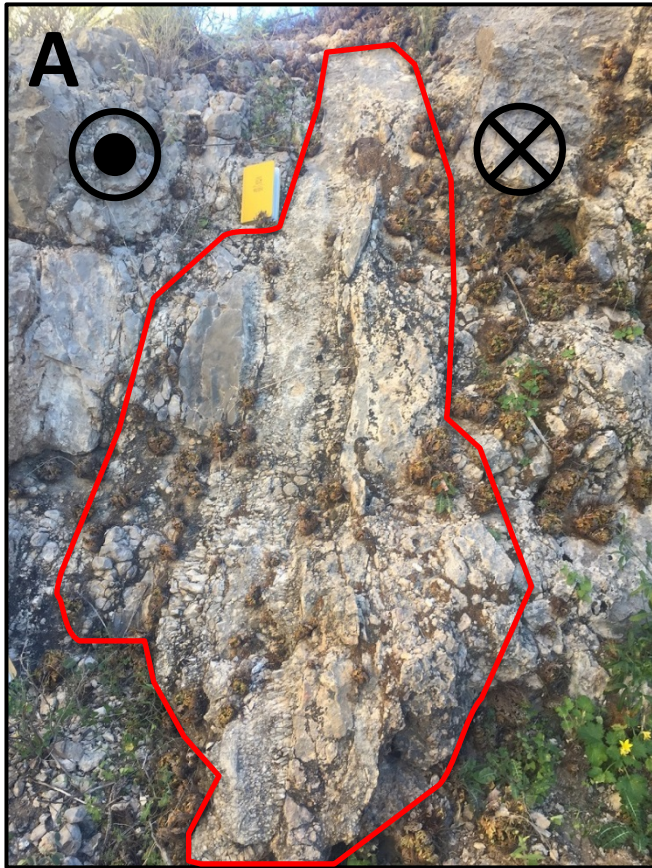


Figure 4.26 - A) A view to the south of the large fault zone that is associated with MSS-1 (S136). This location contains a series of one to two foot thick calcite veins with associated fault breccia. B) Large sigmodal shaped calcite vein (S135) that could have been created by shearing along MSS-1.



Figure 4.27 - Vertical stylolites(black) found near the MSS-1 fault zone at location S136.

Another extensive strike-slip fault that was discovered has been labeled MSS-2 (Figure 4.23). It was first identified at location S278 where the fault plane is exposed along the outer boundaries of a three- to four-foot-wide breccia zone (Figure 4.28). The average strike and dip of the fault plane is N3°E, 90° (Figure 4.25) and the average plunge and bearing of the slickensides is 2°, N3°E. Chatter marks on the fault plane indicate dextral movement, which is unique among all the other strike-slip faults in the area. This fault was traced to location S279 (Figure 4.23), approximately 1,000 feet to the north. At this location there are abundant mineralized veins and small tension gashes trending in multiple directions. The fault plane has a strike and dip of N16°E, 80° SE (Figure 4.25); slickenlines display two orientations: 14°, N25°E, and 30°, N32°E.



Figure 4.28 - Slickenlines exposed on the outer boundary of a three-foot-wide breccia zone of MSS-2 (S278).

Minor Strike-Slip Faults

Minor strike-slip faults in the study area have only small outcrops of horizontal slickenlines and are associated with small calcite veins and minimal fault breccia. Six minor (SS-1 to SS-6) strike-slip faults were found in the study area (Figure 4.29). All of the minor strike-slip faults have indications of sinistral movement.

The first minor strike-slip fault plane (SS-1) was found at location S24, in the Santa Elena Limestone (Figure 4.30). At this locality there are small amounts of fault breccia and calcite mineralization. Well-developed slickenlines and faint chatter marks were found on the fault plane. The average strike and dip of the fault plane is N60°W, 87°SW, (Figure 4.31) and the slickenlines have an average plunge and bearing of 11°, S58°E. This fault plane was only exposed for approximately 100 feet and in some places it displays signs of normal fault movement.

No horizontal slickenlines were found along SS-2 but other shearing indicators were discovered. For example, tension gashes (Figure 4.32) were found on a ten-foot-high, vertical cliff face that trends N3°W. This cliff was composed of Buda Limestone and could represent a minor fault splay from the major strike-slip fault (MSS-1) that is located 100 feet to the southwest. This possible strike-slip fault has a strike and dip of N12°W, 90° (Figure 4.31).

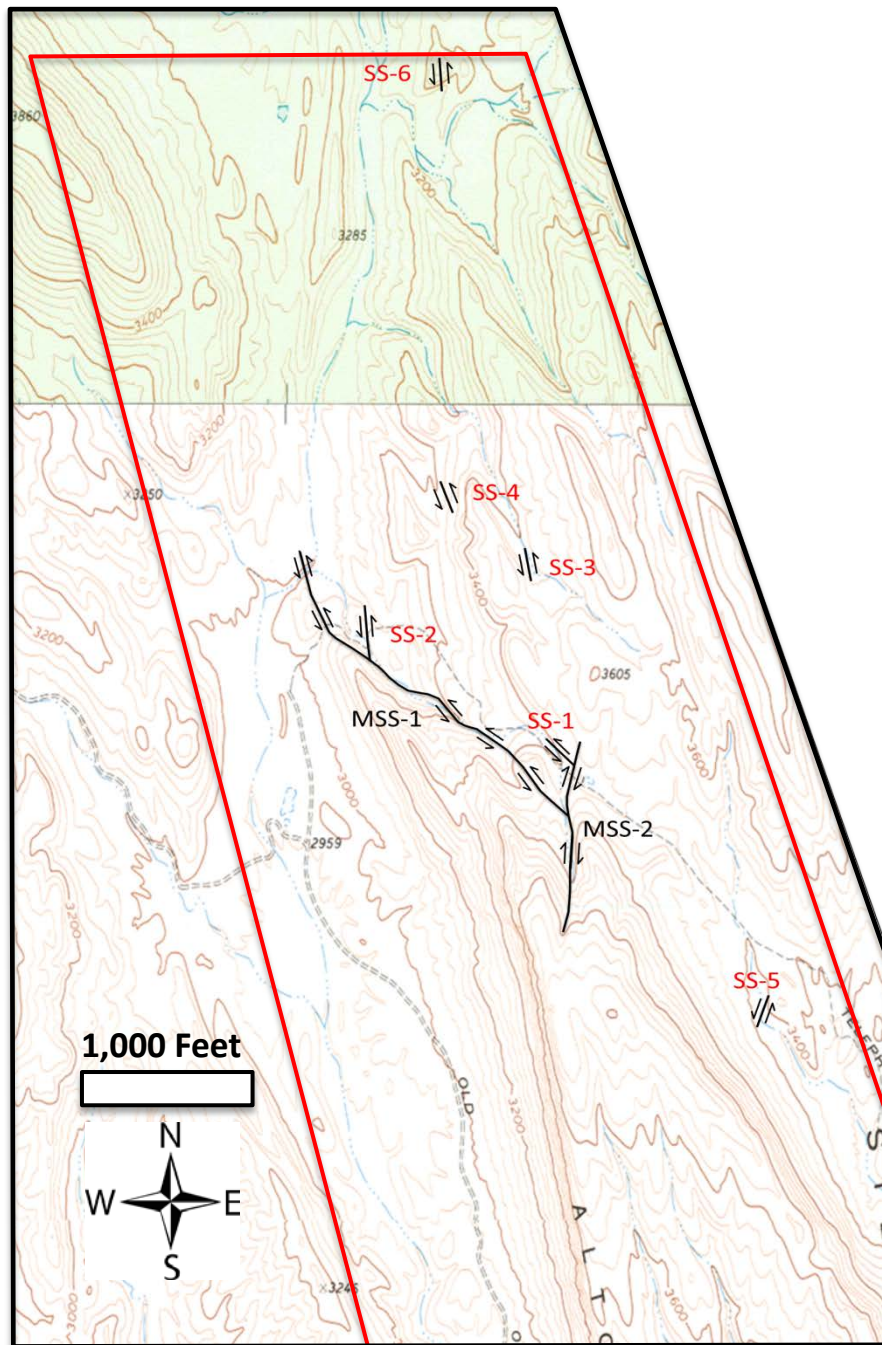


Figure 4.29 - Topographic map displaying the location of all the minor strike-slip faults (SS-1 to SS-6) that were discovered in the study area.

Strike-slip fault SS-3 was discovered in the Santa Elena Limestone, while tracing normal fault N-9. At this location there are multiple strike-slip fault planes within a two-foot thick fault zone. These fault planes have an average strike and dip of N10°W, 90°, (Figure 4.31) and the slickenlines have an average plunge and bearing of 5°, S10°E.

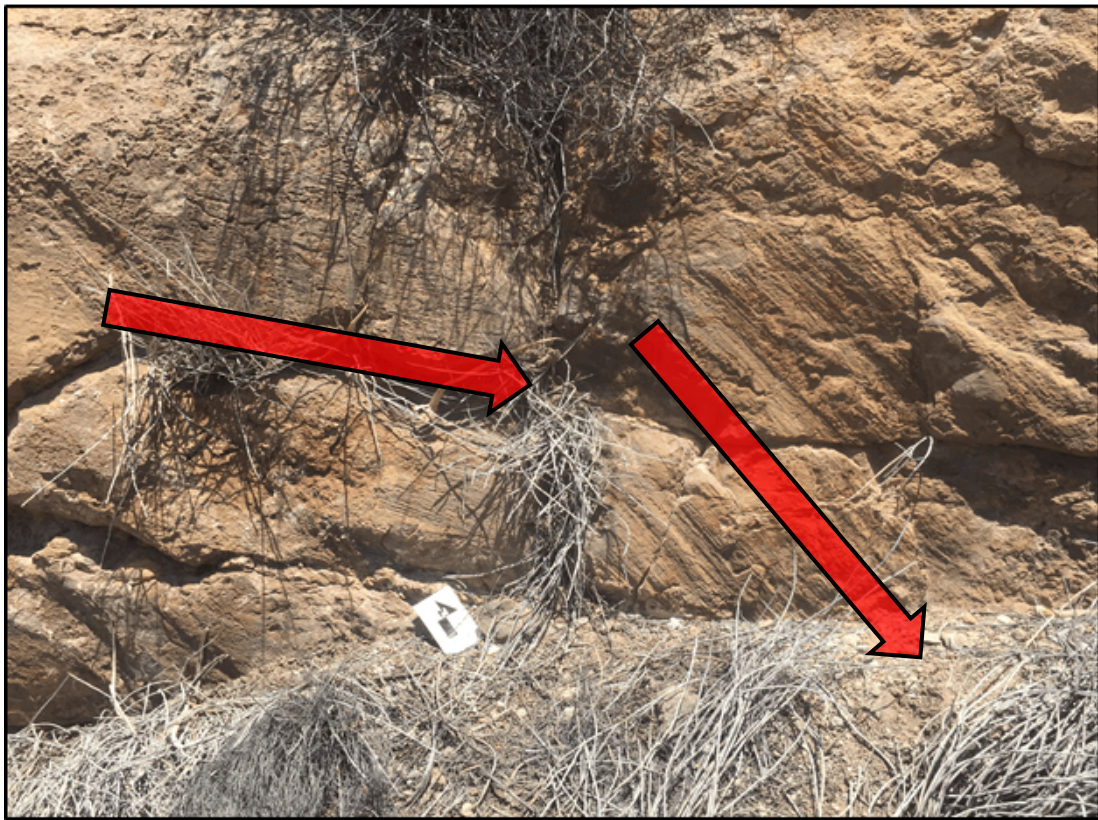


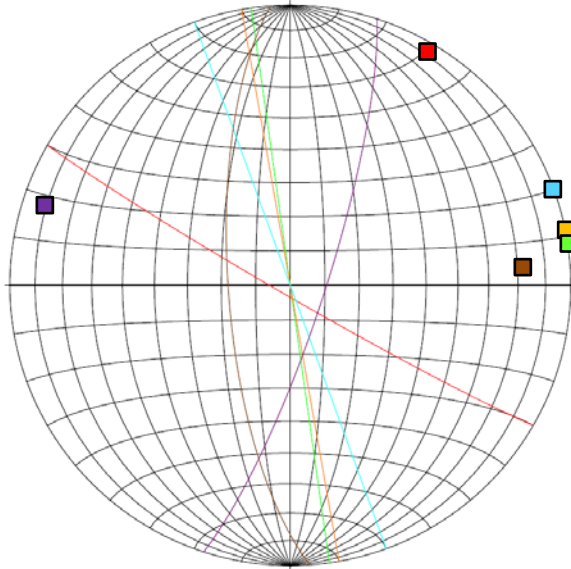
Figure 4.30 - Distinct slickenlines found on fault plane SS-1 at location S24. The two distinct slickenline orientations are labeled with the red arrows.

Minor strike-slip fault SS-4 is located in a slot canyon that trends N15°W and is approximately 15 to 20 feet deep (Figure 4.32). A one-foot-thick fault zone was found along the eastern wall of this canyon. This fault zone is composed of a series of one to two inch thick calcite veins and multiple mineralized fault planes. The strike and dip of the fault plane is N20°W, 90° (Figure 4.31) and the slickenlines have a plunge and bearing of 5°, S20°E.

In the southern portion of the study area, a strike-slip fault, SS-5, was found in the Boquillas Formation. The fault plane is adjacent to a one-foot zone of calcite mineralization but was not found in any other locations. The strike and dip of the fault plane is N18°E, 80°SE, (Figure 4.31) and the plunge and bearing of the slickenlines is 15°, S6°E.

SS-6 is another minor strike-slip fault that was discovered in the Boquillas Formation, but in the far northern portion of the study area (Figure 4.29). One- to five-inch-long dogtooth spar calcite crystals were found in a two-foot-wide fault zone (Figure 4.32). The fault plane has a strike and dip of N4°W, 72°NE with slickenlines that have a plunge and bearing of 18°, N6°E.

Stereonet Diagram Displaying the Strike and Dip of Minor Strike-Slip Faults (SS)



Strike and Dip of Minor Strike-Slip Faults			
SS	Color	Strike and Dip	n
SS-1	Red	N60°W, 87°SW	1
SS-2	Green	N8°W, 90°	1
SS-3	Orange	N10°W, 90°	1
SS-4	Cyan	N20°W, 90°	1
SS-5	Purple	N18°E, 80° SE	1
SS-6	Brown	N4°W, 72° SE	1

Figure 4.31 - Equal area stereonet displaying the average orientations of minor strike-slip fault planes found in the study area. Mean vectors of the poles are plotted on the stereonet as squares and the strike and dips of the minor strike-slip faults are located in the table.

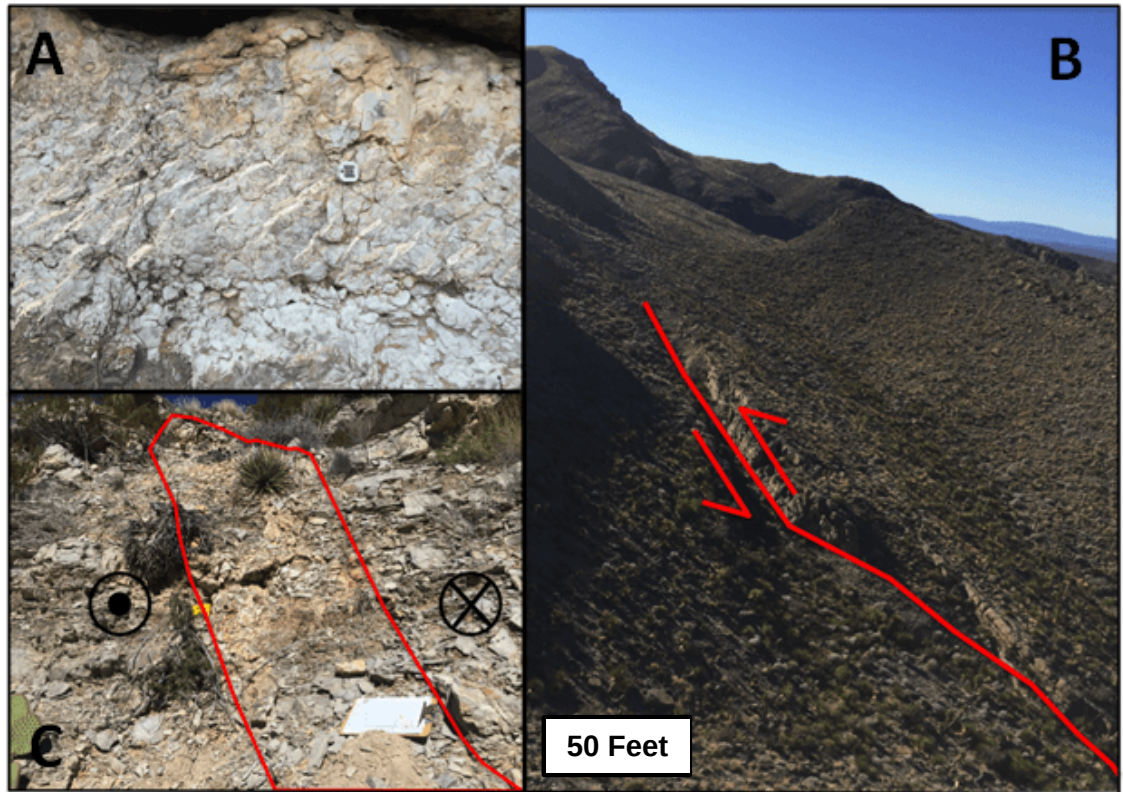


Figure 4.32 - A) Tension gashes found on the possible fault plane of SS-2 (S43). B) View to the southwest at location S208 shows the slot canyon where fault SS-4 was found. C) The two foot fault zone (red) associated with SS-6 (S269).

Major Normal Faults

The topography of the study area is dominantly controlled by the presence of major normal faults. These normal faults have created very high, near-vertical cliffs, large amounts of vertical displacement and, in some places, distinctive red breccia zones ranging from five to 20 feet thick. Other features that seem to be associated with normal faulting include the precipitation of five to ten inch rhombohedral calcite crystals and zones of liesegang banding.

The largest normal fault (MN-1) is on the western side of Alto Relex (Figure 4.33). Most of the actual fault plane has been eroded away or covered by alluvium, but a 900-foot, near-vertical fault-line scarp can be observed (Figure 4.34). In several areas, breccia associated with this fault is more resistant to weathering than the surrounding Boquillas Formation and sticks up as fins that have a distinctive reddish color, which makes this fault zone easy to identify. The matrix of this breccia (Figure 4.35) varies in color from red to orange to black, and the clasts (60%) range from cobble to pebble size, consisting of mostly limestone. The composition of these limestone clasts must have been altered because they do not react with acid and typically have a hardness between 5 and 7.

This fault has dropped the Boquillas Formation against the Lower Santa Elena Limestone, indicating that there is at least 1,000 feet of vertical

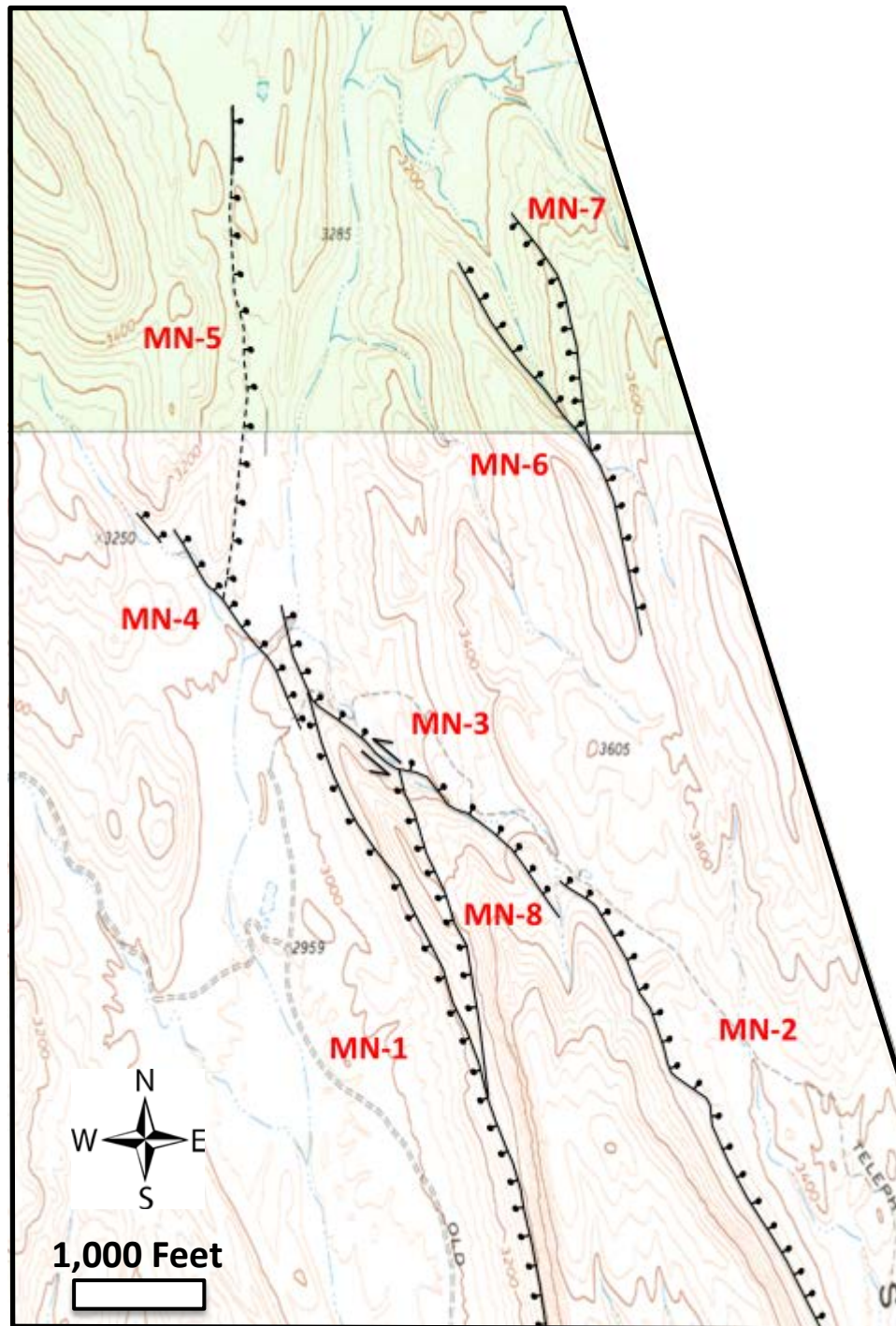


Figure 4.33 - Locations of major normal faults in the study area.

displacement. Portions of the fault plane crop out along the outer boundaries of this red breccia zone and indicate an average strike and dip of N30°W, 65°SW (Figure 4.37). Slickenlines have an average plunge and bearing of 65°, S70°W. The fault-line scarp created by this fault continues southward beyond the study area for approximately three miles. This is a basin bounding fault that is located on the western side of the Alto Relex horst block.

Another major normal fault (MN-2) was found on the eastern side of Alto Relex (Figure 4.33). A three to five foot zone of unaltered fault breccia (Figure 4.38) was found along this fault. In some areas, large (five to ten inch) rhombohedral calcite crystals are associated with this breccia (Figure 4.38). The Boquillas Formation is found on the downthrown (eastern) block of this fault and has an average strike and dip of N32°W, 80°NE (Figure 4.37). This near-vertical bedding suggests that a drag fold was created by MN-2. Cliffs on the eastern side of Alto Relex generally have 100 to 200 feet of topographic relief. Based on this relief and stratigraphic relationships, a vertical displacement of approximately 600 feet can be interpreted. The average strike and dip of this fault plane is N30°W, 66°NE, (Figure 4.37) and the average plunge and bearing of the slickenlines are 50°, N82°E. MN-2 is the basin bounding fault on the east side of the Alto Relex horst block.

Normal fault MN-3 is unique because the fault planes are found alongside the strike-slip fault planes of MSS-1. At locations where this fault plane is

exposed it displays oblique slickenlines and has chatter marks that suggest that the east side went down. MN-3 could also be an extension of MN-2 that was displaced by the right-lateral strike-slip fault MSS-2. The average strike and dip of MN-3 is N53°W, 65°NE, and the average plunge and bearing of slickenlines are 35°, S30°E (Figure 4.37). Approximately 400 feet of displacement can be interpreted along this fault.

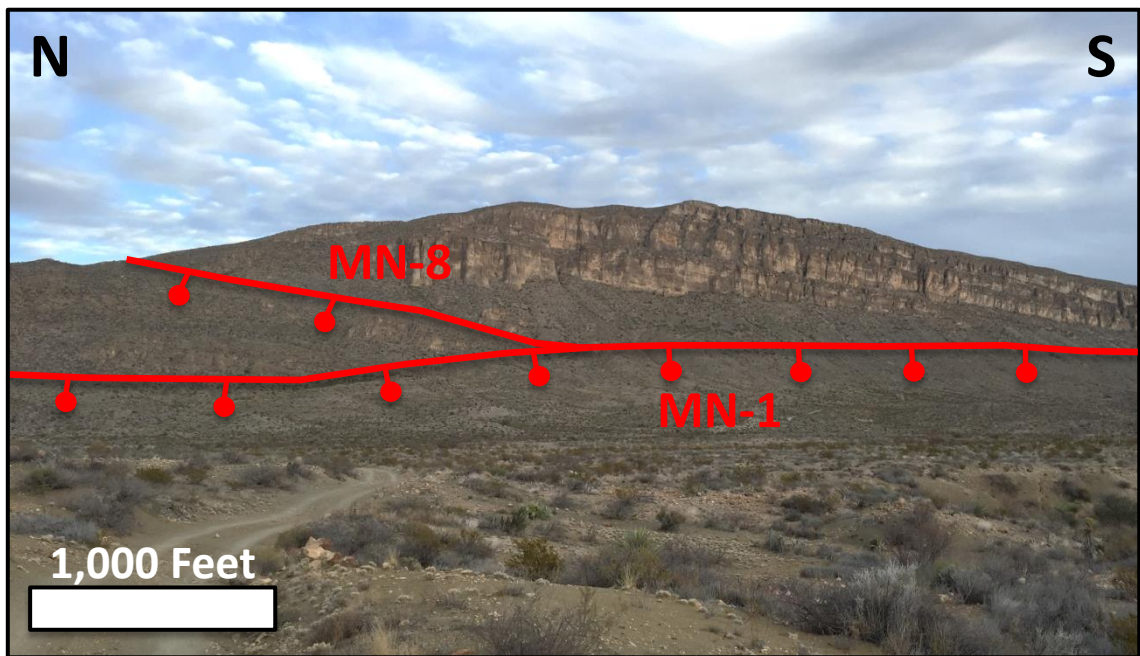


Figure 4.34 – An eastward view of the fault line scarp located on the western side of Alto Relex. The approximate locations of major normal faults MN-1 and MN-8 are shown in red.

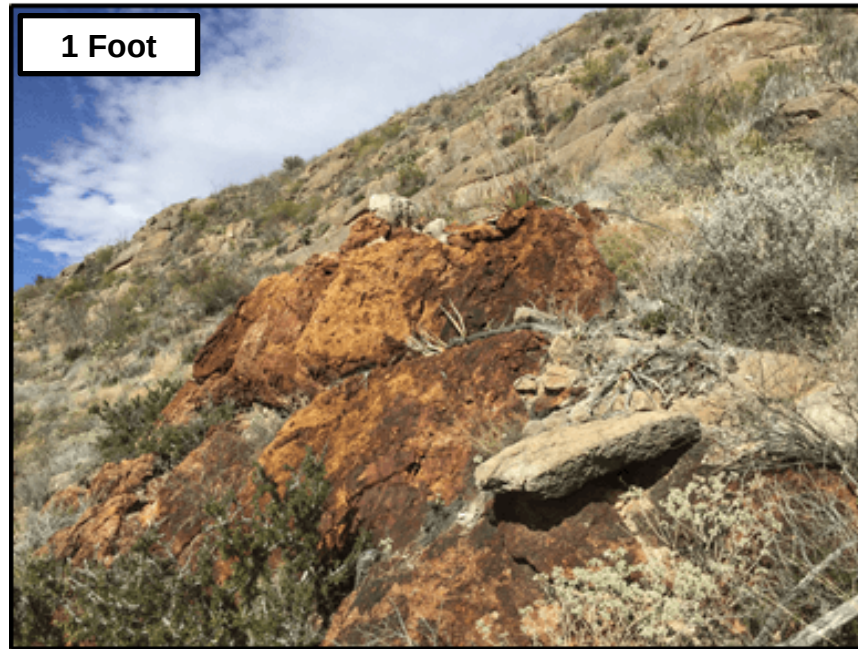
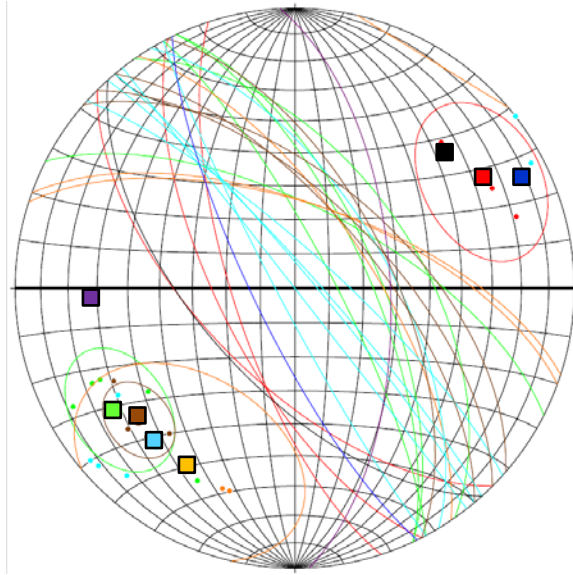


Figure 4.35 - Red fault breccia associated with MN-1 (S201).



Figure 4.36 – The fault plane of major normal fault MN-4 (S196) which is associated with large outcrops of red-stained vertical “fins”.

Stereonet Diagram Displaying the Strike and Dips of Major Normal Faults (MN)



Average Strike and Dips of Major Normal Faults			
MN	Color	Strike and Dip	n
MN-1	Red	N30°W, 68° SW	3
MN-2	Green	N35°W, 69° NE	5
MN-3	Orange	N59°W, 66° NE	3
MN-4	Cyan	N36°W, 84° NE	6
MN-5	Purple	N3°W, 62° NE	1
MN-6	Brown	N40°W, 63° NE	5
MN-7	Black	N42°W, 62° SW	1
MN-8	Blue	N26°W, 78° SW	1

Figure 4.37 – Equal area stereonet displaying the orientations of major normal faults found in the study area. Mean vectors of the poles are plotted on the stereonet as squares and the average strike and dips of the faults are located in the table. The trends of these normal faults have a bimodal distribution of dip direction, which is indicative of horst and graben fault zones.

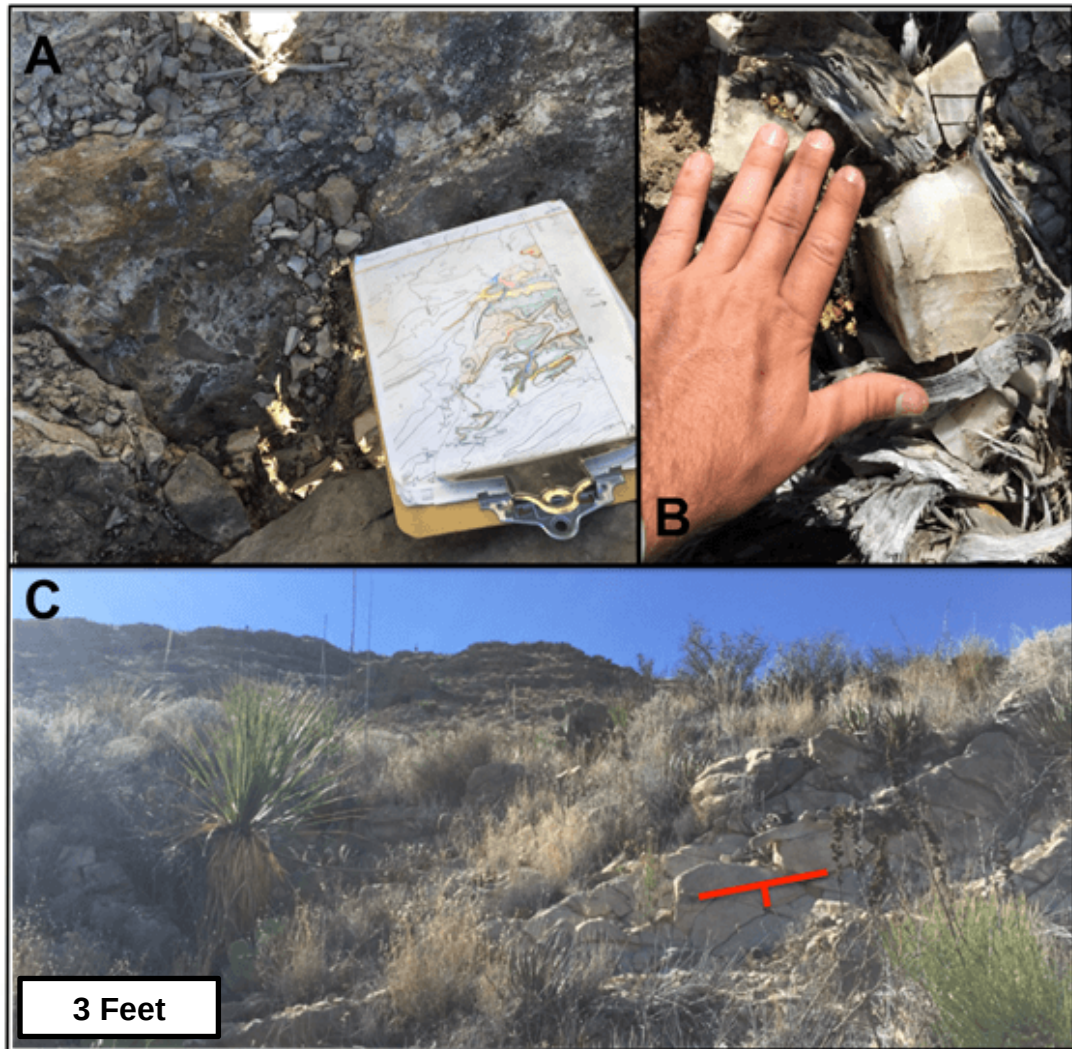


Figure 4.38 – Different features found along fault MN-2. A) Breccia zone (S151). B) Large calcite rhombs (S242). C) Vertical bedding (S248) of the Boquillas Formation (Kbo). These features were common along normal faults found on the eastern side of Alto Relex.



Figure 4.39 - Eight-foot tall fault plane with large breccia zone found along MN-4. View to the north from location S32/141.

Large normal fault MN-4 (Figure 4.33) is in the Boquillas Formation and trends almost parallel to MN-1 but it is dipping to the northeast. The fault breccia zone ranges from three to ten feet thick and at one location (S32) an eight-foot tall fault plane was found with abundant slickenlines (Figure 4.39). These slickenlines are in red breccia similar to those found along the fault plane of MN-1.

Chatter marks indicate that the east side of this fault went down. The amount of displacement along this fault is unknown but it does contain large amounts of fault breccia. In some areas, such as S143, a five-foot-thick zone of liesegang banding was found bordering this fault zone. Liesegang banding is further evidence of hydrothermal alteration along this fault zone. The average strike and dip of the MN-4 fault plane is N45°W, 75°NE, (Figure 4.37) and the average plunge and bearing of slickenlines is 70°, N51°E. Aerial imagery suggests that this fault zone continues northwestward into the McKinney Hills laccolith and could be over two miles long.

The major normal fault MN-5 (Figure 4.33) also has red breccia that is similar to the breccia found along fault zones related to MN-1 and MN-4. However, in this area the breccia was weathered and appeared as float pieces that were dispersed in a linear pattern along the landscape. Slickenlines were commonly found on pieces of the fault breccia. Measurements were taken on a possible intact fault plane segment that seemed to match the trend of the trail of breccia float. The probable strike and dip of MN-5 is N3°W, 62°NE, (Figure 4.37) with slickenlines that have a plunge and bearing of 57°, N58°E. The amount of vertical displacement could not be determined at this location.

MN-6 (Figure 4.33) was found in the northeastern portion of the study area and contains a calcite-rich fault zone that ranges from one to four feet thick. The displacement of this fault is easily determined due to the cliff-forming nature of

the Santa Elena Limestone on the upthrown (western) block and the slope-forming Del Rio Clay in the downthrown block (eastern) (Figure 4.40). There is approximately 700 feet of displacement along this fault. The average strike and dip of this fault is N45°W, 60°NE, (Figure 4.37) and the slickenlines have an average orientation 58°, N48°E.

MN-7 (Figure 4.33) is trending parallel the major normal fault MN-6 but is dipping in the opposite direction (SW). The area between MN-6 and MN-7 could represent a small, down-dropped graben. The amount of displacement is approximately 150 feet. The average strike and dip of the fault is N42°W, 62°SW, (Figure 4.37) and the slickenlines have an average plunge and bearing of 44°, S18°W.

The normal fault plane MN-8 (Figure 4.33) is located on the northern side of Alto Relix. This fault has juxtaposed the Upper Santa Elena Limestone and the Lower Santa Elena Limestone. This fault has a strike and dip of N26°W, 78°SW and could have approximately 300 feet of vertical displacement.

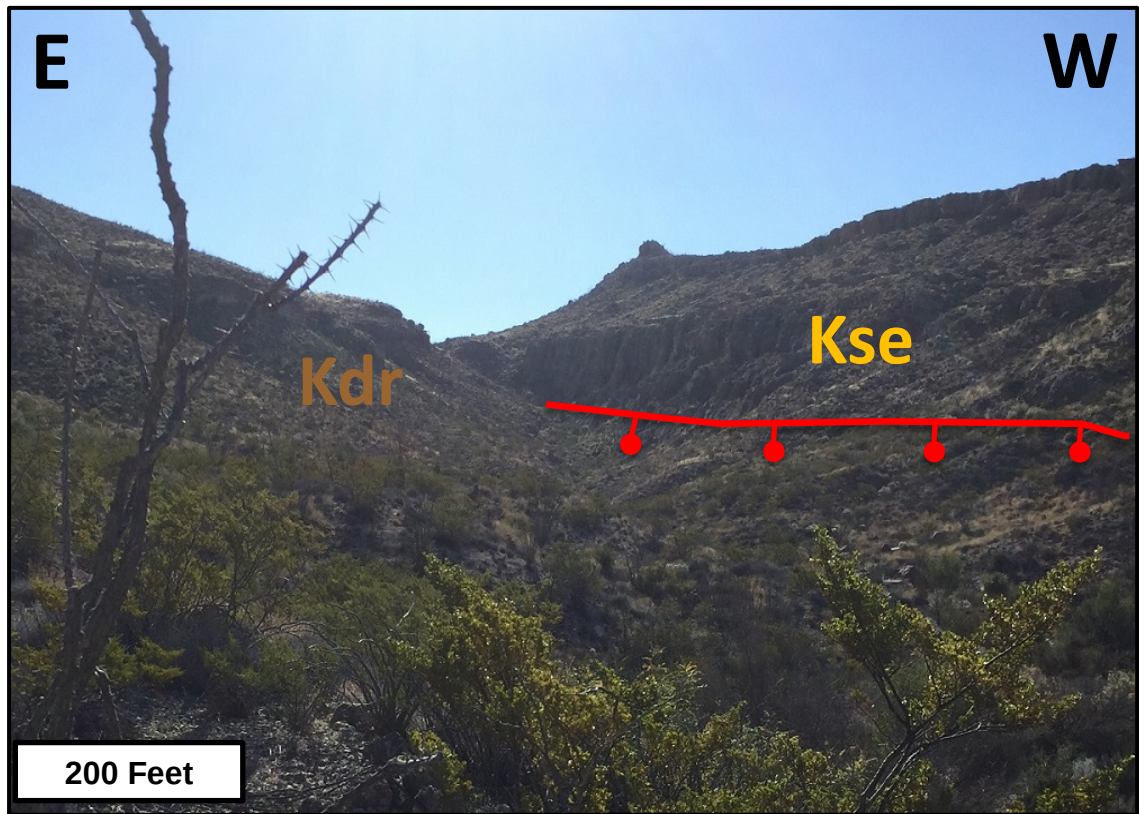


Figure 4.40 - Valley that was created by MN-6. Note the cliff forming Santa Elena Limestone to the west and the slope forming Del Rio Clay on the east.

Minor Normal Faults

Minor normal faults in the area typically have only one to five feet of displacement, small calcite deposits and minimal fault breccia. These faults (N-1 to N-14) were found in multiple rock units and are fairly common in the study area (Figure 4.41).

The fault planes discovered at N-1, N-2 and N-3 (Figure 4.41) are important to this study, because slickenlines have indications of both left-lateral strike-slip and oblique normal faulting (Figure 4.31). These locations have previously been mentioned in the strike-slip fault section above (SS-1, MSS-1 and SS-3). Finding two distinctively different slickenside orientations may indicate fault reactivation.

Minor normal fault N-1 has an average strike and dip of N31°W, 75°SW (Figure 4.42) and the slickensides have a plunge and bearing of 48°, S22°E. No obvious dip-slip displacement was identified in this location.

N-2 has an average strike and dip of N40°W, 75°SW, (Figure 4.42) and the slickenlines have a plunge and bearing of 58°, S40°W. There was approximately 10 to 15 feet of vertical displacement along this fault.

N-3 (Figure 4.41) was traced for approximately 4,000 feet and in one location displayed strike-slip movement. However, the majority of slickenlines found on this fault plane were suggestive of normal dip-slip movement. The

contact between the Del Rio Clay and the Buda limestone is displaced as much as ten feet in some locations. The average strike and dip of this fault is N28°W, 55°NE, (Figure 4.42) and the average plunge and bearing of the slickenlines are 50°, N30°E.

N-4 and N-5 are important because they are located adjacent to the McKinney Hills laccolith. Fault N-4 displayed approximately 15 feet of displacement, lacked distinct slickenlines and has a strike and dip of N43°W, 82°SW (Figure 4.42). N-5 has a strike and dip of N72°E, 46°SE, and the slickenlines have a plunge and bearing of 45°, S49°E (Figure 4.42). The orientation of this fault plane is dissimilar to other normal faults found during this study.

N-6 to N-14 (Figure 4.41) are all minor normal faults (Figure 4.43) that could represent synthetic or antithetic fault planes associated with zones of major normal faulting. Fault plane orientation, amount of displacement, interpreted length and distinctive features associated with these faults are listed in Table 4.1.

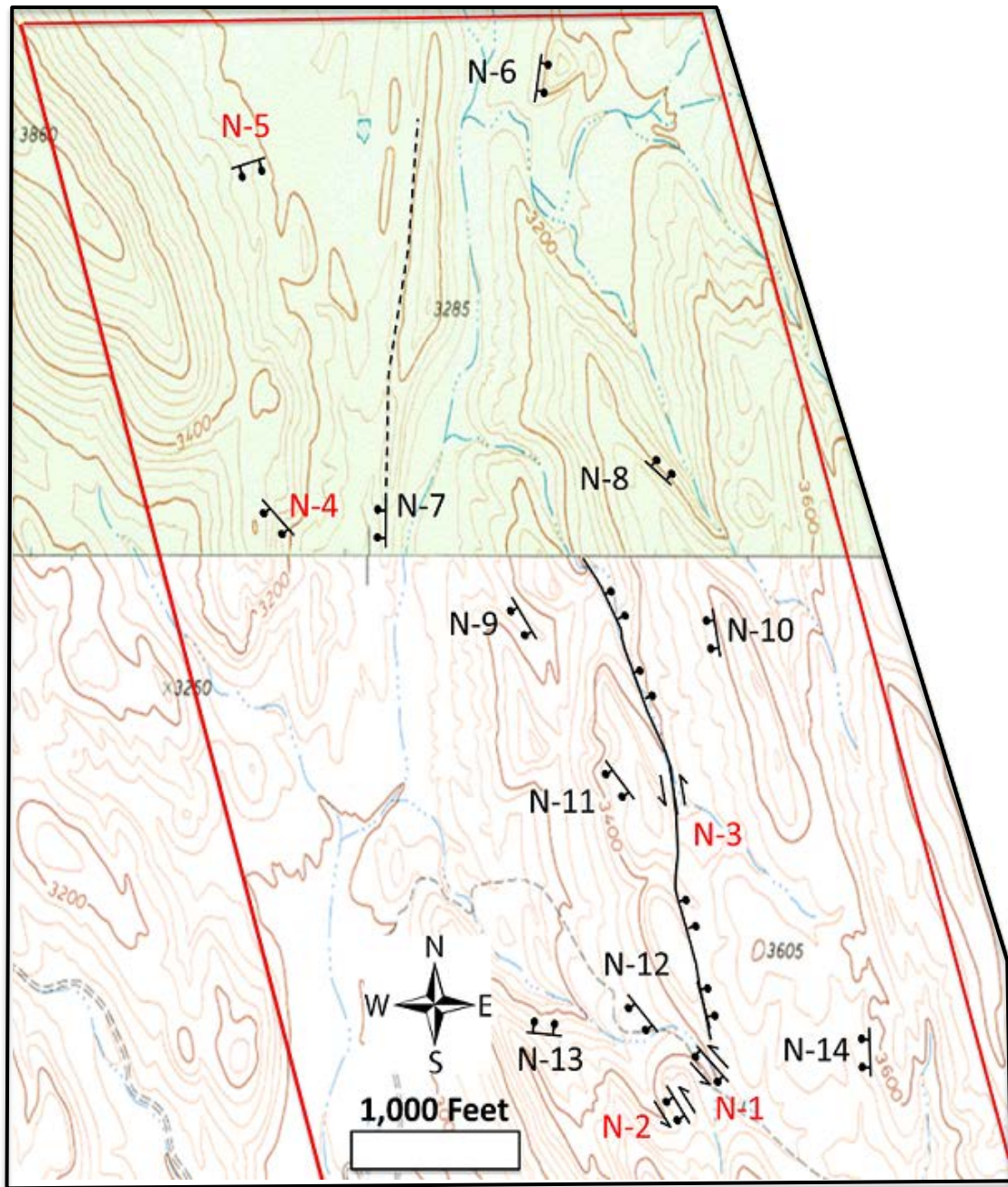
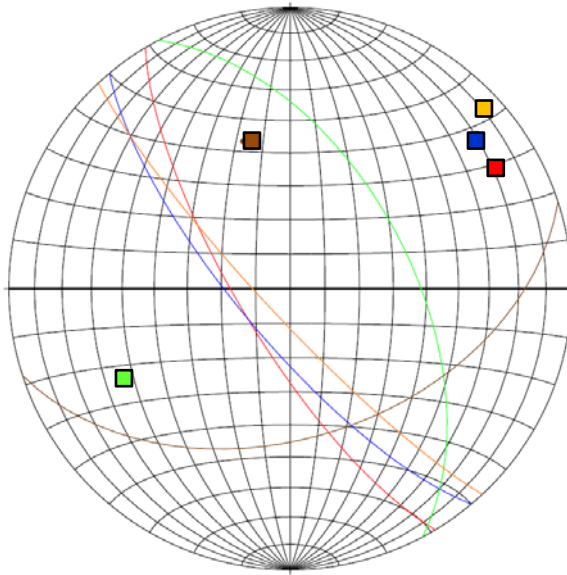


Figure 4.41 - Topographic map displaying the locations of all the minor normal faults that were discovered in the study area. The faults that are discussed in the minor normal faults section are highlighted in red.

Stereonet Diagram Displaying the Strike and Dips of
Discussed Minor Normal Faults (N)



Strike and Dip Measurements from Minor Normal Faults			
N	Color	Strike and Dip	n
N-1	Red	N31°W, 75° SW	1
N-2	Blue	N40°W, 75° SW	1
N-3	Green	N28°W, 55° NE	1
N-4	Orange	N43°W, 82° SW	1
N-5	Brown	N72°E, 46° SE	1

Figure 4.42 - Equal area stereonet displaying the fault plane orientations of the discussed minor normal faults. Mean vectors of the poles are plotted on the stereonet as squares and the strike and dips of the faults are located in the table. Some of these orientations are dissimilar to other minor and major normal faults found during this study.



Figure 4.43 - Typical minor normal fault in the study area (S40).

Fault Location	S&D of Fault Plane	P&B of Slickenlines	Displacement	Estimated Length	Other Features
N-6	N8°E, 58° SE	50°, N70°E	2 Feet	35 Feet	Large Calcite Crystals
N-7	N0°, 73°W	No Slicks	2 Feet	15 Feet	
N-8	N40°W, 67° NE	55°, N60°E	N/A	300 Feet	Breccia/Calcite
N-9	N35°W, 62° SW	No Slicks	10 Feet	200 Feet	
N-10	N2°W, 67° SW	No Slicks	15 Feet	500 Feet	
N-11	N38°W, 86° SW	84°, S67°W	N/A	100 Feet	Calcite Mineralization
N-12	N22°W, 90°	No Slicks	N/A	25 Feet	Calcite Mineralization
N-13	N85°W, 35° NE	No Slicks	N/A	200 Feet	Large Calcite Crystals/ Breccia
N-14	N10°W, 90°	No Slicks	1 Foot	100 Feet	

Table 4.1 – Data acquired from minor normal faults N-6 to N-14. Data includes the strike and dip (S&D) of the fault plane, plunge and bearing (P&B) of slickenlines, amount of vertical displacement, the estimated length and other features that were associated.

Igneous Intrusions

Two different types of igneous intrusions were discovered during this study: the McKinney Hills laccolith and sills. Both of these intrusions could have created deformation of the surrounding host rock. The intrusion characteristics and the deformational features are discussed in the following sections.

McKinney Hills Laccolith

A small eastern section of the McKinney Hills laccolith is within the mapping area (Figure 4.6). This intrusion was injected into the Pen Formation and is responsible for over 500 feet of topographic relief. The contact between the Pen Formation and this intrusion is covered by float in the study area. Minor normal faults N-4 and N-5 are located near this intrusion and could be related to its emplacement. The strike and dip of N-5 is N43°W, 82° SW, and the strike and dip of N-6 is N72°E, 46° SW. N-5 has an anomalous orientation compared to other normal faults found in this study.

The altered fault breccia that is associated with some of the major normal faults in the study area are all located near the McKinney Hills laccolith. This altered fault breccia also has a distinctive iron red color similar to the weathered syenite of McKinney Hills.

Sills

Two mafic sills (S-1 and S-2) were found in the northern portion of the study area (Figure 4.44). These sills were intruded into the Boquillas Formation, which is stratigraphically lower than the McKinney Hills intrusion. In both locations where these sills are exposed, the contact between the sills and the Boquillas Formation is dipping in the same direction as the bedding. The igneous rocks in sills S-1 and S-2 are heavily fractured and display spherical weathering (Figure 4.45).

Sill S-1 (Figure 4.44) is a fairly thick (7 to 15 feet), continuous mafic sill that crops out along the steep side of a N-S trending cuesta. This sill thickens to the south and commonly displays baked and chilled margins (Figure 4.45). At one location (S40), the sill splits into two layers; the top sill is approximately three feet thick and the bottom sill is around eight feet thick. Above the top sill a zone of deformation was discovered (Figure 4.45). This deformation includes a possible reverse fault and small-scale folding. The two sills combine northward and do not separate again to the north. Deformation zones are not found along the northern margins of this sill. S-1 can be traced for approximately 4,000 feet and is constantly concordant with bedding. Above this intrusion extensive boudin-like features can be found in the Boquillas Formation (Figure 4.45).

S-2 (Figure 4.44) was not as extensively exposed as S-1 but was found in two locations. It has a consistent thickness of about ten feet and also displays a baked and chilled margin. This sill is concordant with bedded of the Boquillas Formation and no deformation zones were discovered around this location.

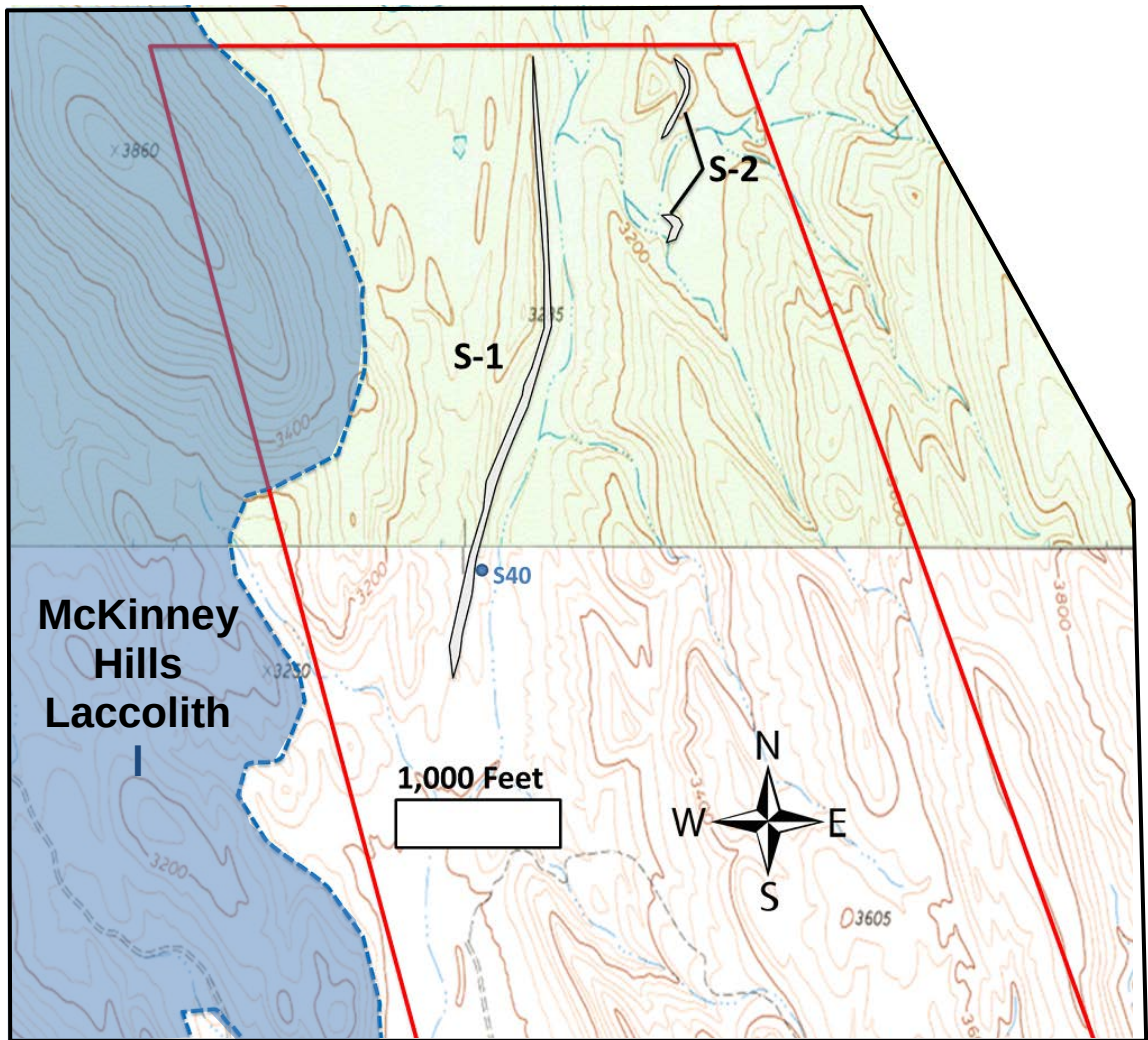


Figure 4.44 - Topographic map of the northern part of the study showing the location of sills S-1 and S-2. Outlined in blue is the approximate boundary of the McKinney Hills laccolith.

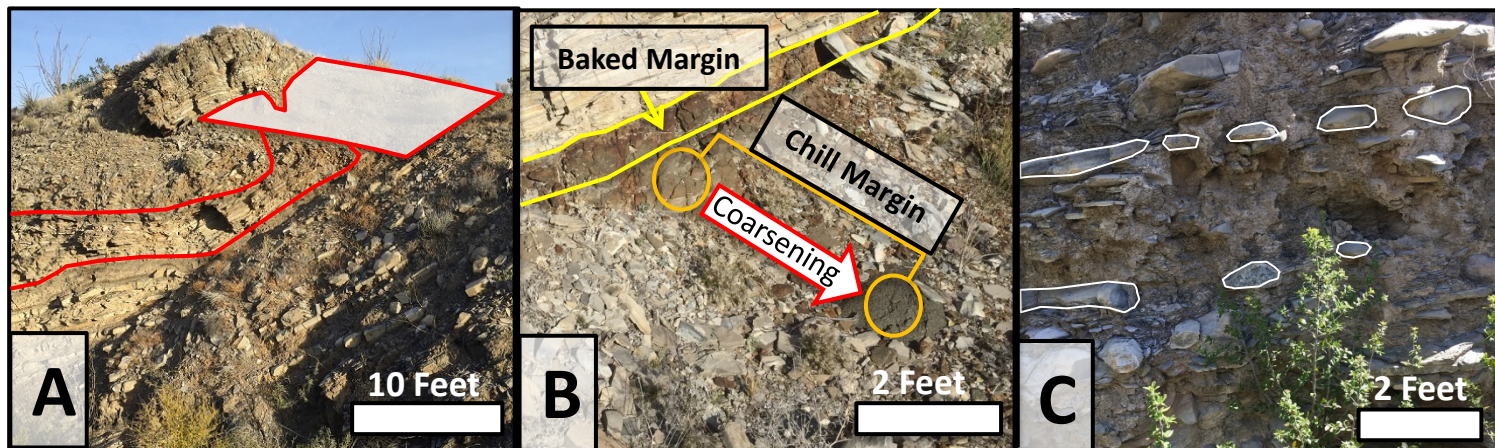


Figure 4.45 - A) Three foot sill (white) that has produced deformation of the Boquillas Formation (S40). Bedding has been traced (red) to show drag fold created by this intrusion. B) Baked (yellow) and chill margin (orange) typically observed on the sills in the study area (S173). B) C) Boudin like structures (white) found above the sill intrusion at location S40.

CHAPTER V

DISCUSSION AND INTERPRETATIONS

The study area has been subjected to multiple tectonic and igneous events that have created a variety of features including folds, thrust faults, strike-slip faults, normal faults, fault reactivation, sills and a large laccolith intrusion. In the following sections multiple geologic interpretations are discussed regarding how these features were produced or emplaced.

Mechanics of Map Scale Folding

This section discusses different geologic interpretations of events that could have created map scale folding (MSF-1 and MSF-2) in the study area. Typically, map scale folding of Cretaceous rock units in BBNP has been associated with two major tectonic events, the Laramide Orogeny and Basin and Range Extension. Multiple authors suggest that the structural trend of both these events was influenced by the Texas Lineament, a Proterozoic basement shear zone (Cobb and Poth, 1980; Moustafa, 1988; Page et. al, 2008)(Figure 3.3).

Anticline (MSF-1)

The large anticline (MSF-1) at the north end of Alto Relex (Figure 5.1) may be related to another large anticline called Roy's Peak anticline. This feature is approximately 0.5 miles west of the study area, trends roughly due north (varying from about N20°W to N18°E) and is approximately five miles long and one mile wide (Figure 5.1). The northern part of Roy's Peak anticline bends slightly to the northeast and if it continued bending, it would be on trend with the anticline that was found during this study (MSF-1). Thus, MSF-1 could represent an eastern continuation of Roy's Peak anticline (Figure 5.1). This anticlinal system appears to have been later cut and separated by Basin and Range normal faulting.

The broad anticline MSF-1 and Roy's Peak anticline were probably originally created during Laramide compression. The compression direction for the Laramide Orogeny has been interpreted by Moustafa (1988) to be approximately N70°E. His interpretation was based in part on calcite twinning strain analysis (Moustafa, 1988). Maler (1990) and Erdlac (1988) studied tectonic stylolites in the Big Bend area and concluded similar compressional directions of N58°E, N62°E and N75°E, respectively.

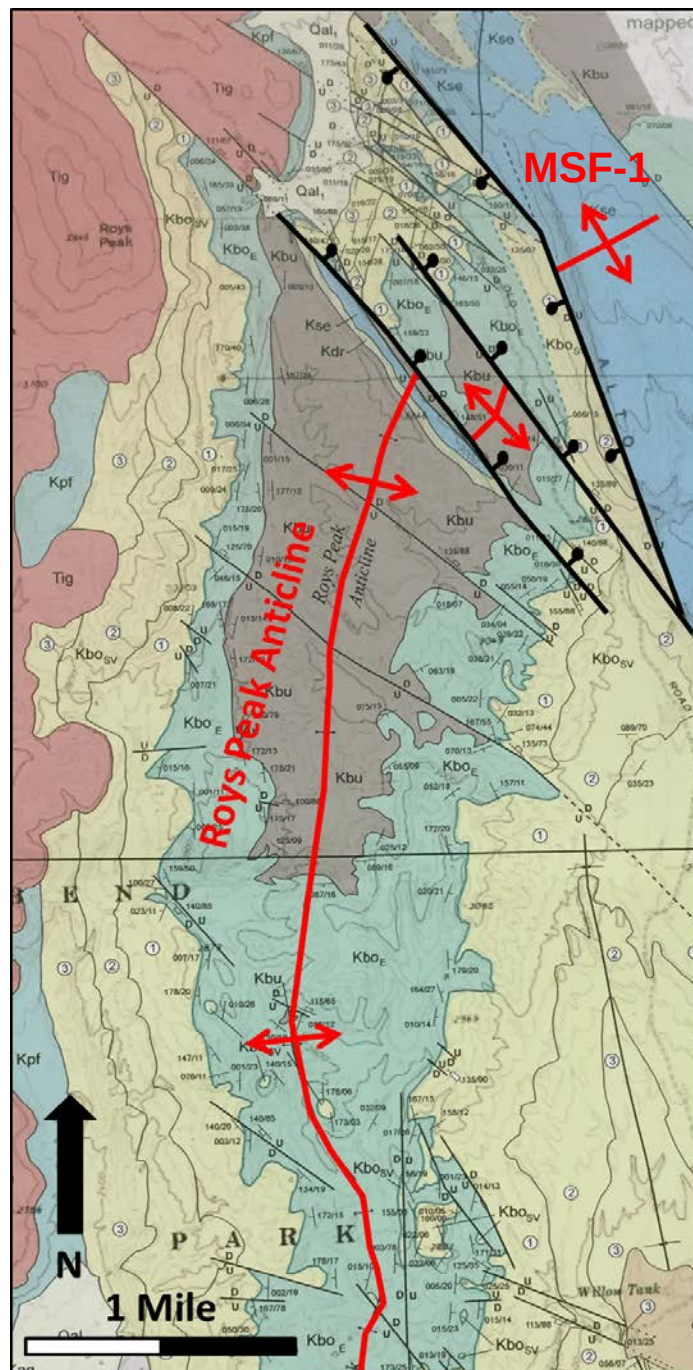


Figure 5.1 - Geologic map produced by Cooper and others (2011) with the axial plane of Roys Peak Anticline and MSF-1 highlighted in red.

Other map scales folds in BBNP that were created by this compressional direction trend between N15°W and N30°W (Page et al. 2008). The southern area of Roy's Peak anticline matches this trend. However, the overall trend of N10°E and the northeastward (N18°E, N60°E) bend on the northern portion could be the product of basement reactivation of the Texas Lineament (Figure 5.2). Muehleberger (1980) suggests that this is an approximately 50 miles wide zone that trends N60°W through Trans-Pecos, Texas. Cobb and Poth (1980), Moustafa (1988) and Page and others (2008) suggest that this fault zone was reactivated during the Laramide Orogeny with a left-lateral sense of shear. The anticline MSF-1 could have been the result of an underlying left-lateral strike slip fault that is trending parallel to the Texas Lineament (Figure 5.2). Therefore, this anticline would have been created by transpressional forces that were created when the Laramide Orogeny reactivated the Texas Lineament. Figure 5.2 is a diagram showing how anticlines can be created in a strike-slip fault system. Evidence that suggests the reactivation of the Texas Lineament in the study area and other locations in BBNP, includes the presence of sinistral strike-slip faulting and the N50° to 60° W structural grain (Dickerson, 1980; Muehlberger, 1980).

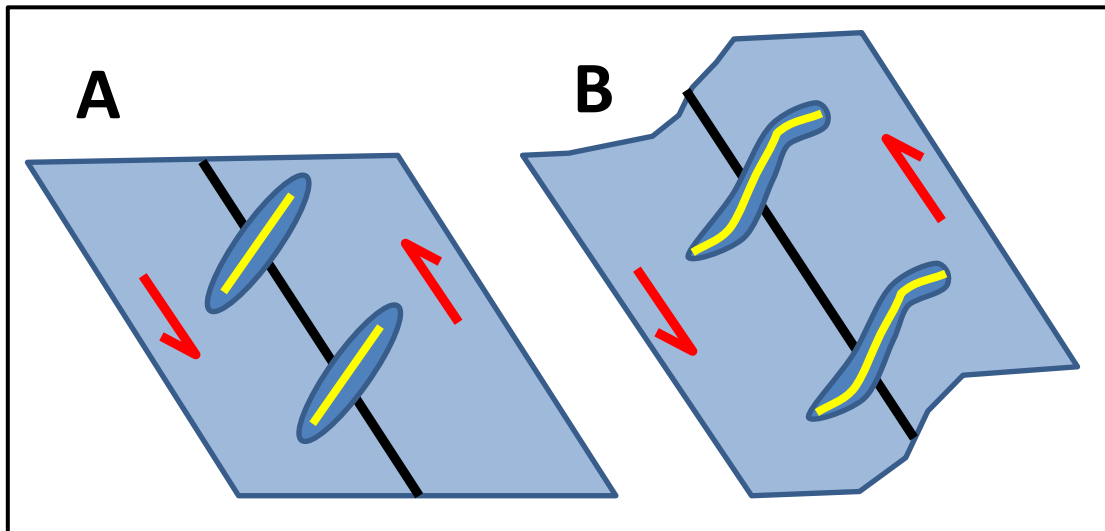


Figure 5.2 - Schematic diagram displaying how en-echelon folds are produced within a strike-slip fault zone. A) The folds are first developed 45 degrees from the main fault. B) As the shearing increases the folds begin to rotate with respect to movement.

Alternative Explanations for MSF-1

- 1) Another interpretation of how this large anticlinal feature (MSF-1) might have been produced includes transpressional stresses from the Laramide Orogeny and does not involve basement reactivation. Large strike-slip fault systems sometimes display braided patterns of anastomosing contemporaneous faults. When observing the overall geometry of Alto Relex and the Sierra del Carmen Mountains in map view, a faint braided-type pattern can be observed in the topography

(Figure 5.3). Significant evidence of a left-lateral strike-slip faulting was discovered during this study on the eastern side of Alto Relex. No evidence of strike-slip faulting was found on the western side of Alto Relex. Evidence of a strike-slip fault in this location might be elusive since it was overprinted by Basin and Range normal faulting or it could have been buried beneath alluvium. However, if there was indeed a sinistral strike-slip faulting on both sides of Alto Relex, the interior of this feature would have undergone transpressional stress. In this case, MSF-1 would represent an anticlinal fold created by strike-slip faulting. Anticlines are frequently found along strike-slip faults. Such folds are usually non-cylindrical, doubly plunging, have steeply dipping axial planes, commonly stepped, overlapping and arranged in an en echelon manner. However, in this study there is only one large-scale anticlinal fold with no evidence of others and the fold cannot be traced laterally. According to the model suggested by the hypothesis, the axial plane orientation of these folds would probably strike approximately N45°E. This is dissimilar to the axial plane orientation of MSF-1 (N63°E) and without any evidence of a strike-slip fault found on the western side of Alto Relex, this model is not likely to be the reason this feature was created.

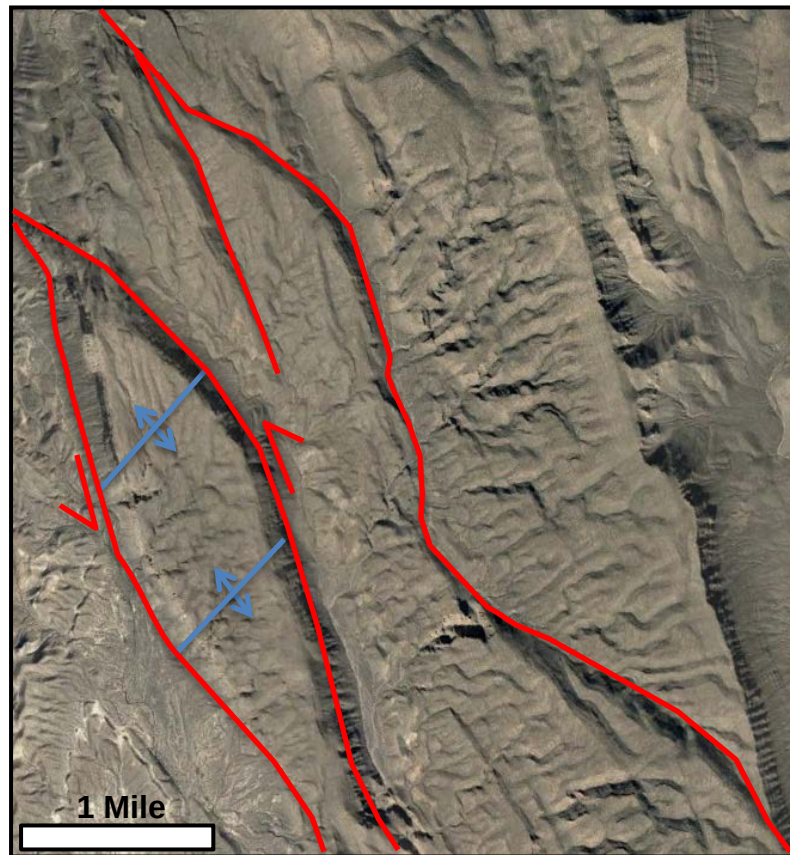


Figure 5.3 – Satellite image of Alto Relex and a portion of the Sierra del Carmen Mountain Range. Red lines display the location of major faults. These faults display a faint anastomosing characteristic that is common with strike-slip systems. If there were active left-lateral strike-slip faults on each side of Alto Relex during the Laramide Orogeny, the interior of Alto Relex would have been subjected to transpression forces and could have created anticlines. The blue lines represent the approximate axial plane orientation of these anticlines.

2) An additional interpretation is that the MSF-1 fold was created by a positive flower structure (Figure 5.4). MSF-1 is only observed on the western side of Alto Relex, near a right stepping bend of a normal fault. Similar to the last scenario, if this fault was once a left-lateral strike-slip fault, a positive flower structure would have developed. However, no indications of sub-vertical thrust faults were discovered during this study. Still, this flower structure could have been created by blind thrusts.

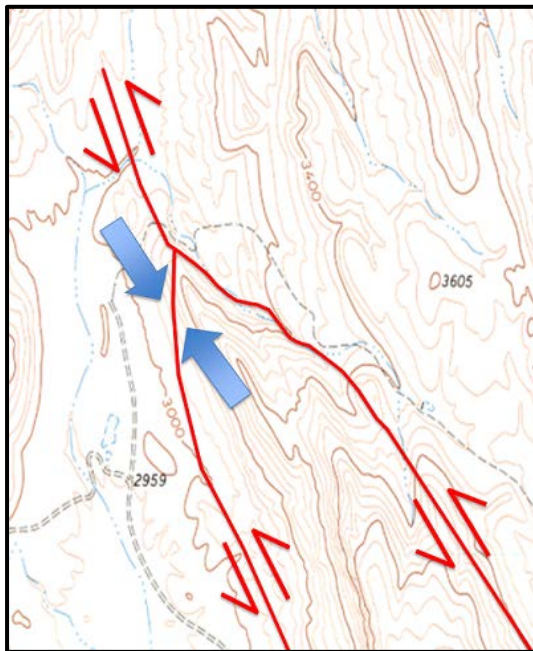


Figure 5.4 – Topographic map displaying the possible locations of left-lateral strike-slip faults on each side of Alto Relex. The right stepping bend on the western fault could have been an area that was subjected to transpression. The blue arrows indicate the direction of this stress. A positive flower structure would likely be produced in this scenario.

Monocline (MSF-2)

The creation of monoclines in BBNP is typically attributed to two different mechanisms, including contractional fault propagation folding and extensional fault propagation folding (Lopez et al., 2015; John, 1966; Page et al., 2008; Cobb and Poth, 1980) (Figure 5.4).

The MSF-2 monocline trends N5°W and could have been created during Laramide compression. This scenario postulates a blind reverse fault in the subsurface that is striking north and dipping to the east. Most of the minor thrust faults found in the study area are located near MSF-2 and could have been created associated with flexural slip during the creation of this flexure. These thrust faults are evidence that compressive forces were present in this location and could have created this feature.

Eastward dipping reverse faults are at odds with what is expected to be created by northeastward compression. However, eastward dipping reverse faults associated with the Laramide Orogeny have been discovered further north in the Santiago Mountains and at Persimmon Gap (Dickerson, 1980). In this location, Laramide thrusting has been interpreted to have a westward transport direction, which could be related to a north trending basement ridge uplift (Dickerson, 1980).

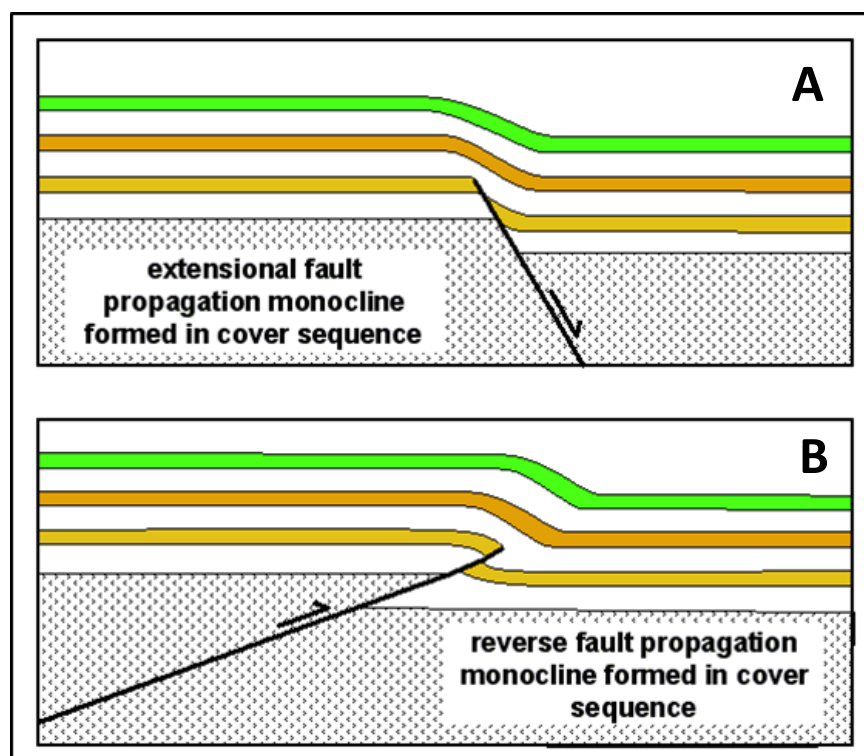


Figure 5.5 – Diagram displaying the different ways that have been suggested for the creation of monoclines (from Norton, 2017). A) This diagram shows how monoclines can be created by basement normal faults. B) Diagram showing how monoclines can be created by basement thrusting.

Another interpretation is that MSF-2 was created during Basin and Range extension. MSF-2 would then represent a drape fold that was created by a blind normal fault, striking north and dipping west. Only one major normal fault found during this study matches this slight northwest trend.

Both contractional and extensional monoclines have been found approximately 20 miles north of the study area at Big Brushy Canyon (Lopez, et al., 2015). The contractional monoclines have an average axial plane of N28°W,

85°NE and were interpreted to be fault propagation folds above blind reverse faults (Lopez et al., 2015). The extensional monoclines in their study area have an average axial plane of N38°W, 64° SW and were interpreted to be drag folds or extensional propagation folds (Lopez, Welch and Satterfield, 2015).

Based on the presence of minor thrust faults and the similarity of orientations between the monocline (MSF-2) found in the study area and those found at Big Brushy Canyon, it is likely that the Laramide Orogeny created this feature.

Mechanics of Outcrop Scale Folding

Outcrop scale (smaller) folds in the Boquillas Formation are found in multiple areas throughout Trans-Pecos, Texas. Some postulated theories on how these folds formed include flexural-slip associated with Laramide compression, soft-sediment deformation or as features related to teepee structures.

If these folds were created by soft-sediment deformation, they would most likely represent slump folding. Slump folding can occur when sediment is liquefied on a continental slope (Southard, 2007). These folds are commonly tight, isoclinal to recumbent and have a downslope vergence (Southard, 2007). In this study, the folding is not tight, isoclinal or recumbent. The folding present also

displays axial planes that are mostly sub-vertical, so it is doubtful that these folds were a result of soft-sediment deformation.

In some areas the folding in the Boquillas has been attributed to the creation of teepee structures. Teepee structures are thought to be related to lateral expansion of a rock layer or caliche wedging (Lock et al., 2001). Veni (1994) suggested that the hydration of clays could also be the driving factor in creating these teepees. Teepees structures are typically sharp, angular anticlines that contain a brecciated core (Lock et al., 2001). In the small folds found in the study area, there is lack of both caliche and brecciation zones. Thus, it is not likely that the folds in the study area are related to teepee structures.

Evidence that these folds were created by compression during the Laramide Orogeny is their axial plane orientation. All of the outcrop scale folds found during this study have a similar strike orientation of N30°W, which is nearly perpendicular to the maximum compressional direction of N58° to 75°E that was determined by Maler (1990) and Moustafa (1988). Some of these folds also verge northeast towards the compressional direction. However, one set of folds (Fo-5) verges to the southwest and has northeast dipping axial planes. This change in dip direction may have been caused by a slight change in local stress intensity or have to do with the mechanical properties of the rocks at this location.

Seven miles south of the study area, extensive outcrop scale folding that has been attributed to Laramide compression can be found in Ernst Tinaja

Canyon (McGinnis, 2017; Silberstorf, 2017). At this locality, multiple folds can be found with slickenlines between layers (Silberstorf, 2017). The average strike and dip of fold axial planes in this location was N13°W, 70° SW, which is very similar to those observed during this study (Silberstorf, 2017).

Outcrop scale folds discovered during this study are parallel folds, which are commonly associated with folding that is created by flexural slip (Donath and Parker, 1964). Flexural slip (Figure 5.5) occurs when beds have a high competency contrast and are subjected to horizontal compression. The bedding-parallel slip during folding can result in slickenlines between layers of bedding. No slickenlines of this type were discovered in this study but slipping would be expected to occur between alternating thin beds of limestone and shale. Outcrop scale folds in the study area were all found in locations where the Boquillas Formation had alternating thin limestone beds between thick shale packages. This stratigraphic relationship is a good example of a unit that has a low mean competence and a high competence contrast.

Folding was not present in locations where the Boquillas Formation contained more limestone than shale beds. This stratigraphic combination is not suitable for flexural-slip because it increases the mean competence and lowers the competence contrast.

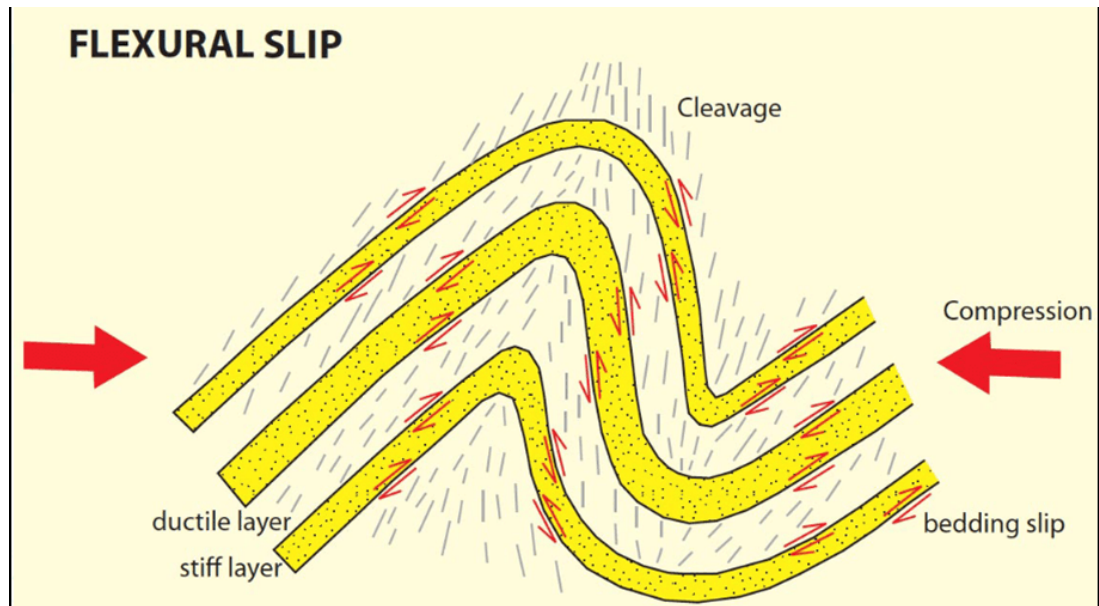


Figure 5.6 - Diagram illustrating the mechanics of flexural slip in a layered rock formation that contains alternating ductile (incompetent) and stiff (competent) layers (from Hatcher, 1995)

Faulting

Numerous faults were found in the study area, including minor thrust, strike-slip and normal faults, which indicate that this area has undergone a complex tectonic history. In this section, possible causes and implications of faulting are discussed.

Laramide Compressional and Transpressional Faults

The only compression event that has directly affected Cretaceous rock units in the study area is the Laramide Orogeny.

Laramide northeast compression created multiple thrust and reverse faults in the Santiago and Sierra del Carmen Mountains (Dickerson, 1980). Only minor thrust faults were found during this study, but as mentioned earlier, there may be a significant blind thrust beneath the monocline (MSF-2).

The majority of the minor thrust faults (T-1 to T-4) have an average strike of N20°W with dips that vary from 12° to 48° SW. The orientation of these minor thrust faults matches the overall orientation of the Sierra del Carmen Mountains (Cobb and Poth, 1980). This mean orientation suggests that these faults were probably produced by the same Laramide compression that produced the surrounding Sierra del Carmen Mountains (Imrecke et al., 2015). Thrust faults

T-5 and T-6 dip to the northeast and could represent back-thrusting during this event.

Several of these thrusts were found within the Del Rio Clay almost parallel with bedding and could represent surfaces or faults associated with flexure slip during the creation MSF-2. In some areas (T-1, T-3, T-4 and T-6) these fault planes are sub-parallel to bedding and are found between an upper resistant limestone bed and a less resistive clay bed. As previously mentioned, this competency contrast would be an ideal stratigraphic position for flexure slip to be produced. The N5°W trend of the monocline is also similar to the common N20°W thrust fault orientation.

Several authors have associated left-lateral transpression with the Laramide Orogeny (Maler, 1999; Moustafa, 1988; Cobb and Poth, 1980; Pearson, 1989; Erdlac, 1990). Moustafa (1988) mapped multiple left-lateral strike-slip faults in the Sierra del Carmen Mountain range (Figure 5.7). The regional pattern of these mountains suggests that the Texas Lineament (which underlies this area) was reactivated during this orogeny (Cobb and Poth, 1980; Page et al., 2008).

The most notable sinistral strike-slip fault found in the study area is MSS-1. This fault was probably created due to reactivation of the Texas Lineament basement fault. Evidence supporting this interpretation includes the trend of the fault and the sense of shear. When the Texas Lineament was reactivated during

Laramide compression, it was a left-lateral shear zone that was trending N60°W (Muehlberger, 1980). Like the Texas Lineament, MSS-1 is a left-lateral strike-slip fault that is trending approximately N52°W. Cobb and Poth (1980) proposed that left-lateral movement during the Laramide was mainly striking N50°W.

Some minor strike-slip faults (SS-1 and SS-2) could be related to the larger strike-slip fault, MMS-1. SS-1 could be a minor left-stepping fault, parallel to the major fault zone, and SS-2 could represent a minor synthetic P shear (Figure 5.8).

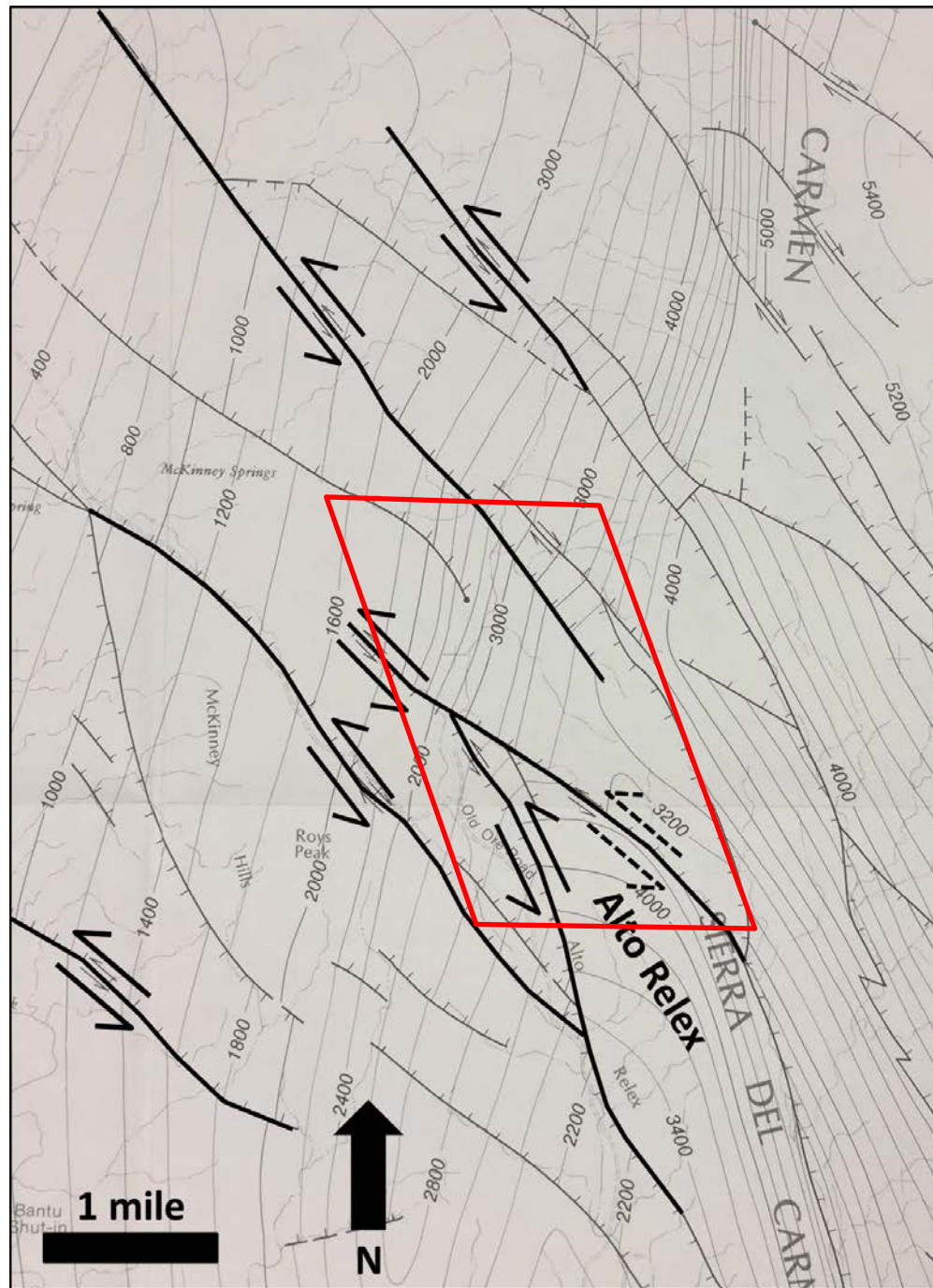


Figure 5.7 - Left-lateral strike-slips faults that were mapped by Moustafa (1988). Approximate location of the study area is highlighted in red.

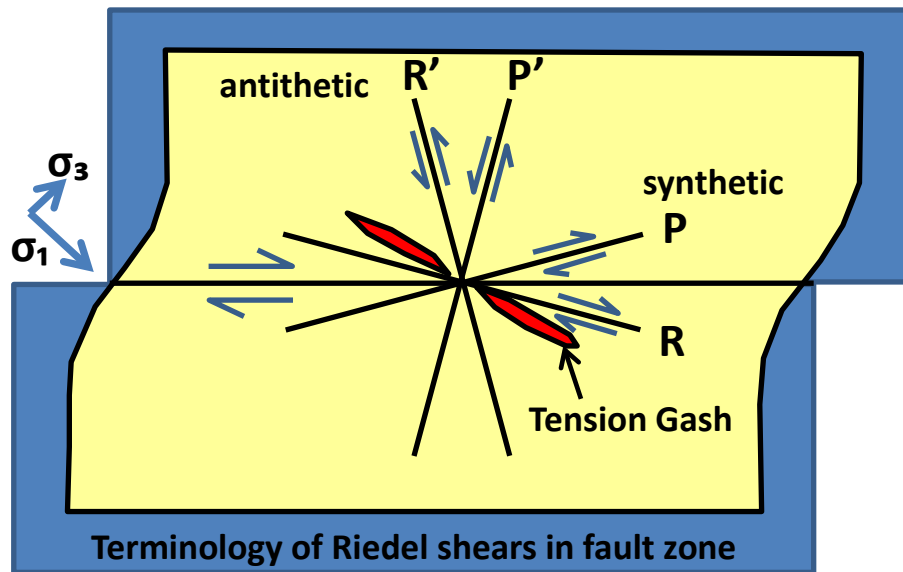


Figure 5.8 – Terminology of Riedel shears and other associated faults in a strike-slip fault zone. Riedel (R) shears are typically the first subsidiary faults to occur and typically develop between 10 to 20 degrees in the clockwise direction on a dextral fault and counterclockwise on a sinistral fault. R' shears are antithetic and are conjugates to Riedel shears. P shears are usually minor synthetic faults oriented opposite of Riedel shears. P' is the conjugate fault created by P shears.

Basin and Range Tensional and Transtensional Faults

Cretaceous rocks in BBNP were subjected to extension during the Basin and Range event. This episode began affecting southwest North America during the early Oligocene (31-32 Ma) but did not affect the Trans-Pecos region until the Early Miocene (23-24 Ma) (Henry and Price, 1986). This extension created multiple down-dropped basins and uplifted mountain ranges (Henry and Price, 1986; Page et al., 2008). The onset extensional direction in BBNP was oriented

approximately N67°E and later changed to approximately N67°W (Henry and Price, 1986). In this study, numerous major normal faults were discovered that have an average orientation of N31°W, which is approximately perpendicular to the early extensional direction of Basin and Range.

Some of the major normal fault zones are associated with distinctive red breccia (MN-1, MN-4 and MN-5) (Figure 4.33). Some of the clasts in this breccia contain laminations that resemble limestone beds of the Boquillas Formation but they do not react with acid. The fact that this fault breccia does not react with acid is striking because not only do some of the clasts look like limestone, but the study area contains multiple thick limestones rock formations. This breccia could have been altered by hydrothermal fluids that may have been associated with nearby igneous intrusions. This suggests that some normal faulting in the study area could have occurred before or simultaneous with the emplacement this igneous intrusion. The McKinney Hills laccolith is likely the source for the hydrothermal fluids that caused this alteration. Evidence for this interpretation includes the close proximity between the altered fault breccia and the McKinney Hills laccolith and the fact that the fault breccia displays a similar maroon color to the weather McKinney Hills syenite. Another bit of evidence is that not all major normal faults in the study area are associated with this red breccia, just those near McKinney Hills. This intrusion has been aged dated to 32.2 +/- 0.3 Ma (Turner et al., 2011), so these normal faults could have occurred much earlier

than previously reported by Henry and Price (1986) who suggested that faulting happen around 23 to 24 Ma.

In some locations (MN-3, N-1, N-2, N-3), oblique normal faulting was found in areas that contained indications of left-lateral strike-slip movement. This suggests that Basin and Range normal faulting might have reactivated some preexisting Laramide fault zones.

It has been suggested by several authors that Basin and Range extension had a right-lateral transtensional component (Erdlac, 1990; Dickerson, 1980; Muehlberger, 1980; DeCamp, 1985). This transtensional component was likely related to the reactivation of the Texas Lineament with a right-lateral sense of shear. Only one major right-lateral strike-slip fault was discovered during this study. This fault trends almost N-S along the eastern side of Alto Relex. In one location, this strike-slip fault displaces the major normal fault found on the eastern side of Alto Relex by about 100 feet (Figure 4.23). Silberstorf (2017) discovered a major N-S trending right-lateral strike-slip fault seven miles south of this location.

Several of the minor left-lateral faults that were found during this study had a few chatter marks that suggested a component of right-lateral movement. In one location along the sinistral strike-slip fault zone of MSS-1, there was a large tension gash that was suggestive of right-lateral shearing. This may be more evidence of fault reactivation during the Basin and Range.

On the southeastern side of the study area the dominate dip direction changes from SW/NW (R-1) to SE (R-2). This could represent a relay ramp that was created between two N-S trending normal faults (Figure 5.7). A relay ramp is a location where bedding has been reoriented between two overlapping normal faults.

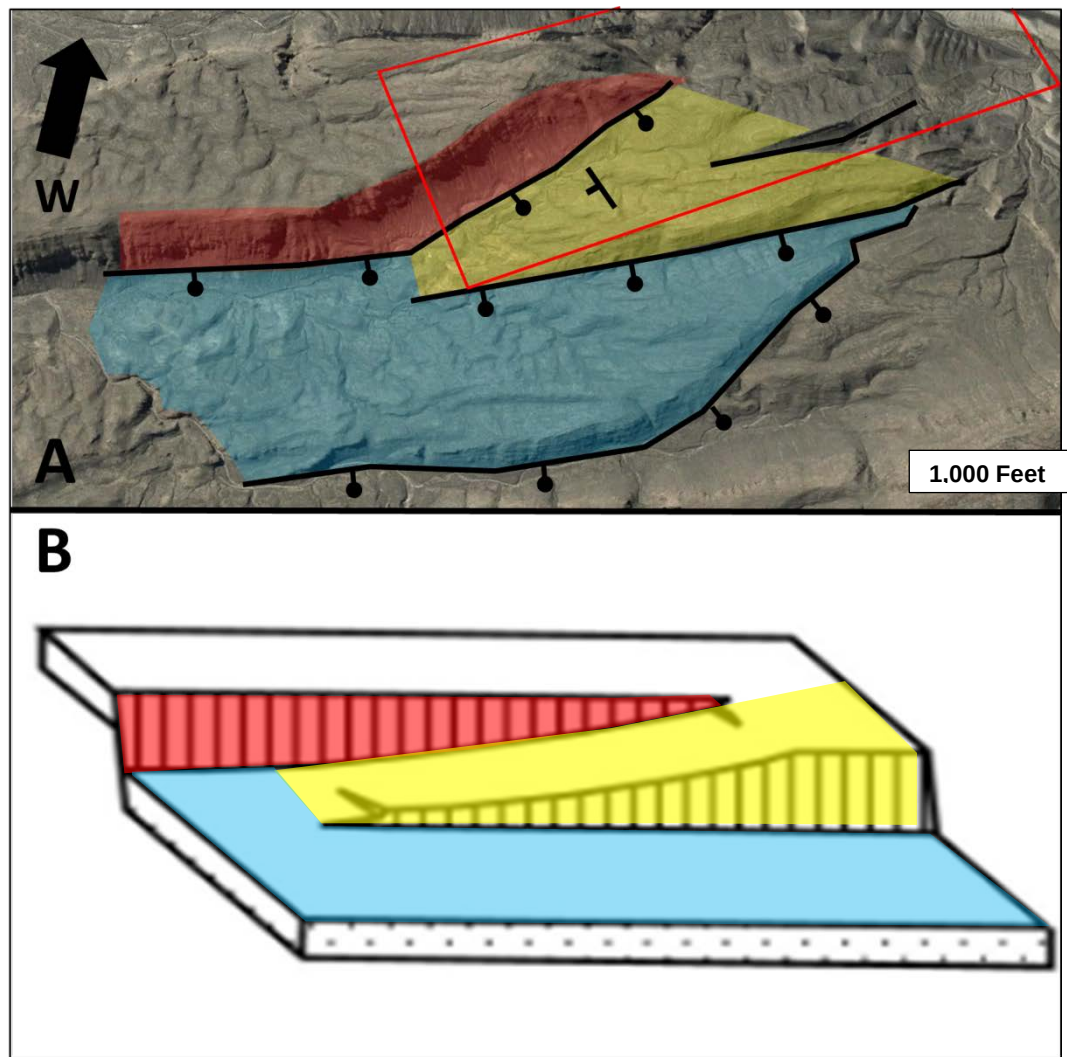


Figure 5.9 - A) Shaded relief image of the study area displaying a possible relay ramp on the eastern side of Alto Relex. The study area is highlighted with the red box. The red shading is the fault-line scarp on the eastern side of Alto Relex. The yellow shading is the location of the possible relay ramp, and the blue shading is marks the top of the eastern fault block (modified from Google Eart, 2017). B) Drawing of a common relay ramp structure (modified from Peacock and Sanderson, 1994).

Igneous Emplacement

McKinney Hills laccolith, immediately to the west of the study area, covers over 11 square miles and is estimated to be between 650 to 1,300 feet thick (Turner et al., 2011). Martin (2007) proposed that this magma used Laramide northeast dipping reverse faults as a preferential pathway. Once the magma reached a point where it was naturally buoyant within the host rock, lateral propagation began to occur (Martin, 2007). As more magma was added, it not only expanded laterally but this laccolith also pushed vertically upward and created structural relief. This intrusion likely caused domal uplift that would have created extension stresses in the overlying country rock.

Some minor normal (N-4 and N-5) faults in the study area were found in close proximity to the McKinney Hills laccolith and N-5 does not match the typical normal fault orientation created by Basin and Range. These faults could have been produced by the emplacement of this intrusion.

During this study, two sills were mapped just east of the McKinney Hills laccolith. Both of these sills were intruded into the thinly bedded Boquillas Formation.

Sills can be emplaced into rock formations in at least two different ways, passively or forcefully. Features associated with forcefully emplaced sills include concordant sill margins, deformation zones, boudin-like features that indicate

there was ductile stretching of rock layers and the presence of xenoliths (Cullen, 2013). Passively emplaced occurs when sills generally have a specific magmatic foliation and lack deformation zones (Cullen, 2013).

The boundin-like features and deformation zones found along the southern margins of S-1 suggest that this sill was forcefully injected. However, as this sill was traced northward this deformation disappears and in this area the sill may have been passively emplaced. Forceful emplacement at the southern end of S-1 could signify that it is closer to the magmatic source or feeder dike. All margins surrounding S-2 suggests that it was passively injected due to the lack of deformation zones.

The fact that McKinney Hills laccolith is emplaced stratigraphic higher than the sills suggests it was first to be intruded. The change in composition between the felsic syenite of McKinney Hills and the mafic sills could also suggest a different magmatic source or a bimodal magma chamber.

CHAPTER VI

CONCLUSIONS

The main goal of this thesis research was to map and understand the structural evolution of the Alto Relex area.

The first deformational event that directly affected the Lower and Upper Cretaceous rock units in the study area was the Laramide Orogeny during the Late Cretaceous to early Paleogene (70 – 50 Ma). This compression may have resulted in reactivation of a basement strike-slip fault zone, the Texas Lineament, which could have caused the study area and the surrounding Big Bend region to experience compressional and transpressional stresses. Features that were created during this compressional regime include minor thrust faults and map and outcrop scale folds (Figure 5.1). The large anticline (MSF-1) found on the northern end of Alto Relex is likely an eastern extension of Roy's Peak anticline and may have been produced by transpressional stress created when the Laramide Orogeny reactivated the underlying basement strike-slip fault. This proposed transpression would not only have helped in the creation of MSF-1 but also produced multiple left-lateral strike-slip faults in the study area.

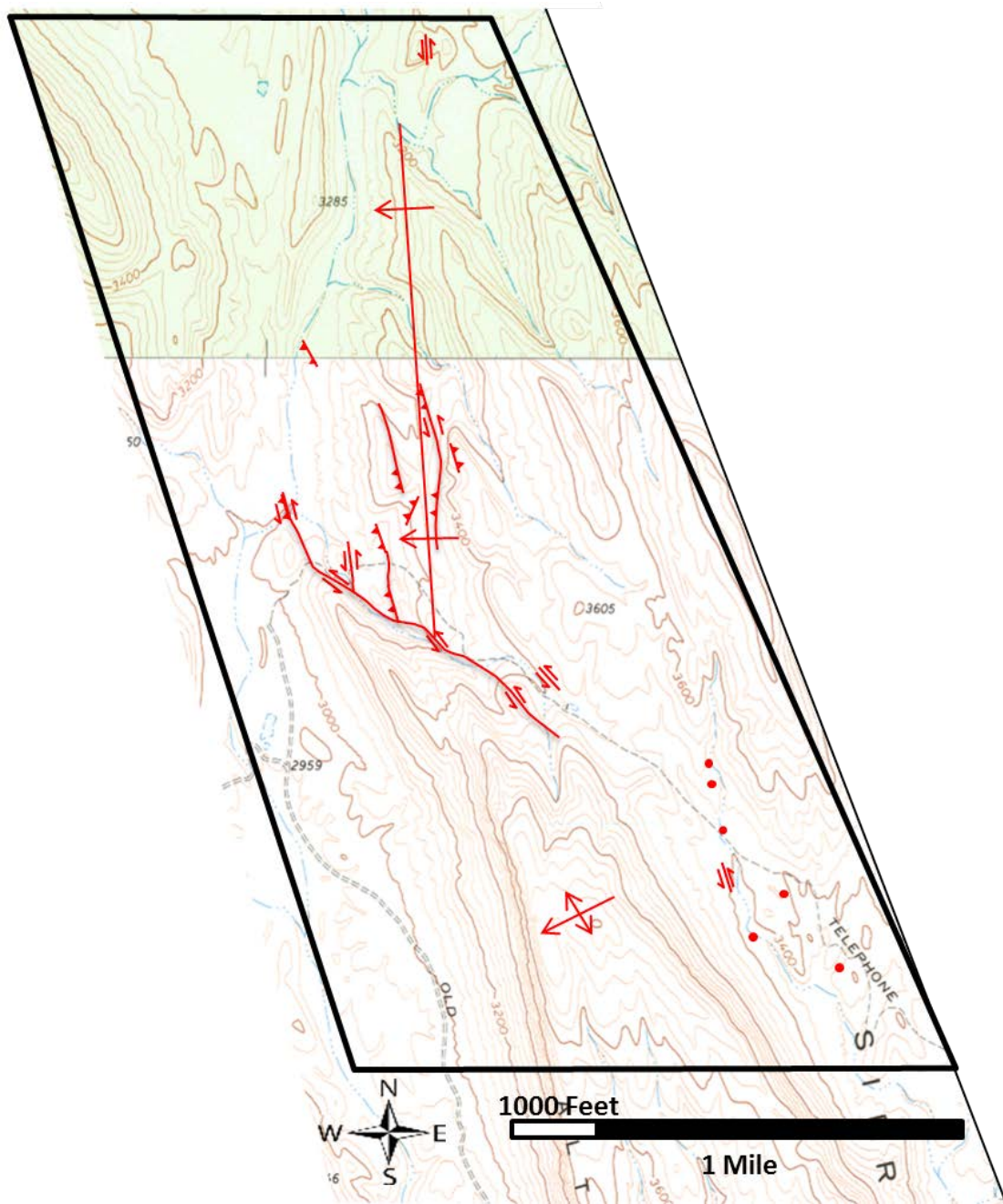


Figure 6.1 – Topographic map of study highlighting (red) the structural features that were created in the study area during the Laramide Orogeny. These features include map scale folds, outcrop scale folding (red dots), minor thrust faults and strike-slip faults.

The monocline (MSF-2) was probably formed by a blind, east-dipping reverse fault. The map scale folds just mentioned are evidence of Laramide compression, which also likely caused the regional southwest to northwest dip observed throughout the Sierra del Carmen Mountains. Smaller, outcrop scale folds were also probably associated with this event and may have been created by flexural slip along bedding planes.

During the Late Paleogene (around 32 Ma), the nearby McKinney Hills laccolith was injected into the Pen Formation (Figure 5.2). This event probably caused localized uplift that created normal faulting along and away from the roof of this intrusion. Some normal faults in the area may be associated with this emplacement. Nearby sills may have been injected during an earlier magmatic event. The southern margins of sill S-1 displays evidence of forceful emplacement and the northern margins seem to have been more passively injected. This suggests that the riser dike or magmatic source for this sill came from a southern location. Sill S-2 was passively injected and probably had a different magmatic conduit than S-1.

Basin and Range extension was the last major tectonic event to affect the study area. The topography of the Sierra del Carmen Mountains is dominantly controlled by the faulting that occurred during this event (Figure 5.3). Henry and Price (1986) proposed that faulting did not occur until earliest Neogene (approximately 23 Ma). However, in the study area some fault breccia associated

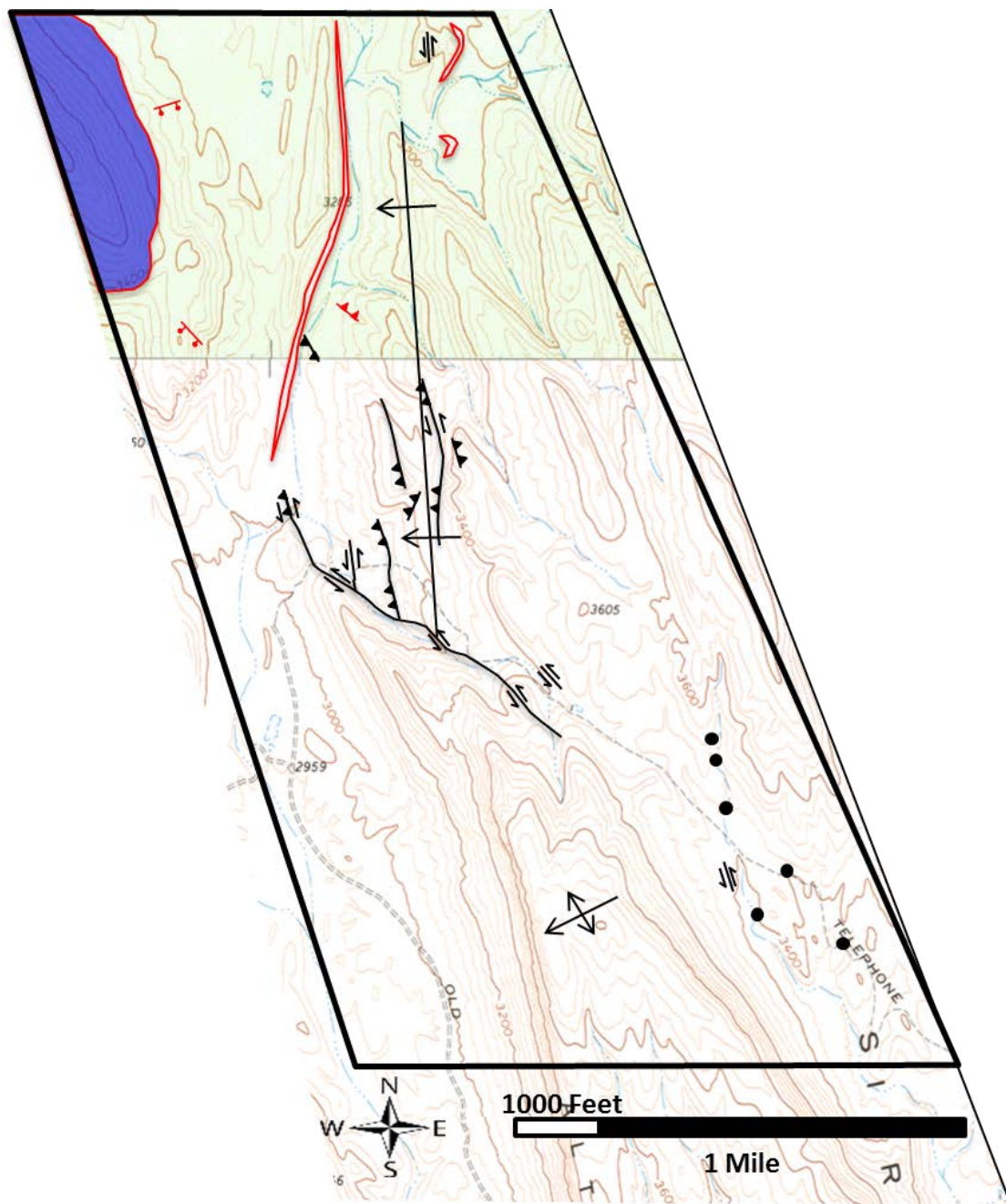


Figure 6.2 – Topographic map of the study area highlighting (red) the location of igneous intrusions that were emplaced in the study area and the deformation that can be related to this emplacement. McKinney Hills is shaded in blue and the sills are outlined in red.

with the major normal faults seems to have been hydrothermally altered. This hydrothermal alteration could have been produced when magma from McKinney Hills laccolith was still thermally affecting the host rock. Therefore, some normal faulting could have begun shortly after the emplacement of McKinney Hills. Not all major normal faults in the study area have this altered fault breccia but all of the fault orientations suggest that they were created during early Basin and Range extension. During this extension, Alto Relex was uplifted and a relay ramp feature on the eastern side was produced. The large anticline made up of MSF-1 and Roys Peak anticline was separated by large grabens created by major normal faulting. Within the study, area several pre-existing left-lateral Laramide strike-slip faults were reactivated by Basin and Range normal faults. The Texas Lineament was also right laterally reactivated which created transtensional stresses. This stress likely created MSSF-2, a large north-oriented, right-lateral strike-slip fault. Some originally Laramide left-lateral strike-slip faults in the study area also show evidence of right-lateral reactivation.

Future Works

Future studies could include continued geologic mapping to the south and east of the study area. This would help to determine the extent of major fault zones and to understand the regional geology of the Sierra del Carmen Mountain

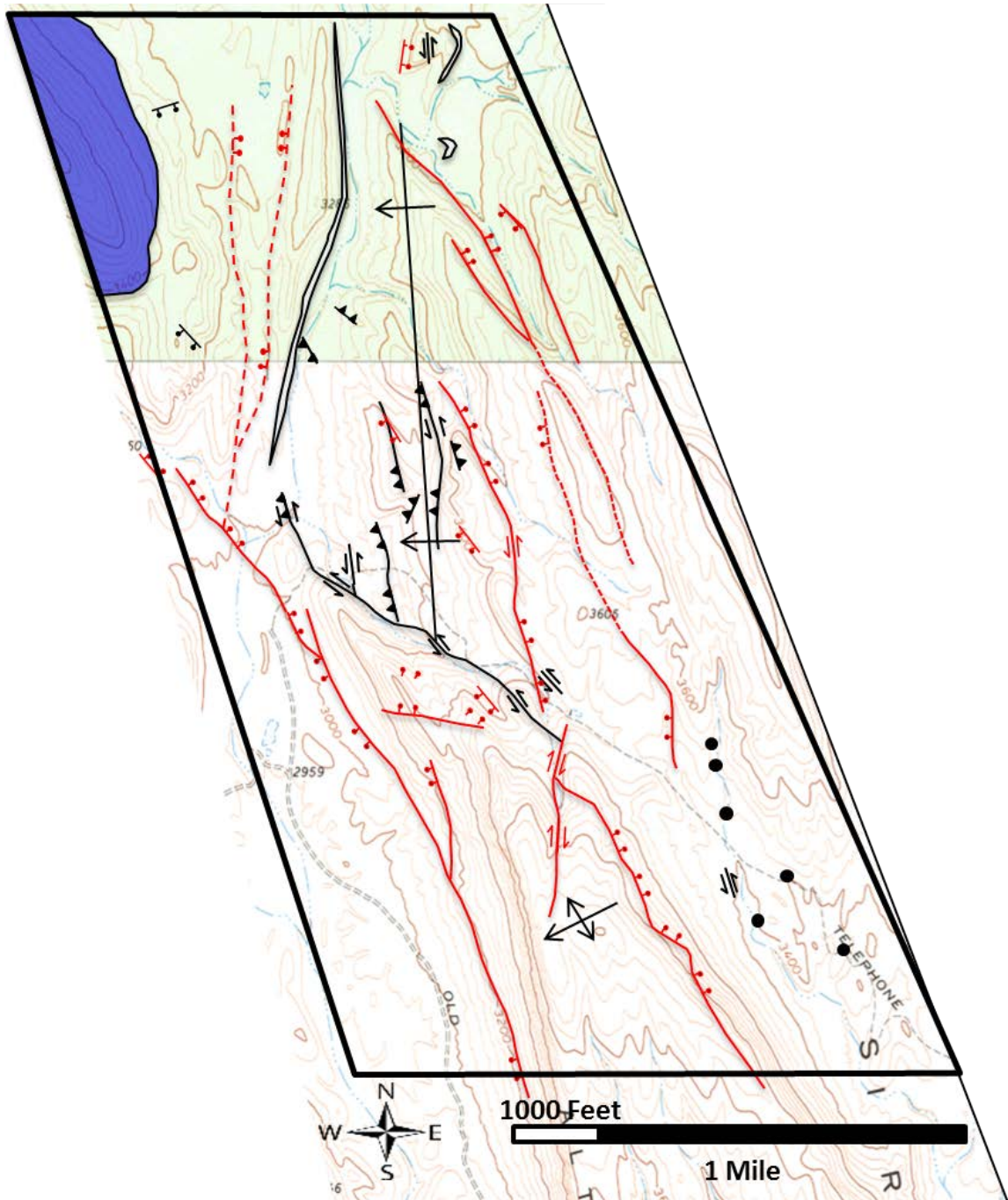


Figure 6.3 – Topographic map of the study area highlighting faults (red) created by Basin and Range extension within the study area. This deformation includes widespread normal faulting and dextral strike-slip faulting.

range. Mapping to the east would help delineate the geometry of the relay ramp structure. Detailed mapping around Roys Peak anticline could reveal more details about the geomechanical processes that were responsible for its creation. A drone or unmanned aerial vehicle (UAV) could be used to capture high-resolution photographs of the area. With these photographs one could map the different geologic units and get a close approximation of fault locations. This method would significantly speed up the mapping process and make it possible to map steep cliffs without climbing gear.

Orthoimagery could be used and manipulated to help reveal contacts and faults and a lineament analysis would give you an idea of fault locations. To accurately conduct a lineament analysis, high-resolution LIDAR data would be beneficial.

Conducting calcite twinning strain analysis and/or studying the orientation of tectonic stylolites might reveal a specific compressional direction for the Laramide Orogeny. This would be useful in determining the mechanics of different features that were created in the Sierra del Carmen Mountains.

Studying the mineralogical properties of the Liesegang banding and altered fault breccia found around the fault zone of MN-3 with X-ray spectrometry would reveal its chemical composition.

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APPENDICES

Appendix A

The following section discusses significant fossils that were observed in the Santa Elena Limestone, Del Rio Clay and the Boquillas Formation.

Santa Elena Limestone



Figure A1- Rudist were marine bivalves that lived from the Late Jurassic to the Late Cretaceous (Jablonski, 1996). They typically created dominate reef systems or bioherms. In and around the study area they typically display a straight to banana-like geometry. This image was taken inside the study area at location S26.



Figure A2-Trochosmilia Protectans ranged from one to three inches long and were replaced by iron-colored chert. These fossils had a similar geometry to that of a horn coral.

Del Rio Clay



Figure A3- Thalassinoides and Spongeliomorpha are burrows that are found in marine and coastal environments (Yanin and Baraboshkin, 2011). These burrows were found with vertical, inclined and horizontal cylindrical shafts that commonly branched. Diameter of borrows ranged from 0.2 to 1.5 inches. *Thalassinoides* has a smooth cast exterior and *Spongeliomorpha* has a striated cast exterior. The pictures above were taken at location S82 in the study area.



Figure A4- Turritellas found in this study were tightly coiled with an elongated cone-like geometry. These fossils were often found as one to two inch fragments. These fossils were located at location S52/S81 (northtexasfossils.com).



Figure A5- Anothopygus texanus is an echinoderm from the Lower Cretaceous. Only one of these specimens was found at location S52/S81.



Figure A6- Tylostoma tumidum was a marine gastropod that was present during the Lower Cretaceous. This snail is moderated fat, with an elevated spire and was commonly found as casts or “steinkerns.” These fossils were extensively found around location S52/S81.



Figure A7- Mariella (Wintonia) brazoensis is a stratigraphic indicator for the lower Del Rio Clay. This fossil was discovered at location S52/S81.



Figure A8- *Paracymatoceras hilli* is the only nautiloid that was found at location S52/S81.



Figure A9- Packstone composed of abundant *Ilymatogyra arietina* oysters, this one foot bed marks the contact of the uppermost Del Rio Clay and the Buda Limestone. *Ilymatogyra arietina* is a 0.5 to 1 inch, twisting oyster that existed during the Lower Cretaceous. This photo was taken at location S29.

Boquillas Formation



Figure A10- *Allocrioceras hazzardi* is a heteromorphic ammonite that ranges from one to three inches in diameter. In outcrop it is either found displaying the shell structure (above) or completely replaced with calcite. This fossil was not found during this study.



Figure A11- Inoceramus (Cladoceras) undulatoplicatus was a large, marine, bivalve. The shell of this fossil is ranges from 0.2 to 0.0625 thick. This specimen was found at location S183.



Figure A12- The ammonite found in this study is likely a *Calycoceras* (*Conlinoceras*) *terrantense*, which was present during the Late Cretaceous. This fossil was a mold that was approximately 8 inches in diameter and found in location S292.

Appendix B

Appendix B Key:

- Stop = Field Location
- Unit = Geologic Units
 - o Qal = Quaternary Alluvium
 - o Tmh = McKinney Hills Intrusion
 - o Ts = Sills
 - o Kp = Pen Formation
 - o Kbo = Boquillas Formation
 - o Kbu = Buda Limestone
 - o Kdr = Del Rio Formation
 - o Kse = Santa Elena Limestone
- Feature(s) = This section will briefly describe the feature that is associated with the measurements
- S&D = Strike and Dip
- P&B = Plunge and Bearing
- Trend = Azimuth direction taken on various features
- ILA = Interlimb Angle

Stop	Units	Feature(s)	S&D	P&B	Trend	ILA
S6	Kse	Thrust Fault?	N35W, 35 NE	31, N40E		
S7	Kdr	Bedding	N46E, 24 NW			
S8	Kbu	Tension Gashes			N7E	
S9	Kbu/Kbo	SSF Fault?/Contact	N12W, 20 SW			
S10	Kbu					
S11	Kbu					
S12	Kdr	Bedding	N11W, 20 SW			
S13	Kdr	Bedding	N2W, 23 SW			
S14	Kbo	Bedding	N45W, 70			

			SW			
S15	Kbu	Bedding	N10E, 19 NW			
S16	Kdr	Thrust Fault	N2W, 12 SW	9, S70W		
S17	Kse	Sample Collected				
S18	Ts	Sample Collected				
S19	Tmh	Joint Sets	N50W, N50E			
S20	Kse	Normal Fault	N41W, 84 NE			
S21	Kbu	Thrust Fault	N10W, 22 SW			
S22	Kse	Bedding	N32W, 9 SW			
S23	Kse	Tension Gashes				
S24	Kse	Normal Fault	N31W, 79 SW	41, S22E/11, S42E		
S25	Kbo	Outcrop Fold	N8W, 85 SW	8, S3E		
S26	Kse	Bedding	N20E, 34 NW			
S27	Kbu	Bedding	N10W, 20 SW			
S28	Kbo	Bedding	N10E, 28 NW			
S29	Ts	Sill			S20W	
S30	Kbo	Bedding	N14E, 37 NW			
S31	Kbo	Normal Fault	N47W, 51 NE	49, N40E		
S32	Kbo	Normal Fault	N37W, 84 NE	70, N53E		
S33	Kbu	Bedding	N0, 20 W			
S34	Kbu/Kse	Contact				
S35	Kdr	Bedding	N10E, 20 NW			

S36	Kse	Bedding	N28E, 20 NW			
S37	Kbu	Normal Fault?	N85W, 26 SW	12, S45E		
S38	Kdr	Bedding	N2W, 21 SW			
S39	Kbo	Bedding	N9E, 32 NW			
S40	Kbo/Ts	Bedding	N37W, 27 SW			
S41	Kbo	Bedding	N20E, 31 NW			
S42	Kbo	Bedding	N9W, 31 SW			
S43	Kse	Bedding	N18W, 30 SW			
S44	Kse/Kbu	Bedding	N21W, 21 SW			
S45	Kdr	Thrust Fault	N14W, 26 SW	26, N78W		
S46	Kdr	Thrust Fault?	N14W, 48 SW	46, S73W		
S47	Kse	Bedding	N8W, 12 SW			
S48	Kse	Bedding	N27E, 9 NW			
S49	Kse	Normal Fault	N41E, 55 NW	42, N2W		
S50	Kse	Bedding	N5W, 7 SW			
S51	Kbu	Bedding	N10W, 14 SW			
S52	Kdr	Thrust Fault	N5E, 17 NW	16, S60W		
S53	Kse	Thrust Fault	N23E, 12 SE	8, N82E		
S54	Kse	Bedding	N46E, 4 NW			
S55	Kbu/Kbo	Bedding	N70E, 15 SE			
S56	Kbo	Bedding	N80E, 48 SE			
S57	Kbo	Folding	N27W, 83 SW	25, S20E		
S58	Kbo	Folding	N25W, 88	29, S28E		

			SW			
S59	Kbo	Bedding	N63W, 30 SW			
S60	Kbo	Bedding	N61W, 25 SW			
S61	Kbo	Normal Fault	N32W, 84 SW			
S62	Kbo	Bedding	N63W, 10 SW			
S63	Kbu	Bedding	N10W, 13 SW			
S64	Kse	Joint Sets	N29W, 83 NE			
S65	Kse	Bedding	N13W, 15 SW			
S66	Kdr/Kbu	Contact				
S67	Kse	Bedding	N23W, 6 SW			
S68	Kse	Thrust Fault?	N62W, 41 SW	34, S53W		
S69	Kse	Bedding	N45W, 63 SW			
S70	Kbu	Bedding	N12E, 9 SE			
S71	Kbu	Normal Fault	N10W, 90			
S72	Kse	Bedding	N11W, 45 SW			
S73	Kse	Bedding	N25W, 30 SW			
S74	Kbo	Bedding	N35W, 60 NE			
S75	Kbo	Bedding	N13E, 29 NW			
S76	Kdr	Thrust Fault	N20W, 41 SW	41, S59W		
S77	Kdr	Thrust Fault	N16W, 43 SW	42, S75W		
S78	Kse	Normal Fault	N75E, 73 SE			
S79	Kse/Kdr	Contact				

S80	Kse	Calcite Veins			N20W, N3E	
S81	Kse	Thrust Fault	N15W, 7 NE	7, N80E		
S82	Kse	Bedding	N4W, 25 SW			
S83	Kdr	Thrust Fault	N17W, 14 NE	8, N74E		
S84	Kdr	Strike-slip Fault	N38W, 86 SW	84, S67W		
S85	Kse	Strike-slip Fault	N35W, 82 NE			
S86	Kse	Bedding	N16W, 24 SW			
S87	Kse/Kdr	Contact				
S88	Kbo	Bedding	N4W, 12 SW			
S89	Kse	Bedding	N26E, 20 NW			
S90	Kse	Bedding	N40W, 14 NW			
S91	Kse	Normal Fault?	N77E, 90			
S92	Kse	Normal Fault?	N15E, 72 NW			
S93	Kse	Bedding	N66E, 9 NW			
S94	Kse	Bedding	N75E, 6 NW			
S95	Kse	Normal Fault?	N40W, 87 SW			
S96	Kse	Bedding	N82E, 6 NW			
S97	Kse	Normal Fault?	N20W, 90			
S98	Kse	Bedding	N86E, 19 NW			
S99	Kse	Dog-tooth Spar			N23W	
S100	Kse	Bedding	N10W, 14 NE			
S101	Kse	Bedding	N5W, 10 NE			
S102	Kse	Bedding	N43W, 6 SW			

S103	Kse	Bedding	N39W, 22 SW			
S104	Kse	Calcite Veins			N20W	
S105	Kse	Cliff			N15W	
S106	Kse	Bedding	N60W, 7 SE			
S107	Kse	Bedding	N65W, 7 SE			
S108	Kse	Mineralized veins			N50W	
S109	Kse	Bedding	N0, 10W			
S110	Kse	Fault Breccia?			N22W	
S111	Kse	Tension Gashes/Bedding	N20W, 8 SW		N20W	
S112	Kse	Tension Gashes			N55W	
S113	Kse	Bedding	N86E, 5 SW			
S114	Kse	Normal Fault?	N10W, 90			
S115	Kse	Strike-slip Fault	N5E, 90	15, N5E		
S116	Kse	Strike-slip Fault	N41W, 85 NE	9, N38W		
S117	Kse					
S118	Kse	Strike-slip Fault	N40W, 75 SW	5, S40E		
S119	Kse	Tension Gashes			N42W	
S120	Kse	Calcite Veins			N40W	
S121	Kse	Oblique Fault	N26W, 85 SW	20, N30W		
S122	Kse	Breccia			N35W	
S123	Kse	Strike-slip Fault	N38W, 90	13, N38W		
S124	Kse	Normal Fault	N46E, 60 SE			
S125	Kse	Bedding	N4W, 17 SW			
S126	Kse	Normal Fault	N30W, 81 SW	52, S28E		
S127	Kse					
S128	Kse	Strike-slip Fault	N55W, 90	35, S46E		
S129	Kse					
S130	Kse	Strike-slip Fault	N54W, 72 NE	19, N46W		

S131	Kse					
S132	Kse	Normal Fault	N34W, 68 NE	35, S30E		
S133	Kse					
S134	Kse	Strike-slip Fault	N52W, 80 SW			
S135	Kse	Strike-slip Fault	N52W, 81 SW	12, N57W		
S136	Kse	Oblique Fault	N60W, 90	30, S60E		
S137	Kse	Bedding	N10W, 14 SW			
S138	Kse					
S139	Kbo	Normal Fault	N28W, 85 SW	84, S52W		
S140	Kbo	Normal Fault	N31W, 63 NE	62, N45E		
S141	Kbo	Normal Fault	N48W, 79 NE	76, N40E		
S142	Kbo	Normal Fault	N42W, 84 NE	74, N40E		
S143	Kbo	Normal Fault	N40W, 85 NE	81, N35E		
S144	Kbo					
S145	Kse	Normal Fault	N18W, 72 SW	70, S75W		
S146	Kbu	Bedding	N6W, 20 SW			
S147	Kse	Bedding	N20W, 10 SW			
S148	Kse	Bedding	N12W, 13 SW			
S149	Kbu	Bedding	N60W, 13 SW			
S150	Kbu/Kse					
S151	Kse	Bedding	N52W, 14 NE			
S152	Kbu/Kbo					

S153	Kbo	Fold	N28W, 80 SW	14, S13E		140
S154	Kbu	Bedding	N4W, 18 SW			
S155	Kbu	Bedding	N10W, 25 SW			
S156	Kbu	Normal Fault	N35W, 62 NE			
S157	Kdr	Bedding	N5W, 15 SW			
S158	Kdr	Bedding	N12E, 24 NW			
S159	Kdr	Bedding	N14E, 28 NW			
S160	Kdr	Bedding	N6W, 17 SW			
S161	Kdr	Bedding	N44W, 17 SW			
S162	Kdr	Bedding	N6E, 6 NW			
S163	Kdr	Bedding	N8E, 26 NW			
S164	Kbo	Strike-slip Fault	N4W, 72 NE	18, N4W		
S165	Kbu	Bedding	N15E, 22 NW			
S166	Kbu/Kbo	Bedding	N10E, 24 NW			
S167	Kbo					
S168	Kbu	Bedding	N14W, 22 SW			
S169	Kbo	Bedding	N7E, 11 NW			
S170	Kbo/Ts	Bedding	N5E, 20 NW			
S171	Kbo/Ts					
S172	Kbo	Bedding	N16E, 27 NW			
S173	Kbo					
S174	Kbo/Ts	Bedding	N5E, 24 NW			
S175	Kbo/Ts	Bedding	N19E, 26 NW			

S176	Kbo	Bedding	N5E, 32 NW			
S177	Kbo	Bedding	N5E, 24 NW			
S178	Kbo	Bedding	N2E, 34 NW			
S179	Kbo	Bedding	N1E, 23 NW			
S180	Kbo	Bedding	N0, 21 W			
S181	Kbo	Normal Fault?	N3W, 62 NE	57, N58E		
S182	Kbo	Bedding	N87W, 17 NE			
S183	Kbo	Bedding	N12E, 22 NW			
S184	Kbo	Bedding	N22E, 32 NW			
S185	Kbo	Bedding	N10W, 32 SW			
S186	Kbo	Bedding	N4E, 20 NW			
S187	Kbo	Normal Fault	N72E, 46 SE	45, S49E		
S188	Kbo	Bedding	N0, 22 W			
S189	Kbo	Bedding	N17E, 14 NW			
S190	Kbo	Bedding	N9E, 17 NW			
S191	Kbo	Bedding	N3E, 35 NW			
S192	Kbo	Bedding	N38W, 12 SW			
S193	Kbo	Bedding	N5E, 20 NW			
S194	Kbo	Bedding	N8W, 24 SW			
S195	Kbo	Bedding	N20E, 27 NW			
S196	Kbo	Bedding	N19E, 34 NW			
S197	Kbo	Bedding	N4E, 23 NW			
S198	Kbo	Bedding	N2E, 46 NW			
S199	Kse	Normal Fault	N27W, 68 SW	65, S70W		
S200	Kse	Normal Fault?	N9E, 90	90, N85W		
S201	Kse	Normal Fault	N45W, 63 SW			

S202	Kse	Bedding	N9W, 16 SW			
S203	Kse	Bedding	N5E, 12 NW			
S204	Kdr	Bedding	N24W, 30 SW			
S205	Kse	Bedding	N3W, 28 SW			
S206	Kse	Strike-slip Fault	N20W, 90	5, S5E		
S207	Kse	Bedding	N2W, 27 SW			
S208	Kse	Bedding	N30W, 20 SW			
S209	Kse	Bedding	N10W, 9 SW			
S210	Kse	Normal Fault	N32W, 85 NE			
S211	Kse	Calcite Veins	N20E, 7 NW		N30W, N15W	
S212	Kse	Normal Fault	N12W, 85 NE	80, N80E		
S213	Kse					
S214	Kse	Thrust Fault	N5W, 9 NE	7, N72E		
S215	Kbu	Bedding	N35W, 9 SW			
S216	Kbu	Bedding	N7W, 5 SW			
S217	Kbu	Bedding	Flat			
S218	Kbu					
S219	Kbu					
S220	Kdr	Bedding	Flat			
S221	Kbu	Bedding	N80E, 4 NW			
S222	Kdr	Bedding	N9W, 7 SW			
S223	Kdr	Bedding	N25W, 15 SW			
S224	Kdr	Bedding	N23W, 8 SW			
S225	Kdr	Normal Fault	N2W, 67 SW			

S226	Kse					
S227	Kdr	Bedding	N22E, 3 NW			
S228	Kdr	Bedding	N28W, 3 SW			
S229	Kdr	Bedding	N28W, 15 SW			
S230	Kdr	Bedding	N4W, 9 SW			
S231	Kbu	Bedding	N77W, 11 SW			
S232	Kbo	Bedding	N65W, 12 SW			
S233	Kbo	Normal Fault?	N2W, 57 SW			
S234	Kbo	Bedding	N4E, 26 SE			
S235	Kbo	Bedding	N89E, 36 SE			
S236	Kbu	Bedding	N85E, 7 SE			
S237	Kbo	Fold	N18W, 90	22, S10W		145
S238	Kbu	Bedding	N70E, 18 SE			
S239	Kbo					
S240	Kbo	Bedding	N45E, 37 SE			
S241	Kbo	Bedding	N18E, 38 SE			
S242	Kse	Normal Fault	N28W, 79 NE	45, S58E		
S243	Kbo	Bedding	N76E, 24 SE			
S244	Kbo	Bedding	N26W, 24 SW			
S245	Kse	Normal Fault	N25W, 66 NE			
S246	Kse	Normal Fault	N63W, 66 NE	50, N82E		
S247	Kse	Normal Fault	N31W, 30 NE			
S248	Kse	Normal Fault	N35W, 54 NE	45, N80E		
S249	Kbo	Bedding	N32W, 80 NE			

S250	Kbo	Bedding	N68W, 25 SW			
S251	Kbo	Bedding	N41W, 43 SW			
S252	Kbo	Bedding	N42W, 46 SW			
S253	Kbo	Bedding	N71W, 18 SW			
S254	Kbu	Bedding	N82E, 8 SE			
S255	Kbu	Bedding	N72E, 4 SE			
S256	Kbu	Bedding	N40W, 9 SW			
S257	Kbo	Normal Fault	N15W, 68 SW			
S258	Kbo	Bedding	N10W, 20 SW			
S259	Kbo	Bedding	N5E, 31 NW			
S260	Kbo	Bedding	N13W, 27 SW			
S261	Kbo	Bedding	N12E, 34 NW			
S262	Kbo	Bedding	N15E, 34 NW			
S263	Kbo	Bedding	N14E, 23 NW			
S264	Kbu	Bedding	N40E, 19 NW			
S265	Kdr	Bedding	N5E, 28 NW			
S266	Kbo/Ts	Bedding	N17E, 18 NW			
S267	Kbo	Bedding	N8W, 13 SW			
S268	Kbo	Bedding	N17E, 11 NW			
S269	Kbo	Bedding	N20W, 18 SW			
S270	Kse	Normal Fault	N85W, 35 NE			

S271	Kse	Bedding	N85E, 18 NW			
S272	Kse	Bedding	N82E, 13 NW			
S273	Kse	Normal Fault	N26W, 78 SW			
S274	Kse	Bedding	N88W, 8 NE			
S275	Kse	Bedding	N73W, 21 NE			
S276	Kse	Bedding	N35W, 16 NE			
S277	Kse	Bedding	N54E, 7 NW			
S278	Kse	Strike-slip Fault	N3E, 90	2, N3E		
S279	Kse	Strike-slip Fault	N16E, 75 SE	14, N25E		
S280	Kse	Normal Fault	N16W, 76 SW			
S281	Kdr	Strike-slip Fault	N29W, 82 NE	18, N32W		
S282	Kbu	Thrust	N59W, 45 SW	45, S5W		
S283	Kbu	Normal Fault	N22W, 70 SW	65, S52W		
S284	Kbu	Normal Fault	N67E, 80 SE	75, S30E		
S285	Kbo	Reverse Fault	N52W, 70 NE			
S286	Kse	Normal Fault	N45W, 64 NE	60, N60E		
S287	Kse	Normal Fault	N42W, 62 SW	44, S18W		
S288	Kse	Normal Fault	N30W, 60 SW			
S289	Kse	Normal Fault	N10W, 79 SW			
S290	Kbo	Fold	N47W, 85 SW	16, S40E		
S291	Kbo	Bedding	N23W, 42 SW			
S292	Kbo	Strike-slip Fault	N18E, 80 SE	15, S6W		

S293	Kbo	Bedding	N67W, 32 SW			
S294	Kbo	Bedding	N85W, 17 SW			
S295	Kbo					
S296	Kbo	Normal Fault	N45W, 90			

VITA

Robert Schoen graduated from Golaid High School, Texas, in 2010. He attended Texas A&M University – Kingsville and received a Bachelor of Science of geology in December 2014. After working for an Oilfield Service Company, he decided to go back and continue his education. In August 2015 he began graduate school at Stephen F. Austin State University and received a Master of Science degree in December 2017.

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GSA Style Manual

This thesis was typed by Robert L. Schoen

Plate 1

Geologic Map of the Northern Alto Relex Area in Big Bend National Park, Brewster County, Texas

By: Robert Schoen
2017

Plate to accompany M.S. Thesis:
Geology of the Northern Alto Relex Area,
Big Bend National Park, Brewster County,
Texas

Stephen F. Austin State University

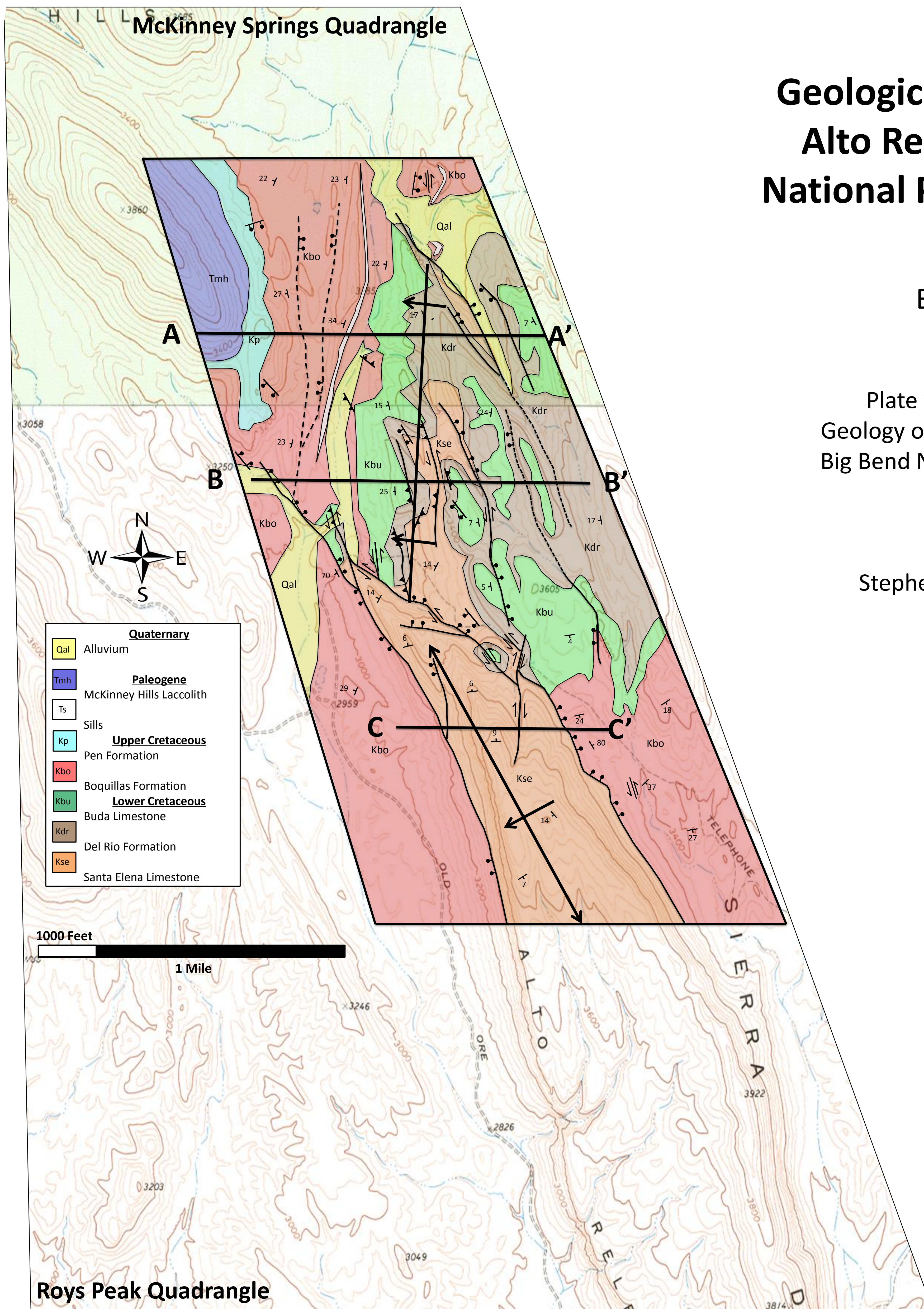


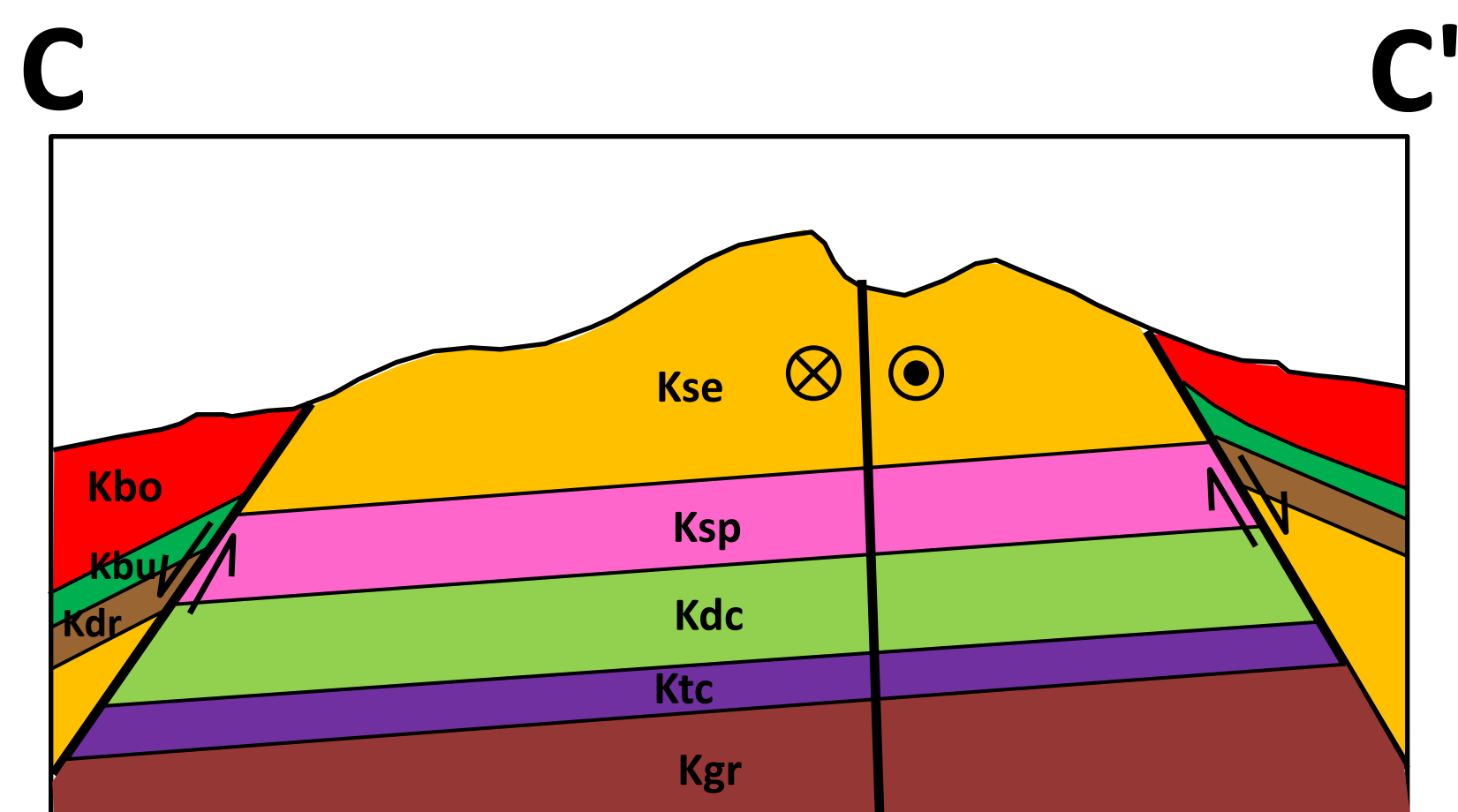
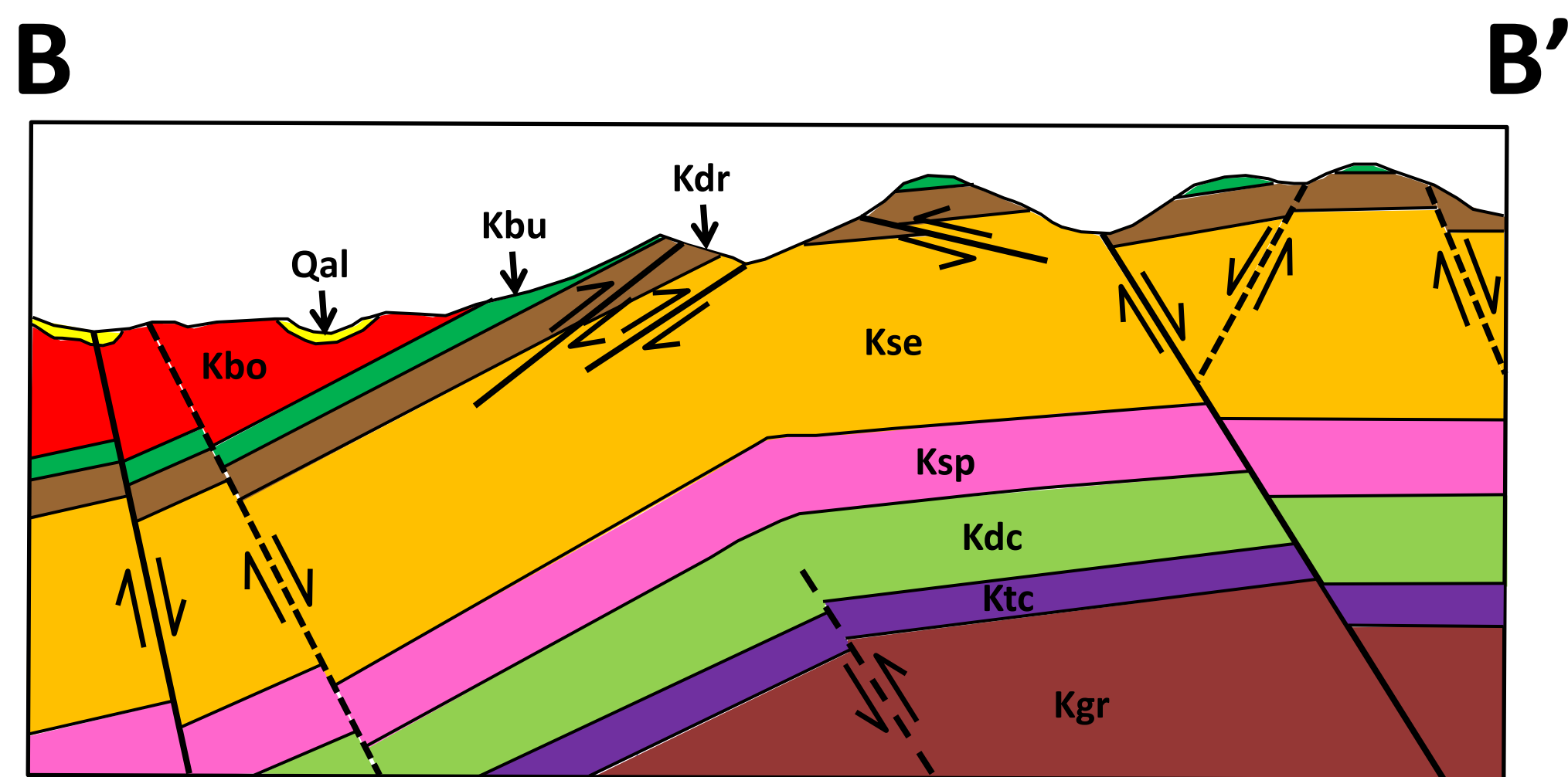
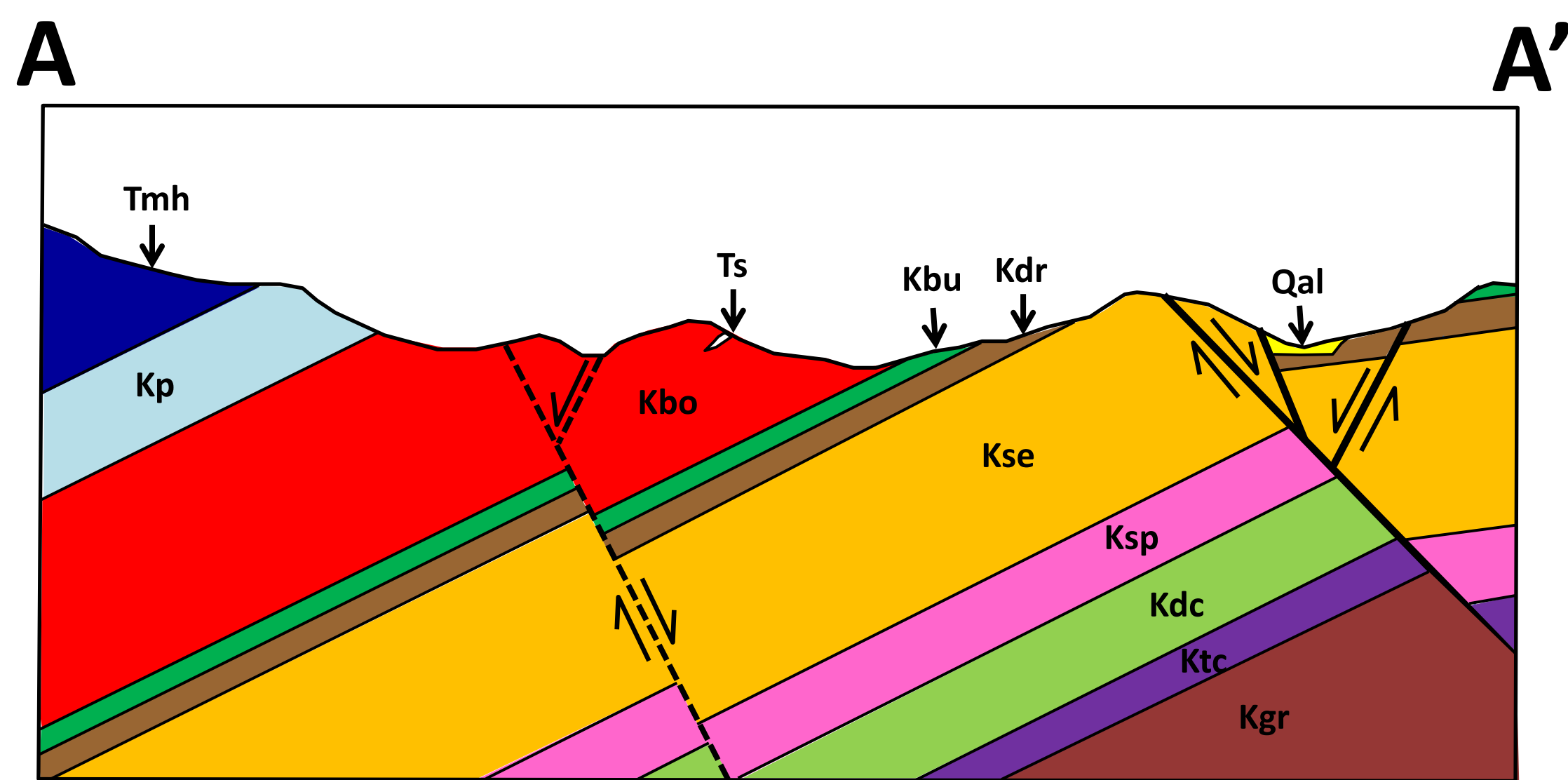
Plate 2

Geologic Cross-sections
of the Northern Alto
Relex Area, Brewster
County, Texas

By: Robert Schoen
2017

Plate to accompany M.S. Thesis:
Geology of the Northern Alto Relex Area,
Big Bend National Park, Brewster County,
Texas

Stephen F. Austin State University



1,000 feet
V.E. = 1
1,000 feet

<u>Quaternary</u>	
Qal	Alluvium
<u>Paleogene</u>	
Tmh	McKinney Hills Laccolith
Ts	Sills
<u>Upper Cretaceous</u>	
Kp	Pen Formation
Kbo	Boquillas Formation
<u>Lower Cretaceous</u>	
Kbu	Buda Limestone
Kdr	Del Rio Formation
Kse	Santa Elena Limestone
Ksp	Sue Peaks Formation
Kdc	Del Carmen Limestone
Ktc	Telephone Canyon Formation
Kgr	Glen Rose Limestone

Plate 3

Locations of Field Stops

By: Robert Schoen
2017

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