LARAMIDE AND POST-LARAMIDE STRATIGRAPHY AND TECTONISM ON THE
SOUTHEAST FLANK OF THE FRA CRISTOBAL MOUNTAINS, NEW MEXICO

by
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ABSTRACT

The purpose of this study is to identify, describe, and map Cretaceous and Tertiary rocks, and to constrain the timing and nature of the Laramide and Cenozoic deformation that occurred in and adjacent to the study area in the Fra Cristobal Mountains. Although bedrock had been found in the study area, no formations had previously been identified.

The Fra Cristobal Mountains are located 15 miles northeast of Truth or Consequences, New Mexico, and on the east edge of the southern part of the Cenozoic Rio Grande rift. The study area covers about one square mile along the southeast flank of the Mountains. Detailed mapping (at a scale of 1:6,000) in the study area documents the presence of the Cretaceous marine Fite Ranch Sandstone (?) Member of the Tres Hermanos (?) Formation, the marine D-Cross Tongue of the Mancos Shale, the marine Gallup Sandstone, the Lower and Ash Canyon members of the terrestrial Crevasse Canyon Formation, the Jose Creek and Hall Lake members of the terrestrial McRae Formation, the Upper Paleocene to Middle Eocene terrestrial Love Ranch Formation, and the Upper Pliocene to Lower Pleistocene terrestrial Palomas Formation. Because the Fite Ranch Sandstone (?) and D-Cross Tongue of the Mancos Shale represent the last high sea level stand in the study area, both units are redefined as members of the Mancos Shale.

Geologic structures mapped include eastward tilted upper Cretaceous strata, a thrust fault with eastward vergence, two (eastern and western) high-angle normal faults with separation down to the northeast and southeast, and inclined folds with axes trending north and northwest. The structures in the study area indicate that two pulses of
Laramide compressional deformation occurred that were followed by extensional deformation. The first pulse of Laramide deformation occurred in the late Maastrichtian which uplifted upper Cretaceous strata that provided detritus for the syn- to post-orogenic sediments represented by the McRae Formation. The second pulse of Laramide deformation formed the Rio Grande uplift, thrust Paleozoic strata over Cretaceous strata, overturned the Tres Hermanos(?) Formation and tilted overlying Cretaceous strata to the east in the study area. As the foreland rose during this time, it was weathered, providing syn- to post-orogenic sediments that formed the Middle Eocene Love Ranch Formation. Continued deformation folded the Love Ranch Formation in the study area and by the end of the Miocene, the Jornada del Muerto and Cutter Sag had formed.

At the beginning of the Oligocene, extensional tectonism began in New Mexico that superimposed a fault block mountain terrane over earlier Laramide structures and formed the Rio Grande rift. At this time, two major bounding fault zones formed; one on the east and the other on the west side of the Fra Cristobal Mountains. In the study area, during this time, two normal faults formed: the western normal fault and the eastern normal fault. The western normal fault of undetermined displacement appears to have formed first, displacing only upper Cretaceous strata. The eastern normal fault, having at least 700 ft of displacement, juxaposed the Tertiary Love Ranch Formation next to the Cretaceous Crevasse Canyon Formation and appears to displace the western normal fault. The Love Ranch Formation was weathered and eroded from the western up thrown block and preserved in the eastern down thrown block of the eastern normal fault. The Palomas Formation resulted from the last extensional deformation event in the study area.
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Chapter 1
INTRODUCTION

Although structures produced during Laramide tectonism have been studied in some detail in the Fra Cristobal Mountains, New Mexico (Nelson and Hunter, 1986; Nelson, 1993), the timing of Laramide deformation and history of syn- to post-Laramide uplift and erosion are not well constrained. A record of uplift and erosion is held in Cretaceous and younger strata on the margins of most Laramide uplifts. On the east flank of the Fra Cristobal Mountains, Foulk (1990) and Nelson (1993) documented a thrust fault that places sub-horizontal sandstone and gypsum strata of the Permian Yeso Formation over vertical to overturned clastic strata. Although the age of the clastic strata was thought to be Cretaceous and younger, it was not known what Cretaceous and/or Cenozoic formations were present. Therefore, this study was designed to determine time constraints for Laramide and Cenozoic deformational events through stratigraphic studies of syn- to post- tectonic strata exposed on the eastern flank of the Fra Cristobal Mountains.

1.1 Purpose

The purpose of this research is to constrain the timing of Laramide and Cenozoic deformation and uplift that occurred in and adjacent to the study area and to characterize Laramide and Cenozoic deformation. To do this, it was also necessary to identify and describe Cretaceous and Tertiary formations exposed on the east flank of the Fra
Cristobal Mountains. In addition, stratigraphic and petrologic information was used to determine provenance and interpret basin geometry.

The objectives of this investigation were accomplished through detailed geologic study of outcrops along arroyos located on the eastern flank of the Fra Cristobal Mountains. This study includes construction of measured sections, a geologic map, and conglomerate clast counts to determine provenance and depositional response to past uplift. Structural fabric, determined from measurement of faults and bedding attitudes, was used to describe the strain accompanying uplift during and after Laramide deformation. This information was used to interpret the depositional and structural history in the study area and to compare it to the regional geologic history.

1.2 Location

The Fra Cristobal Mountains, located in south-central New Mexico, are on the east edge of the southern part of the Rio Grande rift and are part of a Laramide deformation belt that extends from southern New Mexico northward into northern Colorado. The study site lies northeast of the town of Truth or Consequences (fig. 1) and on the southeast flank of the Fra Cristobal Mountains between about longitude 107°03'30" and 107°04'20", and about latitude 33°18'24" and 33°19'18" on U.S. Geological Survey Crocker quadrangle (1:24,000), New Mexico (fig. 1).
Figure 1. Quadrangle and geographic location map. After Mack and Seager (in press).
1.3 Previous Work

Harley (1934) described the geology and ore deposits of Sierra County including geology and prospects in the Fra Cristobal Mountains. During their study of the Caballo Mountains, Kelley and Silver (1952) made a few stratigraphic and structural observations in the Fra Cristobal Mountains and summarized the regional aspects of the stratigraphy and structure in southern New Mexico. Bushnell (1953) studied Triassic and Cretaceous rocks in south-central New Mexico. The stratigraphy and structure in the southern part of the Fra Cristobal Mountains were mapped and described by Thompson (1955a, b; 1961), and the stratigraphy and structure in the central front of the Mountains were mapped by Jacobs (1956). Kelley (1955) summarized the tectonic elements (i.e., the uplifts and basins) in Sierra County. Cserna (1956) described the stratigraphy and structural geology and provided measured Paleozoic sections for the Mountains. McCleary (1960) mapped the stratigraphy in the northern part of the Fra Cristobal Mountains. Kottlowski (1955a, b) studied the surface and subsurface Paleozoic and Mesozoic stratigraphy for southwestern and south-central New Mexico.

The Eocene tectonic framework of west-central New Mexico and eastern Arizona was reported and described by Cather and Johnson (1984). Lozinsky and Hawley (1986a, b) summarized the stratigraphy, provided clast counts and measured sections, and interpreted the late Cenozoic history for the Elephant Butte area, just west of the Fra Cristobal Mountains. Hunter (1986) made a detailed study of the McRae Fomation in McRae basin located in the Laramide Cutter Sag between the Fra Cristobal and Caballo Mountains. Nelson (1986) summarized the geology of the Fra Cristobal Mountains. Seager and Mack (1986) used synorogenic and postorogenic sedimentary rocks (such as those from the McRae and Love Ranch formations) coupled with structural data to
characterize and to bracket the timing of the Laramide deformation in southern New Mexico (see Chapters 3 and 5). Uplift, fault blocks, erosion, and related deposits such as the Love Ranch Formation, were described by Seager and Mayer (1988) for the Salado (not shown in fig. 1) and Caballo Mountains and surrounding area. Ammonite faunas of the Upper Cretaceous were described for southwestern New Mexico by Cobban and others (1989; see Chapter 4). Maxwell and Oakman (1990) mapped the geology in the Cuchillo Quadrangle just west of Elephant Butte Quadrangle (fig. 1). Seager (1990) described the principal mode of Laramide deformation and related deposits of the foreland area of south-central New Mexico. Foulk (1990) studied the structural geometry and kinematic history in the study area and related her conclusions to the extensional tectonism in the region. She also provided a geologic map of the western part of the study area (see Chapter 5 and Plate 1). Seager and others (1997) studied the structural kinematics and depositional history of the Laramide Love Ranch and Potrillo basins (not shown in fig. 1) in southern New Mexico.
Chapter 2

METHODS OF RESEARCH

A part of U.S. Geological Survey Crocker 1:24,000 quadrangle was enlarged to 1:6,000 and used for detailed mapping of lithology and structural features. Mapping was accomplished by Brunton compass, Jacob staff, surface traverse, and aerophotographs. The aerophotographs (1:21,000 scale) were used to locate suspected structures, lithologies, and contacts that were later confirmed by field check and then mapped at 1:6,000. The geologic map is included as Plate I.

Three stratigraphic sections were constructed along three different arroyos using Jacob staff, tape, and Brunton compass methods as described by Compton (1984 p. 229-237). Traverse lines used to construct stratigraphic sections are included in fig. 2 (see Plate I). Using rock characteristics and type, and index fossils, these sections were correlated to other sections between arroyos and known sections outside the study area. Stratigraphic sections and correlations are included as Plates 2-4.

X-ray diffraction (XRD) and Scanning Electron Microscope (SEM) methods were used to identify or confirm identification of selected rock and mineral samples. Petrographic analyses of thin sections and rock samples were used to classify rocks. Samples collected for thin section, binocular microscope, and (or) SEM analysis were based on mineral and (or) textural differences. Etching and staining procedures, as described by Hutchison (1974), were used to identify carbonate minerals and cement. Mineral volume percentages were estimated from thin sections. Igneous rocks were
Figure 2: Location map of stratigraphic section traverses along Arroyo C (C-C'), Arroyo D (D-D'), and Arroyo E (E-E'). See Plates 2 - 4 for stratigraphic sections. Location map modified from Plate 1. Note that traverse lines are not always in arroyos, but adjacent to them.
classified according to Williams and others (1982). Sedimentary rocks were classified according to Pettijohn (1975, p. 158) for siliciclastic sedimentary rocks (fig. 3) with the exception of wacke classification which follows that of Williams and others (1982). Carbonate rocks were classified according to Dunham (1962). Rock color names were determined from the "Rock-Color Chart" of the National Research Council (Goddard and others, 1948). Specific color codes for each determined rock color were not referenced in this study.

Textural descriptions for all rocks were made both megascopically and microscopically. Maturity of siliciclastic rocks was determined as described by Fichter and Poche (1993, p. 210). Roundness was determined by comparison of grains to the roundness scale of Powers (1953, p. 118). Sand grain size was determined using following modified version of the Wentworth Scale:

<table>
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<th>Grain Size</th>
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<td>Very coarse upper</td>
<td>0.5--1.0</td>
</tr>
<tr>
<td>Very coarse lower</td>
<td>0.0--0.5</td>
</tr>
<tr>
<td>Coarse upper</td>
<td>0.5--0.0</td>
</tr>
<tr>
<td>Coarse lower</td>
<td>1.0--0.5</td>
</tr>
<tr>
<td>Medium upper</td>
<td>1.5--1.0</td>
</tr>
<tr>
<td>Medium lower</td>
<td>2.0--1.5</td>
</tr>
<tr>
<td>Fine upper</td>
<td>2.5--2.0</td>
</tr>
<tr>
<td>Fine lower</td>
<td>3.0--2.5</td>
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<td>Very fine lower</td>
<td>4.0--3.5</td>
</tr>
<tr>
<td>Silt</td>
<td>&gt;4.0</td>
</tr>
</tbody>
</table>

Structural fabric of the study area was described from bedding orientation, fault orientation, missing rock units, and from cross sections. Pebble counts in selected conglomerates were used to determine provenance in conglomerate facies and to bracket periods of active uplift (coarsening upward) and/or periods of stability (fining upward). A fabric measuring tape divided into tenths of feet was used as a stretchline to count
Figure 3. Stratigraphic classifications and subdivision of lithic arenites used in this study are modified from Pettijohn (1975) with the exception of wacke classification which follows Williams and others (1982).
pebbles in the conglomerates. The stretchline was placed perpendicular to bedding surface in a conglomerate section and pebbles were counted at the intersection of a clast and the half mark on the measuring tape. The tape was moved when needed 0.5 ft parallel and adjacent from the last stretchline position. Where possible, three hundred counts were made for each bed. Some sites had at least three conglomerate beds per section. Clasts of 2 mm diameter and greater were counted. Graded bedding within the conglomerate beds was used to determine periods of deformation, and imbricated clasts were used to determine flow direction and direction of sediment source area for the conglomerates.

Bedding thickness is described in the following terms:

- Laminated less than one inch thick
- Thin-bedded one inch to one foot thick
- Medium-bedded one to three feet thick
- Thick-bedded greater than three feet thick

Note that lamina thickness as defined as "less than one inch thick" is in accordance with earlier works. Lamina thickness for this study is defined as 0.4 inches (1 cm) or less, and 0.4 inches to one foot defines "thin-bedded." Bedding thickness greater than one foot follows bedding thickness as defined above.
Chapter 3

STRATIGRAPHY OF FRA CRISTOBAL MOUNTAINS

Descriptions of the rock units found in the Fra Cristobal Mountains are summarized below in order to provide information on the source rocks that supplied debris for the formation of post-Cretaceous conglomerates. The Precambrian, Paleozoic, and Cretaceous clasts forming the conglomerates identify the source area at the time of deposition and bracket a time of relative uplift. Differentiation of the clasts was based on color, fossils, and rock type. Rock unit descriptions were compiled mainly from thesis reports and from Nelson (1986). Distribution of the different rock units is presented in fig. 3.

A complete stratigraphic sequence is not present in the Fra Cristobal Mountains due to erosion, depositional onlap, local nondeposition, and/or tectonics (Kelley and Silver, 1952; Nelson, 1986). Silurian, Devonian, Mississippian, Triassic, Jurassic, and Lower Cretaceous rocks are not reported in the Fra Cristobal Mountains (McCleary, 1960, p. 19-20; Thompson, 1961, p. 21; Nelson, 1986). Although a more complete stratigraphic sequence is present in the Caballo Mountains to the south of the study area (fig. 1), the following stratigraphic summary includes only those rock units that have been reported in the Fra Cristobal Mountains and surrounding area (fig. 4).

3.1 Precambrian

Precambrian granitic and metamorphic rocks are exposed mainly along the western and northwestern flank of the Fra Cristobal Mountains (fig. 4); however, only
Figure 4. Generalized geologic map of the Fra Cristobal (after Nelson, 1986).
granitic rock crops out on the east flank of the Mountains just north of Spring Canyon. The predominant rock exposed in the southern part of the Mountains is pink, coarse-grained granite gneiss composed of orthoclase (41%), quartz (22%), microcline (26%), albite (9%), muscovite (2%), and minor amounts of biotite, hornblende, and magnetite (Cserna, 1956; McCleary, 1960, p. 9). Metamorphic xenoliths and roof pendants are more abundant in the northern part of the Mountains than in the southern part. In this area, masses of green schist, having a northerly foliation orientation, are present in the Contact Canyon and Long Canyon areas (fig. 4; Jacobs, 1956, p. 11; McCleary, 1960, p. 9). Also present in the northwestern part of the Mountains are dark-green-to-black chlorite schist, amphibolite, and metamorphosed intermediate plutonic rocks (Nelson, 1986, p. 84).

3.2 Cambrian

The Bliss Formation, which unconformably overlies the Precambrian rock, is the only Cambrian rock reported in the Mountains. In the west-central part of the Mountains, the Bliss Formation is 75 ft thick (Jacobs, 1956, p. 13), and includes upper and lower units that "pinch out" northward (Nelson 1986, p. 85; fig. 4). Silicified, coarse-grained sandstone with abundant oolitic hematite and lesser amounts of glauconite forms the lower unit of the Bliss Formation. McCleary (1960, p. 11) noted that the lower unit is crossbedded.

The upper unit consists of thin-bedded limestone with intervals of fine-grained sandstone and siltstone. A silty, glauconitic limestone at the top of the Bliss Formation merges with the Sierrite Formation of the Ordovician El Paso Group. McCleary (1960, p. 11) found the Red House Formation of the Pennsylvanian Magdalena Group to
unconformably overlie the Bliss Formation in the northern part of the Mountains. Chapin and Nelson (1986, p. 108) divided the Bliss Formation in the northwestern part of the Mountains into three informal units: 1) lower unit, which is a white, locally conglomeratic, quartzose, arkosic sandstone with trace fossils; 2) middle unit, which is a dark purple, medium- to coarse-grained, hematitic, locally trough crossbedded quartz sandstone; and 3) upper unit, which is greenish-brown siltstone, sandstone and thin- to medium-bedded, dark gray limestone.

3.3 Ordovician

3.3.1 El Paso Group. The El Paso Group consists of two formations—the Sierrite and the Bat Cave. Kelly and Silver (1952) named these formations for exposures in the Caballo Mountains. The maximum combined thickness of this group in the Fra Cristobal Mountains is reported to be 157 ft (Nelson, 1986, p. 85; fig. 4). In the central part of the Fra Cristobal Mountains, the Sierrite Formation conformably overlies the Bliss Formation. The predominant rock in the formation is thin-bedded limestone with local shale partings. The bedding is defined by alternating thin bands of chert and thicker bands of limestone. Limestone weathers buff, but is medium to dark gray on fresh surfaces. The Sierrite Formation grades upward into the pinkish-white, medium-bedded, highly silicified limestone of the Bat Cave Formation (Jacobs, 1956, p. 14-15) and closely resembles the limestone of the underlying Sierrite Formation (Jacobs, 1956, p. 16). Jacobs (1956, p. 15) described the Bat Cave Formation as consisting predominantly of a series of brick-red to light gray conglomeratic sandstone beds.

In the southern part of the Fra Cristobal Mountains, Thompson (1961, p. 9) found the Sierrite Formation to consist of 123.5 ft of limestone with some chert and shale and
the overlying Bat Cave Formation to consist of a limestone, conglomerate, and dolomite sequence. Nelson (1986, p. 85-85) divided the Bat Cave Formation into two informal units—a lower thin- to medium-beded limestone and an upper unit of medium- to thick-beded, alternating bands of dark-gray and medium-gray limestone, dolomitic limestone, and dolomite, with chert beds. Near the top of the upper unit, a silicified collapse breccia is common.

Jacobs (1956) and Thompson (1961) did not report fossils in either the Sierrite or Bat Cave Formations during their studies of the stratigraphy in the Fra Cristobal Mountains. However, Nelson (1986, p. 85) described the Sierrite Formation as locally dolomitic and glauconitic, with stromatolite bands as much as 6 in. thick. Nelson also reported that common stromatolitic biostromes and bioherms are present in a lower unit of the Bat Cave Formation.

3.3.2 Montoya Group. Entwistle (1944, p. 16-19) divided the Montoya Group into three members. While studying the stratigraphy in the Caballo Mountains, Kelley and Silver (1952, p. 57-64) used those members proposed by Entwistle and raised them to formation status. In addition, Kelley and Silver (1952, p. 57) added a basal sandstone unit to the group. The members of Montoya Group include (from oldest to youngest) the Cable Canyon Sandstone, Upham Dolomite, Aleman Formation, and the Cutter Formation. Nelson (1986, p. 86) believed that the Cable Canyon Sandstone is probably the only member of the Montoya Group present in the Fra Cristobal Mountains. Nelson (1986) speculated that a small amount of Upham Dolomite may also be present, but added that this has not been confirmed. Six feet of Cable Canyon Sandstone crops out in the west-central part of the Fra Cristobal Mountains (Nelson, 1986, p. 84, fig. 4). The
sandstone is white to mottled gray and brown, well sorted, medium- to coarse-grained with dolomite or calcitic dolomite cement. Pebble conglomerate is present locally. At the upper contact with the Magdalena Group, Nelson (1986, p. 86) reported that there is a major erosion surface and much of the unit consists of silicified collapse breccia related to the unconformity.

3.4 **Pennsylvania**

3.4.1 **Magdalena Group.** The Magdalena Group (fig. 4) as defined in the Caballo Mountains by Kelley and Silver (1952, p. 96) consists of three formations which include (from oldest to youngest) the Red House, Nakaye, and Bar B Formations. Kelly and Silver (1952) correlated the Red House Formation with Derryan and lower Desmoinesian, the Nakaye Formation with upper Desmoinesian and lower Missourian, and the Bar B Formation with upper Missourian, Virgilian, and possibly lower Wolfcampian. Jacobs (1956, p. 16-17) reported that the Magdalena Group crops out along the entire northern part of the Fra Cristobal Mountains, "...forming nearly the entire escarpment and crest..." and is as much as 1240 ft thick. Nelson (1986, p. 86) added that the Magdalena Group forms steep cliffs along the northwest flank of the mountains and forms much of the eastern, homoclinal slope of the Mountains.

3.4.1.1 **Red House Formation.** In the northern part of the Fra Cristobal Mountains, the Red House Formation rests unconformably on the Cambrian Bliss Formation between Amphitheater and Spring Canyons (fig. 4), on beds of the El Paso Group south of Amphitheater Canyon, and on Precambrian rock north of Spring Canyon (McCleary, 1960, p. 15). In the south, the Red House Formation rests on the units of the Montoya
Group (Nelson, 1986, p. 86). McCleary (1960, p. 15) described the lower part of the Red House Formation as predominantly, dark gray shale alternating with fine-grained, dark gray, thin- to medium-bedded limestone, having detrital quartz, fossil fragments, and limestone fragments. Nelson (1986, p. 86) added that the basal unit of the lower part of the formation consists of thin (less than 6 ft) quartz or chert-pebble conglomerate and red sandstone. Green chlorite schist blocks are present in a basal limestone unit where the Red House Formation rests on Precambrian rock. Nelson also reported that, where present, the basal clastic beds grade upward into interbedded black shales, and thin-bedded, gray to black, fossiliferous, micritic limestone, wackstone, and packstone. The upper part of the formation is predominantly medium- to massive-bedded limestone that contains abundant chert nodules, irregular bands, and patches.

3.4.1.2 Nakaye Formation. The Nakaye Formation, the most prominent part of the Magdalena Group, rests conformably on the Red House Formation and has a reported thickness of 700 ft in the central and northern part of the Fra Cristobal Mountains (McCleary, 1960, p. 15-16). The formation consists of 3 to 27 ft of thick, grayish brown to medium gray, fine- to very fine-grained, fetid, and fossiliferous micrite, packstone, and mottled dolomite alternating with thin (less than 3 ft thick) black shales (Nelson, 1986, p. 86). McCleary (1960, p. 16) noted that the massive limestone beds have chert lenses, nodules, and irregular patches. The chert is a medium- to dark-gray on fresh surfaces and is brown on weathered surfaces.

3.4.1.3 Bar B Formation. McCleary (1960, p. 17) found that the Bar B Formation differs from the overlying Nakaye Formation by the increase in the number of shale beds.
The limestone beds are similar to those of the Nakaye Formation and include micrite, packstone, and wackstone alternating with the black shale beds (Nelson, 1986, p. 86).

3.5 Permian

3.5.1 Abo Formation. The Abo Formation is mostly Wolfcampian in age, but the uppermost part is Leonardian (Kelley and Silver, 1952, p. 12). The formation, as much as 411 ft thick, crops out in the Red Gap area of the Fra Cristobal Mountains and in a few outliers near the top and near the north end of the Mountains (Nelson, 1986, p. 86; fig. 3). The Abo Formation rests conformably on rocks of the Magdalena Group (Nelson, 1986, p. 86) and is described as a typical floodplain deposit (Kelley and Silver, 1952, p. 101; Thompson, 1955a, p. 13 and b, p. 155; McCleary, 1960, p. 19). The formation is easily distinguished from other formations above and below it by its red to reddish-brown colors. The predominant rock type is claystone, but siltstone and fine- to very fine-grained quartz and minor potash feldspar sandstone are also abundant. Nelson (1986, p. 86) reported that crossbeds, ripple marks, scour and fill structures, and mud cracks are common in the formation. Thompson (1955a, p. 20; 1961, p. 12), and Nelson (personal communication, 1995) discovered reptile tracks in the formation. Some conglomerate units in the lower part of the Abo Formation consist of either granule to pebble size claystone grains, or of coarse-grained to granule size limestone clasts set in a red claystone matrix (Thompson 1961, p. 12).

3.5.2 Yeso Formation. McCleary (1960, p. 19) reported that the Yeso Formation (figs. 4 and 5) consists chiefly of sandstone and gypsum with lesser amounts of siltstone, limestone, and claystone. It crops out south of the Hackberry Canyon (fig. 5A) and Red
Figure 5.  A) Geologic map of Walnut Canyon area. Pm=Magdalena Gr., Pa=Abo Fm; Pym=Meseta Blanca Mbr., Yeso Fm; Pyl-Los Vallos Mbr, Yeso Fm; Psa=San Andres Fm; TKm=McRae Fm. Symbols with double tick mark bounding TKm and Pas are low-angle normal faults. B) Generalized geologic map of Fra Cristobal Mountains. Dashed box shows location of Walnut Canyon area. Note location of present study area. Modified from Nelson and Hunter (1986).
Gap area in the southern part of the Mountains and, because of facies variations and complex deformation and flowage within this formation, has an estimated thickness of 1185 ft (Nelson, 1986, p. 86). Thompson (1961, p. 13) divided the Yeso Formation into four general units in ascending order 1) a lower clastic unit, 2) a lower-middle clastic/evaporite unit, 3) an upper-middle evaporite unit, and 4) an upper clastic unit. Thompson (1961) suggested that these units were equivalent, respectively, to the Meseta Blanca, Torres (a member of the Yeso Formation in the San Andres Mountains), Cañas, and Joyita Members of the Yeso Formation. Nelson (1986, p. 86) recognized these units as the Mesta Blanca, Los Vallos, Cañas, and Joyita Members of the Yeso Formation.

3.5.2.1 Mesta Blanca Member. The Mesta Blanca Member consists of thin to medium beds of well-sorted, well rounded, subrounded or subangular, very fine- to medium-grained sandstone and siltstone (Thompson, 1961, p. 14; Nelson, 1986, p. 86-87). Locally, the sandstone and siltstone are interbedded with red to light red claystone and green and gray shale (Thompson, 1961, p. 14). Ripple marks and salt casts as much as 10 in. across characterize the lower part of the member (Nelson, 1986, p. 87). Thompson (1961, p. 14) reported that some siltstone-filled channels are found in the claystone and shale. This member is multicolored, and can be dark red, red-brown, pink, orange, yellow, green, gray, tan, and white (Thompson, 1961, p. 14). The Mesta Member rests conformably and is gradational with the underlying Abo Formation (Thompson, 1961, p. 14; Nelson, 1986, p. 86), and has a reported thickness between 459 and 549 ft (Nelson, 1986, p. 87).
3.5.2.2 Los Vallos Member. The Los Vallos Member consists of thin- to medium-bedded limestone that is locally fossiliferous. Colors include light to medium gray, brown, dark brown, and black. The darker-colored beds weather to brown and gray. Commonly, a fetid odor is released from fresh fractures (Thompson, 1961, p. 14). Ooids are reported at its base. Fossils include Productid brachiopods (in particular Dictyoclostus sp.) and some small cephalopods, scaphopods, and algae (Thompson, 1961, p. 15). The limestone beds are interbedded with light, calcareous, fine- to medium-grained, well cemented quartz sandstone; yellow, calcareous, and silty claystone (Thompson, 1961, p. 15); and local gypsum, anhydrite, and salt (Nelson, 1986, p. 87). Nelson (1986) estimated a thickness of 276-366 ft for this member.

3.5.2.3 Cañas Member. The Cañas Member is an evaporite unit consisting predominantly of white to light gray, laminated gypsum, having both crystalline and fibrous textures (Thompson, 1961, p. 16). The evaporite units are interbedded with gray and brown limestone and dolomite, and some yellow, fine-grained, quartz sandstone (Thompson, 1961, p. 16). This member has an estimated thickness between 129 and 147 ft (Nelson, 1986, p. 87).

3.5.2.4 Joyita Member. This member consists of thin- (Thompson, 1961, p. 17) to medium-bedded (Nelson, 1986, p. 87), fine- to medium-grained sandstone. The lower part is red and light gray, rocks near the top of the member are yellow to white, and the uppermost bed is red. Contact with the overlying Glorieta Sandstone of the San Andres Formation is sharp and conformable. Thompson (1961, p. 17) reported a total thickness of 1239 ft and as much as 300 ft is reported by Nelson (1986, p. 87).
3.5.3 **San Andres Formation.** Thompson (1961, p. 18) defined three general units to describe the San Andres Formation. These units include, from oldest to youngest, the Glorieta Sandstone, a transitional unit, and a main limestone unit. The Glorieta Sandstone is a massive, yellow to tan, very fine-grained (Thompson 1961, p. 18) to fine-grained sandstone (Nelson, 1986, p. 87) with well sorted, rounded quartz. It is well cemented with white silica and dolomitic carbonate (Thompson, 1961, p. 18). Contact with the underlying Yeso Formation is conformable and sharp. The upper contact with the transition unit is also sharp. The transition unit is characterized by dolomite, limestone, and sandstone beds. Dolomite beds found in the lower part are brown to dark brown, thin-bedded, finely crystalline, and micritic. Interbedded sandstones are light gray or yellow, thin-bedded and composed of very fine- to fine-grained, well sorted and rounded, and well cemented quartz grains. Near the middle of the unit, brown to gray, finely crystalline limestone is interbedded with a medium-bedded, light brown, fine- to medium-grained crystalline dolomite. The limestone beds becomes more abundant near the top of the unit. Capping this sequence is a prominent thick bedded sandstone composed of white, well rounded, medium- to coarse-grained quartz. This bed weathers to dark brown. At the top of the transition unit are some medium-bedded, tan and brown, fine- to medium-crystalline gained limestone beds. Also present are sandstone beds similar to those below. The limestone unit of the San Andres Formation is the predominant unit of the formation. The lower part consists of brown to dark brown, medium- to thick-bedded, dense to medium crystalline limestone and calcarenite beds. Fossils present include nautiloids, brachiopods (predominantly *Dictyoclostus* sp.) and gastropods. The upper part of the main limestone unit is a thin- to thick-bedded
limestone that is mainly brown to dark brown and finely crystalline (Thompson, 1961, p. 18-20). Thickness estimates for the San Andres Formation range from 300 to 600 ft (Nelson, 1986, p. 87).

3.6 Cretaceous

With the exception of the McRae Formation, Cretaceous strata are only reported to be present in the southeastern and southern parts of the Fra Cristobal Mountains (fig. 4). Thompson (1961, p. 22-26) describes the pre-McRae Cretaceous strata (from oldest to youngest) to include Dakota Formation, Mancos Shale, and Mesaverde Formation. Thompson (1961, p. 24), Foulk (1990, p. 18), and Nelson (1993) mentioned without description the presence of Cretaceous rocks in the study area on the southeastern part of the Fra Cristobal Mountains (fig. 4).

3.6.1 Dakota Formation. The Dakota Formation is exposed in a few small outcrops as much as 50 ft thick at the south end of the Fra Cristobal Mountains. Here, sandstone of the Dakota Formation is a thin-bedded, light gray, medium-grained, subrounded to subangular, well-sorted, and consists mainly of quartz. It forms an apparent disconformity with the underlying San Andres Formation and has a sharp and conformable contact with the overlying Mancos Shale (Thompson, 1961, p. 22-23).

3.6.2 Mancos Shale. The Mancos Shale crops out southwest of Shotgun Ridge (fig. 4) and on the axial portion of the Fra Cristobal anticline (Thompson, 1961, p. 23). It is nonsilty, gray to dark gray, and calcareous with a few thin, flaggy limestones containing pelecypods near its base. Greenish shales at the top of the Mancos grade upward into the
Mesaverde Formation. Thompson (1961, p. 24) estimated a maximum thickness of 400 ft for the Mancos Shale in this area.

3.6.3 Tres Hermanos Formation. Although the Tres Hermanos Formation is not present in the Fra Cristobal Mountains, it has been found in the Engle Coal Field (Mescal Creek area) by Wallin (1983, p. 14-35; fig. 1) and part of the formation (the Fite Ranch Sandstone Member) was found in the study area (see Chapter 4). In the Mescal Creek area, the Tres Hermanos Formation consists of the Atarque Sandstone Member (bottom), Carthage Member, and Fite Ranch Sandstone Member (top; Wallin, 1983, p. 14).

3.6.3.1 Atarque Sandstone Member. The Atarque Sandstone Member forms a transitional lower contact with the Mancos Shale and is 75 ft thick. Interbedded shales, siltstones, and yellowish gray, very fine-grained sandstones for the lower 26 ft of the member. The upper part consists of yellowish gray, fine-grained sandstones with small-to medium-scale, trough-shaped cosets of high to low angle tangential crossbeds (Wallin, 1983). Sparse *Skolithos* and *Mytiloides mytiloides* (Mantell) are present in the sandstone units. Oyster, clam, and gastropod fossils were collected by Wallin (1983, p. 18) from a dark brown, concretionary to tabular zones of sandstones also present in the upper part of the formation.

Wallin (1983, p. 22) interpreted the Atarque Sandstone to be several prograding distributary mouth bars that advanced across a shallow epeiric sea. *Mytiloides mytiloides* (Mantell) found near the top of the formation indicates a middle early Turonian age for the Atarque Sandstone Member (Wallin, 1983, p. 24).
3.6.3.2 Carthage Member. In Mescal Creek, the Carthage Member is 199 ft thick and consists of mainly yellowish gray and light olive gray, discontinuous, thin- and thick-bedded, very fine- to fine-grained sandstones, and medium gray and light olive gray carbonaceous mudstones. Very thin beds of clayey, silty, sandy, carbonaceous calcarenite contain small, disarticulated clam valves, and gastropods (Wallin, 1983, p. 26-29).

Wallin (1983, p. 29) interpreted the Carthage Member as a combination of marginal marine and nonmarine environments deposited on a broad, low energy coastal or delta plain. The formation is interpreted to be mainly a distributary mouth bar deposit with overlying fluvial channel, crevasse splay, swamp, and overbank deposits.

3.6.3.3 Fite Ranch Sandstone Member. The Fite Ranch Sandstone Member averages about 9 ft and varies from several inches to as much as 32 ft in Mescal Creek (Wallin, 1983). It is commonly light olive gray and grain size ranges from fine to coarse sand. Wallin (1983, p. 32) found that small-scale cosets of trough cross-beding and very thin, planar horizontal bedding are the predominate sedimentary structures. Rare fragments of *Inoceramus* sp. are the only fossils found in the Fite Ranch Sandstone.

Wallin (1983, p. 34) found the Fite Ranch Sandstone to record the transgression of the Cretaceous seaway. However, Wallin (1983, p. 35) was not able to determine if the Fite Ranch Sandstone represented a barrier island complex of a mainland beach; but he noted that it had been interpreted as a barrier island complex in some areas to the north.

3.6.4 D-Cross Tongue of the Mancos Shale. In the Mescal Creek area, the D-Cross Tongue is about 240 ft thick and consists of predominately light olive gray, laminated,
noncalcareous siltstone, with lesser amounts of silty shale and laminated, calcareous, very fine-grained sandstone. The D-Cross Tongue forms a planar and nonerosional lower contact with the underlying Tres Hemanos Formation (Wallin, 1983, p. 35). Wallin (1983) found that the D-Cross Tongue contains three unnamed tongues of the Gallup Sandstone. These three tongues consist of yellowish gray, calcareous, well sorted, fine-grained sandstones that are moderately to densely bioturbated (Wallin, 1983, p. 36). Fossils found by Wallin (1983) included Skolithos, Ophiomorpha, the ammonite Prionocyclus novimexicanus (Mancou), and the oyster Lopha sannionis (White).

Wallin (1983, p. 40) interpreted the D-Cross Tongue as the seaward depositional sequence of a transgressing shoreline recorded by the Fite Ranch Sandstone Member of the Tres Hermanos Formation. The fine-grained sandstone tongues document the episodic progradation of a lower shoreface environment. Cobban (1984, p. 76) assigned Prionocyclus novimexicanus to the upper Turonian age of the Cretaceous, thus dating the D-Cross Tongue of the Mancos Shale (see Chapter 4).

Because the Fite Ranch Sandstone Member of the Tres Hermanos Formation and the D-Cross Tongue represent the last major sea level rise in the study area, I have redefined them as members of the Mancos Shale in my study area. Although the overlying Gallup Sandstone Member of the Mesaverde Formation is also a tongue of the Mancos Shale, I consider it as part of the Mesaverde Group because it represents a progradational shoreline (Wallin, p. 47) and lowering of sea level in the study area (see Chapter 4).

3.6.5 Mesaverde Group. Before 1954, the Mesaverde Group was known as the Mesaverde Formation. Bushnell (1953) informally divided the Mesaverde Formation
into the Main Body Member (lower) and the Ash Canyon Member (upper); a convention followed by many later workers such as Thompson (1961; fig. 6). Although Allen and Balk (1954) elevated the Mesaverde Formation to Group status, some workers such as Thompson (1955 and 1961) did not use this convention. Wallin (1983) and Molenaar (1983) divided the Mesaverde Group into the Gallup Sandstone and Crevasse Canyon Formation and further subdivided the Crevasse Canyon Formation into the Coal Bearing (lower), the Barren (middle) and the Ash Canyon (upper) members (fig. 6; see Chapter 4). In their study area, located in the U.S. Geological Survey Engle quadrangle (1:24,000; fig. 1), Mack and Seager (in press) used the same convention of Wallin (1983) and Molenaar (1983), but with the exception of combining the Barren and Coal Bearing members into one map unit--the Lower Member. They resorted to this combination because of the inability to distinguish between the Barren and Coal Bearing members in the field (fig. 6). Similarly, the present study followed Mack and Seager's (in press) convention for the same reason (fig. 6; see Chapter 4).

The Mesaverde Formation as described by Thompson (1961, p. 24-25) is exposed in the southern part of the Fra Cristobal Mountains and in a small outcrop east of Massacre Gap (fig. 4) on the eastern flank of the mountains (Thompson, 1961, p. 24). Following the convention of Bushnell (1953, p. 15), Thompson (1961) divided the Mesaverde Formation into two members--the Main Body and the Ash Canyon.

3.6.5.1 Gallup Sandstone. A detailed stratigraphic section of the Gallup Sandstone in Mescal Creek is presented by Wallin (1983, p. 44). The Gallup Sandstone consists of 75 ft of coarsening-upward sequence of sandstone with a calcareous, moderately sorted, yellowish gray, very fine-grained sandstone at the base and a well sorted, medium-
Figure 6. Correlation chart of Upper Cretaceous strata in the vicinity of Truth or Consequences, New Mexico with rock-stratigraphic terminology used in present study. Modified from Mack and Seager (in press).
grained sandstone at the top. Wallin (1983, p. 43) divided the Gallup Sandstone into a lower bioturbated unit; a thin-bedded, ripple-modified unit; a thick-bedded ripple cross-laminated unit; a trough cross-laminated unit; and an upper laminated unit. Fossils found include disarticulated valves of *Lopha sannionis* and the traces fossils *Ophiomorpha, Helminthoides, Terebellina, and Skolithos* (Wallin, 1983, p. 44-47).

The Gallup Sandstone represents a progradational shoreline. The lower bioturbated unit and the thin-bedded, ripple-modified unit are interpreted as a lower shoreline facies. The overlying thick-bedded, ripple cross-laminated and trough cross-laminated units represent an upper shorefacies. The upper most horizontal laminated unit is interpreted as sand deposited by "swash zone" processes at the strandline (Wallin, 1983, p. 47-48; see Chapter 4).

3.6.5.2 Main Body Member. Interbedded shales and sandstones typify the main rocks of this unit. The sandstones are commonly thin-bedded, buff to light gray, moderately sorted, well cemented, and consist of very fine- to coarse-grained quartz and some feldspar as the predominant minerals present. Common grain size is fine to medium. Most grains are subangular, but angular and subrounded grains are also present. The sandstone beds are generally lenticular and cross-bedded, and commonly weather olive to reddish brown. The shale is predominantly olive drab (Thompson, 1961, p. 24) on a weathered surface. The upper part of the member consists of thin, granule-to-pebble conglomerate beds interbedded with shale and sandstone. Petrified wood, commonly black and dark gray, is locally abundant. Some logs are as much as five feet long and two feet in diameter. Cserna (1956, p. 46) reported that cell walls and the microscopic structures of the wood are well preserved and the largest trunk found was about 20 ft long.
and 2.5 ft thick near its base. Thompson (1961, p. 25) reported that both lower and upper contacts are gradational with the underlying Mancos Shale and overlying Ash Canyon Member conglomerate. Estimated thickness is 2,000 ft.

3.6.5.3 Ash Canyon Member. Thompson (1961) mapped only one outcrop of the Ash Canyon Member located in the south-central part of the southern end of the Fra Cristobal Mountains. Thin to thick interbedded conglomerate and sandstone beds characterize the Ash Canyon Member. The conglomerate consists of subrounded to subangular, elongate (more than spherical), granular to pebble size, clear and gray chert set in a matrix of well cemented, fine-grained quartz sandstone. Mack and Seager (in press) reported that a complete section of the Ash Canyon Member is exposed in the Engle Quadrangle (fig. 1) and is approximately 1200 ft thick.

3.6.6 McRae Formation. Kelley and Silver (1952, p. 115) named the McRae Formation for outcrops in the Elephant Butte quadrangle (type locality; fig. 1) near Ft. McRae which is now beneath Elephant Butte Reservoir. Kelley and Silver (1952) estimated the thickness of the McRae Formation to be 3,000 ft. Bushnell (1953, p. 23) divided the McRae into two members (from oldest to youngest), the Jose Creek and Hall Lake. Lozinsky and Hawley (1986a) and Mack and Seager (in press) also used these member names as map units during their studies in the Elephant Butte and Engle quadrangles respectfully. Lancian dinosaur fauna (Lee, 1905; Lozinsky and others, 1984; Wolberg and others, 1986) and a jaw fragment assigned to *Tyrannosaurus rex* (Gillette and others, 1986) indicate that the McRae Formation is late Maastrichtian in age (Mack and Seager, in press). Although dinosaur bones found in both members of the McRae Formation
indicate a Maastrichtian age, Kelley and Silver (1952), Lozinsky and others (1984), and Wolberg and others (1986) suggested that the Hall Lake Member may cross the Cretaceous-Tertiary boundary. Seager and others (1997) submitted that unfossiliferous upper beds of the McRae may be Paleocene age. However, according to Mack and Seager (in press), this boundary has not yet been identified in the Hall Lake Member. Because of the uncertainty of the age of the upper part of the McRae Formation, this study assigns the entire McRae Formation to the Cretaceous, and speculates that Paleocene age strata were never deposited or were eroded during the deposition of the Love Ranch Formation. The McRae Formation is believed to record the earliest of two pulses of Laramide deformation in the Truth or Consequences region (Seager and Mayer, 1986, p. 52).

In the northern part of the Fra Cristobal Mountains (fig. 4), the McRae consists of horizontal, dark-brown sandstone, conglomeratic sandstone, bedded chert, and mudstone (McCleary, 1960, p. 21). Hunter (1986, p. 60) also added that leaf and wood impressions occur in the finer-grained facies of this unit. In the southern part of the mountains (fig. 4), the conglomeratic sandstone is interbedded with conglomerate containing increasing amounts of volcanic debris. Boulder-size andesite fragments are found in some conglomerates. Angular to subrounded cobbles and boulders of gneiss appear in both the beds containing volcanic material and in the interbedded sandstone beds as the Jose Creek Member nears Precambrian gneiss outcrops. East of the Precambrian occurrence are two small outcrops. They consist of white, coarse-grained, poorly-cemented, crossbedded sandstone, having well-rounded pebbles. Petrified wood, some fragments of gem quality, is present (McCleary, 1960, p. 21-22).
3.6.6.1 Jose Creek Member. In the Walnut Canyon area, located on the southwest side of the Fra Cristobal Mountains (fig. 5A and 5B), part of the upper Cretaceous McRae Formation is exposed only in small tectonic slices above a detachment fault (Kelley and McCleary, 1960, p. 1419; Nelson, 1986). Thickness of the McRae Formation has not been determined in these tectonic slices due to poor exposure (Nelson, 1986, p. 87-88). At this locale, Thompson (1961, p. 26-27) reported that the Jose Creek Member contains dark green, olive drab, gray, and purple shale beds interbedded with less common red, white, and purple sandstone, and more common dark green or gray sandstone. The sandstones consist predominantly of plagioclase and chlorite with some quartz, orthoclase, and black ferromagnesian minerals. The sandstones are poorly sorted, grains are angular to subrounded, and range in size from very fine to medium. Fossils include numerous plant fossils—most specifically, light gray petrified wood (see Chapter 4). Black petrified wood as long as 9-12 ft and over 3 ft in diameter is also present (Nelson, 1986). Hunter (1986, p. 58) determined that this tectonic slice of the McRae strata is a fluvial deposit and is petrographically very similar to the fluvial facies of the Hall Lake Member.

A complete section of the Jose Creek Member is 557 ft thick near Kettle Top Butte (fig. 1) in the Elephant Butte Quadrangle and on the southeastern flank of the Fra Cristobal Mountains; it is only 357 ft (incomplete section) in the Engle Quadrangle (Mack and Seager in press; fig. 1). In the Engle Quadrangle, the lower contact of the Jose Creek Member is unconformable with the Ash Canyon Member of the Crevasse Canyon Formation whereas the upper contact is conformable with the overlying Hall Lake Member (Mack and Seager, in press). Mack and Seager (in press) also note that numerous plant fossils such as leaves and stems in coarse- and fine-grained sandstones
and siliceous mudstones and petrified wood characterize this member in the Engle Quadrangle.

3.6.6.2 Hall Lake Member. Thompson (1961, p. 27-29) reported that the Hall Lake Member is commonly exposed in the southwestern part of the Fra Cristobal Mountains, but is absent in the northern part of the Mountains. The most diagnostic feature of the Hall Lake Member is the maroon color mudstone and sandstone intervals (Mack and Seager, in press). Also present is poorly sorted sandstone consisting of subangular, fine-to coarse-grains of white plagioclase, cream-colored chert, and light green chloritic material all contained in a matrix commonly having purple clay. Mack and Seager (in press) reported that the most distinctive rock types found in the Hall Lake Member is a 5 to 30 ft thick basal conglomerate consisting predominately of maroon, white, gray, and green quartzite clasts (see Chapter 4). Red granite and andesite porphyry clasts are also present. The clasts are well rounded and grain supported, and range from cobble to boulder in size. The conglomerate is commonly 15 to 30 ft above the base of the Hall Lake Member. Rocks of the Hall Lake Member were deposited in a fluvial environment (Mack and Seager, in press).

In the nearby Engle Quadrangle, the lower contact between the Jose Creek Member and the overlying Hall Lake Member is marked by a color change from brown and olive green sandstone and mudstone to purple sandstone and mudstone. The upper contact is believed to be unconformable with the overlying Love Ranch Formation (Mack and Seager, in press).

Thickness of the Hall Lake Member in the Fra Cristobal Mountains is not reported by earlier authors, but Bushnell (1953, p. 30) estimated a thickness of at least
2,900 ft near Kettle Mountain (just off the southwest edge Fra Cristobal Mountains in figure 4). In the Engle Quadrangle south of the study area, Mack and Seager (in press) measured 770 ft of an incomplete section (due to structural complications) and 1300 ft in the Elephant Butte Quadrangle on the southwest side or the Fra Cristobal Mountains.

3.7 Tertiary

3.7.1 Love Ranch Formation. Rocks of the Love Ranch Formation, a widespread fanglomerate facies in south-central New Mexico, document uplift and erosion of the Laramide fault blocks (Seager and Mack, 1986) and locally are as much as 3000 ft thick south of the Fra Cristobal Mountains. The Love Ranch Formation is believed to be early to middle Eocene in age because it is conformably overlain by late Eocene strata of the Palm Park Formation (Mack and Seager, in press). The Love Ranch Formation is believed to also record a second pulse of Laramide deformation in the Truth or Consequences region (Seager and Mayer, 1988, p. 52; see Chapter 5). On the southern edge of the Mountains, Mack and Seager (in press) found the formation to consist of a basal conglomerate overlain by fine-grained redbeds, mostly siltstone and mudstone (see Chapter 4). In the Engle quadrangle, the conglomerate is about 50 ft thick and contains boulders and cobbles of intermediate composition volcanic and/or hypabyssal porphyries. The overlying redbeds are estimated to be 500 ft or less in thickness. In the study area, conglomerate, sandstone, and shale mapped along several arroyos, are believed by Foulk (1990, p. 19) to represent the Tertiary Love Ranch Formation.

3.7.2 Palm Park Formation. About 1.5 miles south of Engle, New Mexico, two outcrops of Palm Park Formation are present, one in a borrow pit adjacent to the Engle-
Upham road (fig. 1) and the other about one mile east of Engle along Highway 52. Purplish gray lahar breccia, 5 ft or less thick, is found at both locations. It has an age of late Eocene to earliest Oligocene (Mack and Seager, in press). This formation has not been reported in the Fra Cristobal Mountains.

3.8 Upper Tertiary and Quaternary

The Palomas Formation is present to the southeast of the Fra Cristobal Mountains. Lozinsky and Hawley (1986 a, b) provided a formal definition for the formation, which is an upper Cenozoic basin-fill deposit. The Palomas Formation, constituting the upper part of the Santa Fe Group, consists of three units (from oldest to youngest): a tan, weakly consolidated to unconsolidated sandstone and conglomerate about 60 ft thick; an overlying 2.1 Ma basalt lava flow (dated by K-Ar method; see Bachmann and Mehnert, 1978); and a reddish brown to tan, pebble and cobble gravel and intercalated coarse sand about 20 ft thick (Mack and Seager, in press; see Chapter 4). An age of Late Pliocene to Early Pleistocene is assigned to Palomas Formation (Lozinsky and Hawley, 1986 a, b; Mack and Seager, in press).

3.9 Upper Quaternary

Upper Quaternary and Recent units consist of alluvium (Middle to Late Pleistocene and younger) and alluvial-fan, terrace, pediment veneer, floodplain, playa, and eolian deposits (Mack and Seager, in press).
Chapter 4

STRATIGRAPHY OF THE STUDY AREA

Exposed post-Paleozoic strata in the study area include Cretaceous, Tertiary, and Quaternary rocks and unconsolidated sediments. The clastic compositions of these rocks and unconsolidated sediments are presented in the following descriptions as estimated volume percent determined by petrographic and binocular microscope, hand lens, and conglomerate clast count. Paleozoic rocks were mapped and described by Foulk (1990) and are not discussed below, but the mapped Paleozoic rocks from Foulk's (1990) study are shown on Plate 1. Three stratigraphic sections were constructed from traverses along or near three different arroyos (fig. 2). These sections were used as a basis for descriptions and correlations of Cretaceous and Tertiary units.

4.1 Cretaceous Sedimentary Rocks

Thompson (1961, p. 24-25) first reported Cretaceous strata on the eastern flank of the Fra Cristobal Mountains. These strata were assigned by Thompson (1961) to the Mesaverde Formation (Group) and were mapped as a small outcrop east of Massacre Gap (fig. 4). On a Tenneco Minerals compilation map, Van Allen and others (1983) also reported an undifferentiated section of Cretaceous strata in the same area. Foulk (1990, p.18) and Nelson (1993) reported Cretaceous strata in the same locality, but also did not differentiate them. Foulk (1990, p.18) found that these Cretaceous strata were more extensively exposed than reported by Thompson (1955a; 1961) or Van Allen and others
(1983), and speculated (without supporting evidence) that these strata represented the Dakota Formation, Mancos Shale, and the Mesaverde Formation (Group).

The present investigation found some strata exposed in the study area to be Late Cretaceous in age. These strata represent (from oldest to youngest) the Tres Hermanos(?) Formation, D-Cross Tongue of the Mancos Shale, the Gallup Sandstone, the Lower and Ash Canyon members of the Crevasse Canyon Formation, and the Jose Creek and Hall Lake members of the McRae Formation (Plate 1). A correlation chart of nomenclature for Upper Cretaceous strata used by earlier workers and by this study in the vicinity of Truth or Consequences, New Mexico, is presented in figure 6.

As presented in Chapter 3, this study groups the Tres Hermanos Formation and D-Cross Tongue of the Mancos Shale as members of the Mancos Shale (fig. 6). The reason for this classification is that these units represent the last major sea rise in the study area. Although the Gallup Sandstone of the Mesaverde Formation is also a marginal marine facies, this study considers it part of the Mesaverde Group because it represents a progradational shoreline and lowering of sea level in the study area.

4.1.1 Mancos Shale
4.1.1.1 Tres Hermanos(?) Formation. Sandstone outcrops on the west end of both Arroyos E and D near the Paleozoic contact (Plate 1; fig. 6; see Chapter 3) may be part of the Tres Hermanos(?) Formation. Sandstone exposed in Arroyo E is reddish brown, thin bedded, fine- to medium-grained with parallel laminae and low-angle trough crossbedding. The upper and lower contacts are covered and only 18.9 ft of sandstone is exposed along the south side of the arroyo. In Arroyo D, the outcrop consists of (from base to top) 4.6 ft of sandstone, 10.0 ft of cover, and 4.2 ft of overturned, interbedded,
laminated, silty sandstone and mudstone (Plate 1 and 2). The lower sandstone is pale yellowish brown and weathers to light brown. It is noncalcareous, well cemented, and has a grain-size range from fine lower sand to silt with an average grain size of very fine upper. It is moderately well- to well-sorted with roundness ranging from subangular to subrounded. The lower sandstone (arkosic arenite) has a composition of quartz (50-55%), plagioclase (10-15%), K-feldspar (3%), chert (5-10%), kaolinite? (10-15%; petrographic analysis), opaque grains (iron oxides; 1-2%), and muscovite (1-2%). Some of the plagioclase has altered to clay. Iron oxide coats and/or outlines most plagioclase grains.

The sandstone (arkosic arenite) of the upper interbedded unit is texturally very similar to the lower sandstone. However, roundness for the upper sandstone is angular to subrounded. Composition consists of quartz (25-30%), plagioclase (5-10%), K-feldspar (3-5%), chert (10%), kaolinite mixed with quartz (30-35%), opaque grains (iron oxides; 1-2%), muscovite (1-2%), rounded sandy claystone (some with iron oxide stain, 10-15%), and rare (less than 1%) granite grains. The granite fragments consist of quartz, plagioclase, and muscovite. The sandstone is noncalcareous and well cemented (silica cement).

The interbedded unit also consists of two types of mudstone--a calcareous yellowish gray type and a noncalcareous light gray to medium gray type. Both are thin bedded.

This sequence of rock is believed to belong to the Tres Hermanos(?) Formation and perhaps to the Fite Ranch Sandstone? Member (see Chapter 3; fig. 6). Where the Fite Ranch Sandstone Member thins in Mescal Creek (fig. 1), Wallin (1983; p. 32) found the average grain size to be fine grained and that small-scale cosets of trough
crossbedding and very thin, planar horizontal bedding are the predominant stratification. Although planar horizontal bedding was not observed in the study area, the grain size and crossbedding are similar to those in the outcrops of Mescal Creek. However, stratigraphic position below the D-Cross Tongue of the Mancos Shale is the strongest support for the conclusion that these rocks are the Fite Ranch Sandstone Member.

Although evidence is lacking for a conclusive depositional environment for these strata due to poor exposure in the study area, Wallin (1983, p. 34) believed that the Fite Ranch Sandstone Member in Mescal Creek represents a shoreface/beach sandstone. Hook and others (1983) interpreted the Fite Ranch Sandstone Member in west-central New Mexico as a barrier island complex.

An igneous source area is indicated by feldspar and muscovite grains and rare granite fragments. Chert grains and other sedimentary rock fragments suggest that sedimentary strata were also present in the source area.

4.1.1.2 D-Cross Tongue of the Mancos Shale. Overlying the Tres Hermanos(?)
Formation is a unit that is found only at the west end of and adjacent to Arroyo D (Plates 1, 2, and 3). This unit consists of interbedded noncalcareous to calcareous mudstone (which is predominant in the section) and fine-grained lower angular to subrounded, discontinuous, laminated sandstone. The mudstone is medium gray and weathers to a dark yellowish orange. The sandstone (arkosic wacke) beds are laminated to thin-bedded, light olive gray, and weather to a dusky yellowish brown. They consist of light gray and white quartz (74%), white feldspar (5%), black opaque grains (iron oxide; less than 1%), and clay (15-20%). The capping limy sandstone (quartz arenite) is thin-bedded, has an average grain size of very fine upper, and a roundness of angular to
rounded. It consists of light gray and white quartz (93%), light gray chert (1%), and black opaque grains (iron oxides; less than 0.5%), and trace (less than 1%) amounts of feldspar. Distorted (bioturbated?) medium gray clay laminae also are present. Nodules in the sandstone are about 1 ft in diameter, consist mainly of silt and fine lower sand, and have desiccation cracks. Rounded clasts (as large as 3 in. in diameter) of the host rock material are present in the nodules and interpreted to be either a rip-up material and/or a result of dissolution. Late Cretaceous Cephalopoda found in the capping sandstone bed include _Prionocyclus wyomingensis_, _Collophoroceras inflatum_, _Prionocyclus novimexicanum_, and _Scaphites whitfieldi_ (figs. 7 and 8) which are upper Turonian in age (fig. 9; Hook and Cobban, 1979, p. 40; Cobban, 1984, p. 76). Small (about 1 cm in diameter) oysters are also present. The upper contact with the Gallup Sandstone (fig. 6; see Chapter 3) is sharp and chosen at the top of the fossil Cephalopoda-bearing sandstone. The lower contact with the Tres Hermanos (?) Formation is covered, and therefore, the total thickness of this unit is unknown. This unit has a measured thickness of only 6.9 ft. Based on the fine-grained, light olive gray sandstone, mudstone, and Cephalopoda, this rock unit correlates with at least part of the D-Cross Tongue of the Mancos Shale (Cobban, 1984, p. 86; fig. 6; see Chapter 3). In Mescal Creek, Wallin (1983, p. 35-40) described sandstone and mudstone with similar grain sizes and colors. However, the thickness and amount of bioturbation and trace fossils described in the Mescal Creek section were not found in the study area. Cephalopoda-bearing limy nodules were found and are very similar to those described by Wallin (1983, p. 40). Also _Prionocyclus novimexicanus_ is reported to be very common in limestone concretions near the base of the D-Cross Tongue of the Mancos Shale (Hook and Cobban, 1979, p. 40; Wallin, 1983, p. 40); thus adding support that this sequence of rock in the study area
Figure 7.  A) Photograph of *Prionocyclus novimexicanus* (A), *Scaphites whitfieldi* (B), and *Plicatula* (C). B) Photograph of *Prionocyclus wyomingensis*. All were found in the D-Cross Tongue of the Mancos Shale and are of late Turonian age (see fig. 9). Scale is 0.5 ft in length.
Figure 8. Photograph of *Ciolopoceras inflatum* of upper Turonian age (see fig. 9). Fossil in a carbonate nodule found in the D-Cross Tongue of the Mancos Shale. Scale is 0.5 ft in length.
Figure 9. Middle Cenomanian to upper Turonian ammonite zones and subzones in western New Mexico. Arrows point to ammonites found in the D-Cross Tongue of the Mancos Shale in this study. Modified from Cobban (1984, p. 76).
is part of the D-Cross Tongue of the Mancos Shale.

The D-Cross Tongue of the Mancos Shale was deposited in a marine shelf environment as indicated by the marine fossils and fine-grained, thin-bedded to laminated sandstone, siltstone and mudstone. Wallin (1983, p. 40) interpreted the D-Cross Tongue to represent deposition of clay, silt, and very fine to fine sand seaward of the transgressive shoreline recorded by the Fite Ranch Member. The source area for the D-Cross Tongue exposed granitic and sedimentary rocks. The feldspars indicate a granitic terrane, and the chert grains and the more rounded quartz grains, suggest a sedimentary source area at least second cycle sediments.

4.1.2 Mesaverde Group

The Mesaverde Group is divided into the Crevasse Canyon Formation and Gallup Sandstone by Wallin (1983) and Molenaar (1983). They further subdivided the Crevasse Canyon into the Ash Canyon, Barren, and Coal Bearing members. In a recent study, Mack and Seager (in press) used the same convention with the exception of combining the Barren and Coal Bearing members into one map unit. This was done because of the inability to distinguish the Barren Member in their field area. Similarly, the Mesaverde Group as defined in this study follows the same convention as Mack and Seager (in press; fig. 6; see Chapter 3).

4.1.2.1 Gallup Sandstone. Strata that overly the D-Cross Tongue crop out only near the west end of, and just south of, Arroyo D (Plates 1, 2, and 3). This unit has a measured
thickness of 367 ft, and for this study is divided into three units—lower, middle, and upper (Plate 2). The lower unit consists of interbedded mudstone and silty sandstone to sandy siltstone. The mudstone is laminated to medium bedded, noncalcareous to calcareous, light olive gray, and weathers to a dark yellowish orange. Some mudstone beds have ripple laminae, mudcracks, and are fissile. The silty sandstone (quartz arenites) to sandy siltstone is laminated to medium bedded, and grain size ranges from silt to very fine lower sand. Beds are medium light gray to medium gray and weather to grayish orange and dark yellowish orange. Composition consists of mainly light gray and white, pitted quartz (95%) and white feldspar (5%). Some samples are clayey. Carbonized plant fragments are also present. Carbonate lenses (grainstone) present at the 130 ft mark of the measured section (Plate 2, too thin to be shown in Plate 3) consist of carbonate grains (93%), angular fine-grained quartz (3-5%), rounded sedimentary rock fragments with kaolinite clay (1%; petrographic analysis), and black opaque grains (iron oxide; 1%). The lenses have discontinuous, wavy, "microfaulted" (soft sediment deformation) lamination and desiccation cracks. Color varies from olive gray to a dusky yellowish brown and weathers to a yellowish gray. On a fresh wet surface, the general laminae and color (light and dark brown) of the lenses is similar in appearance to "oil shale" color and laminae found in northwestern Colorado.

The middle unit is characterized by a sequence of about 170 ft of stacked, thin-bedded sandstone, siltstone, and interbedded laminated to thick-bedded mudstone. The first 50.3 ft of the middle unit consists of calcareous, laminated mudstone with a composition of clay mixed with carbonate (80%), silt to very fine-grained angular quartz (15-20%), and opaque yellowish grains (pyrite?; about 1%). The mudstone is light olive gray and weathers to dark yellowish orange that grades to pale yellowish brown. About
20 ft of cover (Plate 2) separates the interbedded sandstone, siltstone, and mudstone sequence from the basal mudstone. The sandstone (arkosic to quartz arenite) is generally light olive gray and weathers to various shades of yellowish gray and yellowish orange. Grain size is predominantly very fine upper, and grains are angular to subrounded. Grains are well cemented, calcareous, and consist of white and light gray quartz (74-95%), yellowish orange feldspar (3-15%), white feldspar (1-15%), black opaque grains (iron oxide; 1-5%), and trace (less than 1%) amounts of muscovite(?). Sorting varies from moderate to well. Parallel and ripple cross laminae are present in some beds. Overall, bedding thickness increases upward from laminated to medium-bedded. Sandstone beds are more common in the lower half of the unit than the upper half where siltstone beds are more common.

The siltstone beds are mainly light olive gray and weather to shades of brown, yellowish gray, and yellowish orange. They are commonly noncalcareous in the lower to middle part of the unit and calcareous to limy near the upper part of the unit. General composition for the siltstone beds is quartz (87-97%), yellowish-orange feldspar (1-10%), white feldspar (1-2%), and black opaque grains (iron oxides; 2-3%). A few have pinkish orange feldspar (2%) and/or chert (1%) and a few are clayey. Carbonized plant material is present in some beds. A laminated limy siltstone bed, at 204.3 ft, consists of quartz (90%), white feldspar (5%), pyrite fragments (less than 1%), and biotite? (1%). Four feet of stacked limestone (mudstone) are present at 189 ft. These beds are laminated with mudcracks, ripple laminae, horizontal burrows, and shell fragments. Some have mud rip-up clasts.

Mudstones of the middle unit are light olive gray, calcareous to noncalcareous, laminated and thin- to thick-bedded, and some are fissile and/or have carbonized plant
fragments. The upper mudstone of the middle unit contains medium- to fine-grained muscovite. The middle unit has a sharp upper contact with the upper unit of the Gallup Sandstone.

The upper unit of the Gallup Sandstone is about 155.5 ft thick and consists of thin- to medium-bedded sandstone and thin-bedded mudstone. Sandstone is the predominant lithology in this unit and is non- to slightly calcareous and commonly has an average grain size of fine lower. Colors observed for the sandstone beds include yellowish gray, light olive gray, and grayish green. Weathered colors include shades of yellowish-orange and gray and light browns. Nonlithic and lithic sandstone was recognized. The composition for the nonlithic sandstone (subarkosic to quartz arenite) is white to gray quartz (82-96%), orangish yellow K-feldspar (less than 1%-10%), white feldspar (1-20%, plagioclase?), biotite (less than 1%), muscovite (less than 1%), and iron oxide grains (less than 1 to 1%). Composition for the lithic sandstone (lithic to arkosic arenite) is white to gray quartz (15-55%), plagioclase (1-10%), orangish yellow K-feldspar (1-15%), chlorite (0-less than 1%), biotite (0-less than 1%), black opaque grains (1-2%), fine-grained volcanic rock fragments (less than 1-50%), altered rock fragments (volcanic?, 10-20%), and carbonate cement (1-40%). One unit has polycrystalline quartz (2-3 "crystals" per grain, 20-25%). A brownish black, noncalcareous mudstone that weathers to a medium dark gray caps the upper unit. The lower contact between the capping mudstone and the underlying sandstone is covered.

Sedimentary structures found in sandstone of the upper unit include trough crossbedding, wavy cross-ripple laminae, very low angle crossbedding (hummocky), and desiccation cracks(?). The desiccation cracks occur only on the surface of the top sandstone bed.
Fossils found in the upper unit include trace fossils and disarticulated pelecypod valves. Horizontal trace fossils are found at the base of several sandstone units and rare "U" shaped and Skolithos burrows are present near the top of the upper unit (Plate 2). Two limy, fossiliferous sandstone beds are located at the 422.28 ft mark and at the 437.42 ft mark (Plate 1). Both beds have rip-up clasts at their bases and have sharp contacts with underlying thin-bedded medium gray (weathered color) mudstone. Disarticulated pelecypod valves are common in both beds and appear to be some type of mussel (fig. 10).

The contact between the upper unit and the first overlying channel sandstone marks the lower boundary of the first occurrence of terrestrial sedimentary rocks of Crevasse Canyon Formation (see Plate 3). Note that the position of this contact will be variable within different measured sections. The varying location of the contact in a selected section is due to the erosional process of streams as well as due to the randomness of stream channel development through time in a floodplain.

Overall, the rocks suggest shelf, beach or barrier island, and lagoon or bay environments of deposition. The laminated silty sandstone to sandy siltstone and mudstone of the lower unit may represent a shelf deposit. The interbedded silty sandstone and mudstone of the middle unit show an increase in grain size upward, ripple structure, and some parallel laminae that represent a foreshore facies. Hummocky crossbedding (common in the Gallup Sandstone (Harms and others, 1975)), indicating storm activity, may mark the lower midshoreface facies (Boggs, 1987, p. 423). The trough crossbeds, ripple cross laminae, "U" shaped burrows, and Skolithos suggest
Figure 10. Photograph of disarticulated valve of *Crassostrea soleniscus(?)* in the Gallup Sandstone located on north bank of Arroyo D just east of the western normal fault (see fig. 12). Scale is 19 cm (7.5 in.) in length.
that the upper part of the upper unit is a shoreface facies. The capping mudstone may be a bay or lagoon deposit. However, there are not enough data to distinguish between either a bay or a lagoon environment for these rocks.

The two fossiliferous sandstones with rip-up clasts and sharp lower contacts with underlying mudstone indicate a deepening transgressive sequence followed by a shallowing regressive sequence capped by shoreface facies sands as indicated by the *Skolithos*. In Mescal Creek, the Gallup Sandstone (having a thickness of 75 ft) records extensive progradation of shoreface environments which included shoreface, lagoon, and distributary channel facies (Wallin 1983, p.47-54). The source area for detritus in these rocks contained volcanic and granitic rocks as suggested by K-feldspar, plagioclase, biotite, muscovite grains, and granite and volcanic rocks fragments.

Because of the marine fossils, the depositional environments, and the stratigraphic position of this sequence above the marine D-Cross Tongue of the Mancos Shale and beneath the terrestrial rocks of the Crevasse Canyon Formation, this unit is assigned to the Gallup Sandstone.

4.1.2.2 *Crevasse Canyon Formation*. The strata above the Gallup Sandstone include sandstone, limestone, mudstone, and siltstone and can be correlated between Arroyos C, D, and E (Plate 3). These strata are divided into a lower and an upper unit (Plate 2). Both units are located southwest of the eastern normal fault (Plate 1).

4.1.2.2.1 Lower Unit. The lower unit, best exposed in Arroyo D, has a measured thickness of about 500 ft (Plate 2). The lower unit consists of discontinuous sandstone and clayey siltstone, and mudstone. Mudstone and siltstone are the predominant rocks. The sandstone (arkosic to quartz arenite) is thin- to thick-bedded with lengths ranging
from 5 to 38 ft. Geometrically, sandstone beds are discontinuous, lenticular, and concave upward. Single channels are predominate as compared to stacked channels. Some channel sandstones have basal lag or rip-up deposits, low angle (less than 10°) planar crossbeds, and/or parallel laminae; however massive beds are most common. They have sharp lower contacts and sharp or gradational upper contacts. Colors on fresh surfaces include light brownish gray, grayish olive green, grayish olive, and light olive gray. Colors on weathered surfaces include various hues of yellowish brown, reddish brown, brown, and few olive gray. The sand grains are moderate to well sorted with roundness ranging from angular to rounded. Most of the sandstone beds are noncalcareous to slightly calcareous; however one bed is limy. Average grain size for the nonlimy sandstone (quartz to arkosic arenite) varies from very fine upper to fine upper. Composition is white to gray quartz (76-98%), orangish yellow K-feldspar (0 to 7%), white feldspar (1-20%), and magnetite (less than 1%). Pink to red feldspar (5-10%) is more characteristic of sandstone in and near Arroyo E. The limy sandstone (arkosic to subarkosic arenite) unit contains quartz (45-50%), altered K-feldspar (kaolinized?; 10 to 15%), andesine plagioclase (optically negative, average extinction=14°, An28 Ab72; 5%) with carbonate "dusting", pyrite (1%), claystone fragments with quartz (1-2%), angular to subangular chert (5-6%), and carbonate cement (10-15%). Not all the sandstone beds contain lithic grains. All grains are frosted and pitted.

Siltstone is thin-bedded, noncalcareous, and very similar in color, composition, texture, and geometry to the sandstone. One siltstone bed is laminated, noncalcareous, well cemented, and has a blocky surface (maximum width of individual blocks is about 0.82-1.2 in.) and root casts. Color on a fresh surface is yellowish gray and pale yellowish orange and on a weathered surface, yellowish gray. Grain size ranges from medium sand
to silt with roundness varying from subangular to rounded. Siltstone composition is quartz (25-30%), feldspar (3%), black chert or petrified wood? (1-2%), gray chert (1-2%), sandy mudstone grains (5%), and very fine undifferentiated silt (60%).

The mudstones are dark yellow and yellowish gray on fresh surfaces and weather to dark yellow and yellowish gray. They are laminated to thin-bedded, noncalcareous, and have silt size, white to gray quartz, orangish feldspar, and black chert or petrified wood (SEM analysis, fig. 11).

4.1.2.2.2 Upper Unit. The upper unit consists of discontinuous sandstone, mudstone, clayey siltstone, claystone, and scarce limestone. Sandstone beds are more common in this unit than in the lower unit. The upper unit is best exposed in Arroyo D, where it has a measured thickness of about 495 ft (Plate 2). Its true thickness is not known because it is either faulted out at the top of the measured section (Plates 1 and 2; fig. 12) in Arroyo D or is covered as in the other draws (Plate 3). Sandstone colors on fresh surfaces are commonly shades of yellowish orange, brown, and gray and scarce olive brown, red, and orange pink. Colors on weathered sandstones surfaces include various shades of gray, olive gray, brown, and yellowish brown, orange, and gray. Most sandstone outcrops are confined to Arroyos D and E. Tracing sandstone beds along strike between draws suggests that these beds are depositionally discontinuous, and therefore the true lengths for the majority of these beds are not known. However, exposures of some sandstone beds adjacent to, and to the north of Arroyo E (Plate 1) are generally over 50 ft long with a few as much as 253 ft long. Beds vary from thin- to thick-bedded. Stacked channels are more common than in the underlying lower unit, and in Arroyo E they increase in number upward and are as much as 20 ft in total thickness. Some sandstone beds have
Figure 11. SEM semi-quantitative analysis of a black nonmagnetic grain commonly found in sandstone of the Crevasse Canyon Formation. Analysis indicates that this grain is a silica oxide, perhaps rounded chert or petrified wood fragment.
Figure 12. Photograph of the western normal fault (Plate 1). View south with the Gallup Sandstone on both sides of the gouge (reddish brown color). Uplifted block to the west. Gouge about 1 foot wide.
basal or near basal lag or rip-up deposits, ripple cross laminae, low angle trough or planar crossbedding, and/or parallel laminae. These structures are more common in the upper unit than in the lower unit. Horizontal burrows as much as 1.2 in. long and 0.4 in. wide are present near the tops of a few sandstone beds. Iron oxide concretions, varying from 1.2 in. to 0.7 in. in diameter, are common in some sandstone beds in both Arroyos D and E. In Arroyo E, the iron concretions are more common in the upper part of the section. The sandstone (subarkosic to quartz arenites) is noncalcareous to slightly calcareous and is generally moderate to very well sorted and only locally poorly sorted. Grains are commonly frosted and pitted and range from angular to subrounded. Grain size is commonly fine upper for sandstone in Arroyo D and medium lower to fine lower for sandstone in Arroyo E. General composition of the sandstone is white to gray quartz (80-99%), feldspar (less than 1 to 20%), black chert or petrified wood (less than 1 to 2%; SEM analysis), mica (muscovite and/or biotite; less than 0.5% to 2%), magnetite (0 to less than 1%), and chert (less than 1 to 2%). Feldspar colors are predominantly orangish yellow and less commonly red, pink, and brown. The red and pink feldspar is more abundant near the top of the section in Arroyo D and throughout the section in Arroyo E. Shades of gray are common colors for chert and less common colors include black, white, pink/red, yellow, and brownish red. Lower contacts of sandstone beds are commonly sharp with sandstone, mudstone or siltstone, whereas upper contacts can be either sharp or gradational with mudstone or siltstone.

Mudstone beds are very pale orange yellowish gray or white to light gray on fresh surfaces and dark yellowish orange or pale yellowish brown on weathered surfaces. They are laminated to thin-bedded, noncalcareous, and contain greater than 40% (by volume) clay and less than 40% silt-sized grains. In some samples, trace amounts (less than 1%)
of fine-grained quartz are also present. Lower contacts are generally gradational and upper contacts with sandstone are sharp.

Siltstone beds are dusky yellow, yellowish gray, light greenish gray, or very light gray and weather to dark yellowish orange, yellowish gray, or dusky yellow. They are laminated to thin-bedded, noncalcareous, clayey to non-clayey, and have a general composition of white to gray quartz (87-98%), yellowish orange to yellow feldspar (0-10%), and black opaque grains (nonmagnetic; 1%). Some have muscovite or biotite mica (1% or less) and/or medium gray chert (1%). Most of the grains are pitted or frosted. A few beds have carbonized plant fragments. Some of the beds are laminated, either parallel or wavy. Lower contacts are generally gradational and upper contacts are sharp with sandstone or gradational with claystone.

Claystone exposed in Arroyo D is laminated to thin-bedded, poorly cemented, limy to noncalcareous, and is light greenish gray on a fresh surface and yellowish gray on a weathered surface. Selenite clusters as much as 0.4 inches in diameter, carbonate "pods", and slickensides are also present in the claystone.

Two limestone beds are grayish orange to moderate brown and very pale orange and pale brown on fresh surfaces. On weathered surfaces, colors include light olive to yellowish olive brown, pale yellowish orange, and pale yellowish brown. One limestone is coarse crystalline with crude alternating dark and light colored carbonate laminae which is interlaminated with sandstone. The sandstone has an average grain size of very fine lower and consists of quartz, yellowish orange and white feldspar, and black nonmagnetic grains (chert?). The overall appearance is stromatolitic.
Both units were deposited in fluvial environments. The clayey siltstone and mudstone represent flood plain deposits (crevasse splay and soil deposits) whereas the sandstone bodies, based on their geometries, thickness, coarser grain size, planar and trough crossbedding, and basal lag or rip-up deposits are interpreted to be scour and braided stream deposits. Thinner (less than a foot thick) sandstone and siltstone beds may represent crevasse splay deposits. The abundance of pitted and frosted grains found in the sandstones indicates an eolian sand source. The blocky mudstones with root marks present in the lower unit are identified as exhumed paleosols (Mack and Seager, (in press); G.H. Mack personal communication, 1996). The claystone beds above sandstone beds may have been deposited in a marsh or as fining upward fill (clay plugs?) in abandoned channel(s). The limestone beds with their wavey laminae alternating with sand to silt laminae are similar to algae lamination and indicate lacustrine deposits.

Because of the channel sandstone and flood plain siltstone and mudstone and stratigraphic position above the Gallup Sandstone, both units are assigned to the Crevasse Canyon Formation (fig. 6; see Chapter 3). The Crevasse Canyon Formation is defined in northwestern New Mexico by Allen and Balk (1954) as the nonmarine sedimentary rocks above the marine Gallup Sandstone and below the marine Point Lookout Sandstone. In Mescal Creek (fig. 1) near Truth or Consequences, Wallin (1983) and Molenaar (1983) named a sequence of nonmarine rocks the Crevasse Canyon Formation even though the marine Point Lookout Sandstone was not deposited in the area (Molenaar, 1983). Wallin (1983) divided the Crevasse Canyon Formation into three members (from oldest to youngest): the Coal Bearing, the Barren, and the Ash Canyon. Lozinsky (1986) used the name Mesaverde Formation in his map of the Elephant Butte Quadrangle which includes Mescal Canyon. He divided the Mesaverde Formation into the lower "Main Body" and
the upper Ash Canyon Member. While mapping in the Engle Quadrangle (fig. 1), Mack and Seager (in press) followed the terminology of Wallin (1983) and Molenaar (1983) with the exception of combining the Coal Bearing and Barren members of Wallin (1983) into one map unit, the Lower unit (fig. 6; see Chapter 3).

The Coal Bearing unit of Wallin (1983, p. 55), having a thickness of 450 ft, is not recognized in the study area. Part of the Barren Member and Ash Canyon Member may be correlated to the lower unit and upper unit of this study respectively. Wallin (1983, p. 84) described the Barren Member in Mescal Creek as being mud-dominated whereas the Ash Canyon Member is sand-dominated. Sandstone beds of the Barren Member of Wallin (1983) range from fine- to medium-grained and form stacked channels as much as 40 ft thick. Sandstone beds of the Ash Canyon Member have grain size ranging from medium- to coarse-grained (Wallin, 1983, p. 84) and form stacked channels that are as much as 100 ft thick (Mack and Seager, in press). Both members contain mudstone and sandstone, but the Ash Canyon Member also contains pebbly sandstone and pebble conglomerate (Wallin, 1983, p. 84; Mack and Seager, in press). The sandstone beds of both members have trough cross bedding, channel structures, scour deposits, parallel lamination, and ripple structure and are thin- to thick-bedded. Mack and Seager (in press) noted that sandstone of the Lower Member contains iron oxide concretions as much as 2 ft in diameter. Iron oxide concretions, having diameters only less than 2 inches, are found only in sandstone located in the upper part of the section measured in Arroyo E. In Mescal Creek, Wallin (1983) reported a thickness of 1075 ft for the Barren Member and a thickness of 790 ft for the Ash Canyon Member. In the Engle quadrangle, Mack and Seager (in press) reported a thickness of only 830 ft for the Lower Member (Coal and Barren Members combined as one member) and estimated a thickness of 1200
ft for the Ash Canyon Member. The thickness reported for both members by Wallin (1983) and Mack and Seager (in press) differs from that of the study area by several hundred feet (Plates 2 and 3). The thickness difference for the Ash Canyon Member in the study area is attributed to faulting which displaced the upper part of the Ash Canyon Member down to the east and below the present surface.

Similar to the Barren and Ash Canyon members of Wallin (1983), the lower unit is mud-dominated and the upper unit is sand dominated. Sedimentary structures in both units of this study are also similar to those of the Barren Member and the Ash Canyon Member. However, other similarities are lacking or marginal at most. There is enough difference in sandstone geometry and number to distinguish the lower unit from the upper unit. However, because the Coal Bearing and Barren members of Wallin (1983, p. 55) can not be differentiated in the study area, the lower unit is assigned to the Lower Member of Mack and Seager (in press) and the upper unit is assigned to the Ash Canyon Member (fig. 6).

4.1.2.3 McRae Formation. In the southern part of the study area above the Crevasse Canyon Formation and adjacent to Arroyo E (Plates 1, 3, and 4) is a sequence of rocks that are very different from rocks of the Crevasse Canyon Formation. This sequence of rock is divided into a lower and an upper unit (Plate 4). The contact with the underlying Crevasse Canyon Formation is covered. However, it is speculated that this contact is near horizontal or slightly angular (see Chapter 5). This speculation is based on the similarity of bedding dips measured in both the Crevasse Canyon and McRae formations exposed in Arroyo E (Plate 1).
4.1.2.3.1 Lower Unit. Only about 45 ft of the lower unit crops out and consists of alternating sandstone, wacke, clayey siltstone, non-silicified mudstone, and silicified mudstone(?) beds. The sandstone (volcanic arenite) is thin-bedded, noncalcareous, and well cemented. Sandstone color is generally dark yellowish brown on both a fresh and weathered surface. Grain size ranges from very fine sand to fine pebble. One selected sample has an average grain size of fine pebble and consists of white and gray quartz (less than 5%), white plagioclase (25%), iron oxide (1-2%), and volcanic rock fragments (65-70%). Volcanic rock fragments are porphyritic with a fine-grained matrix. The wacke beds are thin- to medium-bedded and have sharp lower contacts and generally have gradational upper contacts with mudstone. Where exposed, the wackes have a sharp contact with the silicified mudstones(?). Colors of wacke beds are yellowish gray and bluish white on a fresh surface and grayish orange and yellowish gray on a weathered surface. Some wacke beds (arkosic volcanic wacke) are partly parallel laminated.

Selected wacke samples are noncalcareous, well cemented, and contain 30 to 50% matrix (a mixture of silt and clay). The average grain size of the sand sized fraction ranges from very fine lower to medium lower and grains are mainly angular to subrounded. In addition to matrix, general wacke composition is white and gray quartz (3-10%), white plagioclase (20-35%), lithic fragments (0-35%; volcanic or siltstone), biotite (0-2%), and iron oxide (1-3%).

Siltstone is medium- to thick-bedded, clayey and sandy, noncalcareous, and well cemented. Siltstone colors on a fresh surface include dusky yellow, yellowish gray, and grayish green to pale olive; whereas weathered surface colors include moderate brown to dark yellowish brown and dark yellowish orange to grayish pink. General grain size content of the siltstone is silt (70-90%), clay (7-25%), and sand (5% or less). The sand
size fraction is mainly fine grained and consists of quartz (less than 5% to 10%), plagioclase (as much as 10%), and chert (1% or less).

The non-silicified mudstone(?) is noncalcareous, well cemented, as much as 18 ft thick, and is laminated or thin-bedded. However, poor exposure prevents consistent determination of bed thickness. Color on a fresh non-silicified mudstone surface is bluish white to yellowish gray, whereas on a weathered surface color is a very pale orange to dark yellowish orange. The sand size fraction consists of quartz and oligoclase having a composition of Ab\textsubscript{72} An\textsubscript{28} (optical analysis).

The silicified mudstone(?) is medium-bedded with sharp upper and lower contacts with sandstone and non-silicified mudstone beds. Thin section analysis shows grain size of the non-silicified mudstone to be clay to silt and to consist mainly of quartz and feldspar. Bulk sample X-ray diffraction analyses of silicified mudstone(?) collected adjacent to Arroyo E (figs. 13 and 14) and of similar silicified mudstone from the central part of the Fra Cristobal Mountains (fig. 15) are very similar and contain mostly quartz and albite. Thin section analysis showed that the rocks from the study area are silicified and consist only of silt-sized grains. Mack and Seager (in press) found 6 to 7 silicified mudstone beds in a similar sequence of rock in the Engle Quadrangle. They found that the silicified mudstone consisted mainly of a mosaic of quartz and clay with variable amounts of sand-sized feldspar, quartz, and biotite (sand-sized fraction of the rock is less than 20%). Mack and Seager (in press) also found quartz bipyramids, some having embayed margins, and very minor volcanic fragments in the sand size fraction. These volcanic characteristics are diagnostic of ash fall tuffs (Carozzi, 1993). Bulk chemical composition conducted on silicified mudstone samples by Mack and Seager (in press) is
Figure 13. Bulk X-ray analysis of samples S45 A13 (A) and S44 A13 (B) from silicified ash bed of the Jose Creek Member of the McRae Formation located in the study area.
Figure 14. Bulk X-ray analysis of samples 13 (A) and S49 A13 (B) from silicified ash bed of the Jose Creek Member of the McRae Formation located in the study area (see Plate 4).
Figure 15. Bulk X-ray analysis of two samples from two silicified ash beds of the Jose Creek Member of the McRae Formation located in the Walnut Canyon area (see fig. 4A).
especially high in SiO$_2$ and low in Al$_2$O$_3$ and MgO, consistent with a silica tuff than with a shale (sic).

Fossil plant impressions, casts, carbonized plant fragments, and petrified wood (near the middle of the section, fig. 16) are abundant in the wackes. A large (about 1.5 ft in maximum length) palm frond fragment was found by W.R. Seager (in 1996) near the lower part of the section and fragments of petrified pine wood (identified by G.H. Seager, 1996) were located near the middle of the section. Siltstone and non-silicified mudstone beds also commonly have casts, molds, and carbonized fossil plant fragments.

4.1.2.3.2 Upper Unit. Only 12.2 ft of medium gray, thin-bedded, coarse to medium pebbly gravel sandstone of the upper unit is exposed in the study area (Plates 1 and 4). The lower contact is covered, whereas the upper contact, although covered, is interpreted to be faulted (Plate 3). The pebbly sandstone (pebbly volcanic arenite) is pale pink on a fresh surface and pale red to grayish red on a weathered surface. It is noncalcareous, well cemented, moderately sorted and has a grain size that ranges from clay to fine upper with an average grain size of fine upper. Sand-sized grains are mainly angular to subrounded. Composition includes quartz (20%), microcline (5-7%), white plagioclase (1-10%; some zoned), fresh and oxidized iron oxide (2-3%), volcanic rock fragments (50-55%), siltstone fragments (5%), and chloritized mica (less than 1%). Pebble clasts include rounded to well rounded, elongate limestone, black chert, altered volcanic rock, orthoquartzite, and granite. Quartzite is the most common clast.

Sedimentary structures are rare or lacking in the majority of the lower unit. However, the mudstone may represent flood plain deposits as indicated by the root traces, fossil plant fragments, and petrified wood. The siltstone, with rare parallel laminae and plant fragments at and near their base, may be crevasse splay deposits. The concentration
Figure 16. Photograph of part of a petrified tree trunk in the Jose Creek Member of the McRae Formation. Scale is 19 cm (7.5 in.) in length.
of fragmented, fossil plant debris near their base may represent a type of rip-up deposit. The silicified mudstone is interpreted to be volcanic ash debris, perhaps ash fall deposits based on their texture, bulk composition, and microscopic petrology which is very similar to rocks described in the Engle Quadrangle by Mack and Seager (in press). Sandstone bedding thickness, discontinuous bedding, rare parallel laminae and basal rip-up deposits may indicate a stream depositional environment. The high concentration of volcanic debris and siltstone fragments in the lower unit documents that volcanic and sedimentary rocks were present in the source.

The discontinuous, thin-bedded, pebble conglomeratic sandstone of the upper unit has sharp interbedded and lower contacts and is interpreted to be a braided stream deposit. Based on pebble clast and overall sandstone composition, the source area contained volcanic, sedimentary, and granitic rocks. Because the pebble clasts are well rounded, they have traveled some distance from the primary source area, or represent at least a secondary weathering cycle from a sedimentary source.

Because the rocks of both units are composed of a high percentage of volcanic debris, and given their stratigraphic position above the Crevasse Canyon Formation, they are assigned to the McRae Formation (fig. 6; see Chapter 3). The lower unit is assigned to the Jose Creek Member based on the high content of fossil plant debris and the silicified ash beds; both features are very similar to those described by Mack and Seager (in press) for the Jose Creek Member in the Engle Quadrangle and by Nelson (1986, p. 87-88) in the Walnut Canyon area (fig. 5).

Based on the composition, pebble-size fraction, and stratigraphic position (about 46 ft) above the Jose Creek Member, the pebble sandstone is suggested to be equivalent to the lower conglomerate of the Hall Lake Member as described by Mack and Seager (in
press) and Hunter (1986, p. 56). Mack and Seager (in press) found that the lower conglomerate of the Hall Lake Member is commonly 15 to 30 ft above the Jose Creek and Hall Lake contact. They note, however, that the basal conglomerate is clast supported, cobble to boulder in size, and quartzite is the predominate clast. They also found in the Engle Quadrangle that the conglomerate thins and grain size becomes finer northward. This could explain the finer grain size and conglomeratic characteristic of the Hall Lake Member in the study area.

4.2 Tertiary

4.2.1 Love Ranch Formation. A sequence of about 700 ft of sandstone, siltstone, and conglomerate (Plate 2) is exposed adjacent to the Crevasse Canyon Formation at the fault contact in Arroyos C and D (Plates 1 and 3), and east of the McRae Formation in Arroyo E. The lower contact in Arroyo E is either faulted, as in Arroyo D, or covered. The upper contact is mainly covered; however, in Arroyo E, it is an erosional contact with the Palomas Formation. The best exposures are in Arroyos C and D (Plates 1 and 3) and are present east of the eastern normal fault.

Colors observed on fresh sandstone surfaces include various shades of red, pink, gray, brown, orange, yellowish brown or orange, and grayish red or pink. Colors on weathered sandstone surfaces are different shades of red, gray, orange, grayish and/or yellowish orange, grayish pink, and grayish green. Sandstone strata range from thin- to medium-bedded, but is commonly thin-bedded. Stacked channels of 4 to 5 ft of thin- to thick-bedded sandstone commonly crop out in Arroyo D. They have either sharp or gradational upper contacts with reddish colored siltstone and generally have sharp lower and upper contacts with conglomerate and other sandstone beds. Lag and rip-up deposits
are commonly found near their lower contacts. Parallel, contorted (rare), ripple, planar, and trough crossbedding or laminae are common in the sandstone beds. Trace fossils found on sandstone bedding planes at or near the upper or lower contacts include horizontal, oblique, and "L" shaped burrows. The "L" shaped burrows (fig. 17) are found only in Arroyo C, at site C8 (Plate 1). Burrows are rare in these deposits.

Sandstone ranges from limy to noncalcareous and has an average grain size that varies from very fine lower to medium upper. Sand grains vary from very angular to rounded with subangular to subrounded being most common. Sorting ranges from well to very poor, but moderate to poor predominates. Sandstone (arkosic to quartz arenite and lithic arenite) composition is commonly quartz (67-99%), feldspar (0-10%), mica (biotite and muscovite, 0-1%), black grains (nonmagnetic, 0-5%), chert (0.5-25%), and other sedimentary rock fragments (0-25%). Quartz grains are commonly gray, white opaque or clear and feldspars are pink, white, or orangish yellow. Some of the more common chert colors are light to dark gray, black, reddish brown, yellow, orange, white, yellowish, reddish, and brownish gray. Sedimentary rock fragments include medium gray and purple-red mudstone; red, greenish yellow, and reddish brown siltstone; light gray, yellowish orange, and green claystone; yellowish green sandstone; medium to light gray, and brownish gray limestone. All grains are commonly frosted and pitted.

Siltstone is generally clayey and/or sandy. Colors on fresh and weathered surfaces include grayish red, pale red, grayish pink, and very pale orange to yellowish orange. Grayish red and pale red are the most common for these units. The siltstone units range from laminated to thick-bedded. Overall thickness (containing laminated bedding) can be greater than 10 ft. Siltstone is well to poorly cemented and ranges from noncalcareous to limy, but commonly is noncalcareous. Some siltstones have as much as
Figure 17. Photograph of parts of "L" shaped burrows at site C8 in Arroyo C. View of upper surface of a sandstone bed in the Love Ranch Formation. Burrows are vertical downward and then form about a right angle parallel along the bedding plane. This photograph shows only the vertical and separate horizontal parts of the burrows. Scale is 0.5 ft in length.
35% sand and 25% clay content. General composition is quartz (83-96%), feldspar (1-10%), black grains (nonmagnetic; 1%), reddish siltstone fragments (from the Abo Formation; 0-5%), and chert (1-2%). SEM analysis of a few samples indicates that the black, rounded to angular, nonmagnetic grains are either chert or perhaps petrified wood fragments. Only one sample ($4C8; Plate 4) had mica (muscovite; 1%). Quartz grains are gray and white; feldspars are shades of red, yellowish orange, pinkish orange, and light green. Chert grains are brownish gray and light to medium gray. The majority of the grains are frosted and pitted and range from angular to rounded with subangular to subrounded grains more common. Fossil root traces are common (fig. 18) and petrified wood fragments are rare (fig. 19).

Conglomerate is generally medium bedded, mainly clast supported, and commonly interbedded with medium-bedded sandstone (fig. 20; Plate 2). Where present, matrix sandstone colors on a fresh surface are yellowish brown and orange, but overall color is generally a shade of gray, a result of the high percentage of gray limestone clasts. On a weathered surface, matrix color varies from yellowish orange and yellowish brown to grayish orange pink. Average grain size varies from very fine to coarse with medium to coarse being most common. The matrix sandstone varies from poorly to well cemented, calcareous to limy, and ranges from well to very poorly sorted, but is generally poorly sorted. Grains of the matrix commonly range from subangular to subrounded and are frosted and pitted.

Matrix sandstone (subarkosic to quartz arenite) composition generally consists of feldspar (less than 1% to 5%), black opaque grains (nonmagnetic chert or petrified wood; less than 1% to 3%), quartz (76-99%), chert (1-5%), and other sedimentary rock grains (1-15%). The other sedimentary rock grains include limestone of various shades of gray.
Figure 18. Photograph of a plan view of root traces in the Love Ranch Formation located in Arroyo D. Root traces (marked by arrows) have a surrounding white oxidized zone. Scale is 19 cm (7.5 in.) in length.
Figure 19. Photograph of part of a petrified tree trunk in the Love Ranch Formation in Arroyo D. Scale is 19 cm (7.5 in.) in length.
Figure 20. Photograph of conglomerate section at site D8 in Arroyo D (see Plate 1). Jacob staff is 5.1 ft in length.
and gray brown, purplish-red to reddish-brown mudstone, clayey and non-clayey siltstone varying from reddish brown to red and orangish yellow, silty to non-silty yellowish brown sandstone, and light grayish white quartzite (rare). Feldspar colors are generally pink, pinkish white, or orangish yellow. The more common chert colors include light to medium gray or brownish gray, orange, black, and brown.

Conglomerate clast size generally ranges from granule gravel to cobble gravel; however, clast size of one conglomerate is as much as boulder gravel. Imbrication is common at most sites, but exposure does not generally allow for paleoflow direction measurement. However, 20 measurements from 3 sites (Plate 1 sites C8, D8, and D11) suggest that flow direction was between S42°E and N41°E (Table 1).

Ternary plots of clast counts were made to determine changes in source area through time that would record uplift and denudation. Twenty-three beds were selected from ten sites (Plate 1) for clast counts. Number of clasts counted varied between 250 and 330 per bed. Limestone is the predominant clast present at all sites. Other clasts include varying amounts of chert, sandstone, siltstone, claystone, volcanic rock, granite, and quartzite. Granite and quartzite clasts are uncommon and are probably of Precambrian age. Based on texture, brachiopod fossil fragments, and distinctive red color, the limestone clasts are Paleozoic in age. The chert clasts, based on color, are similar to cherts described in Paleozoic limestones and are therefore believed to also be of Paleozoic age. The sandstone, siltstone, volcanic rock, and claystone clasts (based on color and texture) are of Cretaceous age. The red color of some siltstone clasts identified them as part of the Paleozoic Abo Formation.

Three types of plots were made. On plot A (fig. 21) chert, sandstone, claystone, non-Abo siltstone, volcanic rock fragments, granite, and quartzite are plotted at apex Q;
Table 1. Flow direction measurements from clast imbrication in conglomerates at sites C8, D8, and D11 (see Plate 1). Each ring division on the rose diagram represents one orientation value. The inter visible ring is 2. Ring values increase outward. Each radius division equals 10 degrees.

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![Rose diagrams showing flow direction measurements](image_url)
Figure 21. Ternary plot A of clasts from conglomerate beds at 10 different sites (see Plate 1). Apex Q=chert, sandstone, claystone, non-Abo Formation siltstone, volcanic rock, granite, and quartzite. Apex F=Abo Formation siltstone. Apex L=limestone.
Abo siltstone is plotted at apex F; and limestone is plotted at apex L. All sites plot near apex L of the ternary diagram. On plot B (fig. 22), chert is plotted at apex Q, Abo siltstone is plotted at apex F, and the other lithic fragments are plotted at apex L. Again all clasts plot near apex L of the ternary diagram. In plot C (fig. 23), the clasts were separated by age with Precambrian quartzite and granite plotted at apex Q, Cretaceous sedimentary and volcanic clasts plotted at apex F, and Paleozoic limestones and chert plotted at apex L. Again, all conglomerates plotted near apex L. Results of the different plots indicate that the source area did not significantly change through time during deposition of the different conglomerate units.

Interbedded sandstone (sublithic, subarkosic, and quartz arenites) of the conglomerate units is pebbly, very fine to fine grained, moderately to well sorted, subangular to subrounded, calcareous to limy, and poorly to well cemented. They consist of quartz (92-95%), pink, white, and/or yellowish orange feldspar (1-3%), black grains (nonmagnetic chert or petrified wood; 1%), grayish orange or gray chert (1-2%), and siltstone grains (Abo Formation; less than 1%). Grains are commonly frosted and pitted. Trough or planar cross beds are commonly present. On a fresh surface, the sandstone is grayish pink to pinkish gray, grayish orange, or very pale orange and on a weathered surface is grayish orange pink, grayish orange, or pale yellowish orange.

Sandstone geometry, channel lag and rip-up deposits, and sharp lower and gradational upper contacts indicate stream deposits. Laminated siltstone and thin-bedded sandstone beds may be crevasse splay deposits. The interbedded conglomerate and sandstone units with trough or planar crossbedding represent braided stream deposit. The clayey siltstone units with root traces indicate soil deposits and are part of the flood plain deposits. The frosted and pitted grains suggest that sand dunes were present in the area.
Figure 22. Ternary plot B of clasts from conglomerate beds at 10 different sites (see Plate 1). Apex Q=chert. Apex F=Abo Formation siltstone. Apex L=limestone, sandstone, claystone, non-Abo Formation siltstone, volcanic rock, granite, and quartzite.
Figure 23. Ternary plot C of clasts from conglomerate beds at 10 different sites (see Plate 1). Apex Q=Precambrian granite and quartzite. Apex F=Cretaceous sedimentary and volcanic rocks. Apex L=Paleozoic limestones and cherts.
Clast and sand grain composition indicates the source area contained Precambrian granite and quartzite; Paleozoic limestone, chert, and siltstone; and Cretaceous sandstone, siltstone, and mudstone. The size of the conglomerate clasts suggests that the source area was probably less than 5 miles away. Limited clast imbrication measurements indicate a predominate northeast to east direction of flow and a minor southeast direction of flow (Table 1). Based on clast types, age, and size, and on flow direction, rocks of the Fra Cristobal Mountains were the source of the debris that formed this unit.

The rock types, stratigraphic position, and the distinctive reddish color of the siltstone indicate this unit to be the Tertiary Love Ranch Formation (fig. 6; see Chapter 3). The Love Ranch Formation is important because it documents uplift and erosion of Laramide fault blocks in the region (Seager and Mack, 1986; Seager and others, 1986; see Chapter 5).

4.2.2 Palomas Formation. A gravel unit overlies the Love Ranch Formation at two sites in the eastern parts of Arroyo C and E (Plate 1). At the Arroyo C site, this unit is a granule gravel to coarse pebble gravel, about 4 ft thick. The unit is partly cemented by caliche. Clasts include angular to subrounded limestone, sandstone, red siltstone, and gray chert. Limestone is the predominate clast type. A volume percentage of each clast type could not be determined because of clay coating the majority of the clasts. The clay coating is derived from surface soil that has been washed down over the clasts. Some imbrication was observed. The lower contact is covered but believed to be sharp with red siltstone of the Love Ranch Formation.

In Arroyo E, 2.3 ft of planer crossbedded, uncemented, clast supported gravel forms a sharp upper contact with a matrix supported conglomerate and forms a sharp
lower contact with laminated sandstone of the Love Ranch Formation. The un cemented
unit consists of angular to subrounded clasts with an average grain size of fine pebble
gravel. The planer sets dip 13.5° to the southeast. The clasts are predominately
Paleozoic limestone and minor red siltstone (Abo Formation), and Cretaceous yellowish
orange siltstone. The overlying matrix supported conglomerate is about 15 ft thick and
shows normal grading. It consists of Paleozoic limestone (95%) and red siltstone (Abo
Formation, about 2%) and Cretaceous sandstone and siltstone (3%). Grain size ranges
from cobble gravel to granule gravel. Overlying this conglomerate are Quaternary soils.

The calcified conglomerate in Arroyo C and the planer conglomerate in Arroyo E
are probably braided stream deposits. The normal graded, matrix supported
conglomerate in Arroyo E is a debris flow deposit. The clast composition indicates that
the Fra Cristobal Mountains were the source area for the conglomerates.

The clast types, grain size, and stratigraphic position indicates that these units are
part of the late Pliocene to early Pleistocene Palomas Formation, a piedmont facies
derived from mountain ranges bordering the Rio Grande rift (Mack and Seager, in
press). This conclusion is supported by observations made by G.H. Mack and W.R.
Seager in the present study area (personal communication, 1996).
4.3 Stratigraphic Summary

This study documents strata of Cretaceous and Tertiary age in the study area. Strata of Cretaceous age include the Fite Ranch Sandstone(?) Member of the Tres Hermanos(?) Formation, D-Cross Tongue of the Mancos Shale, Gallup Sandstone, Lower and Ash Canyon members of the Crevasse Canyon Formation, and the Jose Creek and Hall Lake members of the McRae Formation. Strata of Tertiary age include the Love Ranch and the Palomas formations. The Fite Ranch Sandstone(?) consists of interbedded mudstone and sandstone and was deposited in a shoreface/beach environment or a barrier island complex based on studies by Hook and others (1983) and Wallin (1983) for west central New Mexico. The source area for Fite Ranch Sandstone(?) exposed sedimentary and granitic rocks. The overlying D-Cross Tongue of the Mancos Shale consists of interbedded mudstone and sandstone. Ammonites found in the D-Cross Tongue include *Prionocyclus wyomingensis, Coiopoceras inflatum, Prionocyclus novimexicanus*, and *Scaphites whitfieldi* that indicate upper Turonian age for this unit. The D-Cross Tongue was deposited in a shelf environment and the source area exposed sedimentary and granitic terrain. The Gallup Sandstone consists of mudstone and sandstone. Mudstone forming the lower unit of the Gallup Sandstone was deposited in a shelf environment. Mudstone, siltstone, and sandstone of the middle unit indicate a lower shore depositional environment. Sandstone and mudstone of the upper unit formed in a beach or barrier island and capping mudstone formed in a lagoon or bay environment. The source area exposed volcanic and granitic rocks. The overlying Crevasse Canyon Formation is divided into the Lower and Ash Canyon Members. The Lower Member consists predominately of mudstone and discontinuous, siltstone and minor channel sandstone
beds. The Ash Canyon Member is similar to the underlying member, but has more channel sandstone beds that tend to be thicker and/or stacked. Rare thin-bedded, stromatolitic limestones are also present in the Ash Canyon Member. Rocks of both members of the Crevasse Canyon Formation were deposited in flood plain and stream channel (braided?) environments. The flood plain environment includes soil and crevasse splay deposits. Lake environments are indicated by the stromatolitic limestone beds. The source area for both members exposed granitic, volcanic, and sedimentary.

The McRae Formation consists of sandstone, wacke, and mudstone in the upper part of the Jose Creek Member (the lower member) and conglomeritic sandstone in the lower part of the overlying Hall Lake Member. The Jose Creek Member was deposited in a flood plain that includes soil(?), ash fall, and crevasse splay deposits, whereas the Hall Lake Member was deposited in a fluvial channel environment. The source area for both members exposed predominately volcanic rocks. Chert and siltstone fragments in the Jose Creek Member and well rounded pebbles of granite, quartzite, limestone, and black chert indicate a minor amount of sedimentary rocks were also exposed in the source area.

The late Paleocene to Eocene Love Ranch Formation was deposited in flood plain environments consisting of soils and braided stream deposits. Ternary plots of conglomerate clasts indicate that the source area remained unchanged during the deposition of that part of the Love Ranch Formation exposed in the study area. Clast imbrication measurements indicate a predominate flow direction to the northeast and southeast. Clasts of Paleozoic limestone and siltstone, and Cretaceous sandstone, siltstone, and mudstone combined with conglomerate flow direction data and proximity of the mountains (less than 2 miles west) indicate that the Fra Cristobal Mountains were the source area. Volcanic, granitic, and quartzite rock were exposed in the source area.
The Palomas Formation was probably deposited in a braided stream environment. The Palomas Formation is considered a piedmont lithofacies which is derived from mountain ranges bordering the Rio Grande rift. The clasts of Paleozoic and Cretaceous age found in the formation indicate that the Fra Cristobal Mountains were the source area for the Palomas Formation in the study area.
Chapter 5

STRUCTURE

The Fra Cristobal Mountains are part of a discontinuous chain of north-trending mountains (fig. 24) and constitute an east-tilted horst block that is bounded by two fault zones—the Fra Cristobal fault zone on the east and the Walnut Canyon-West Vein fault zone on the west (fig. 25). The eastern fault zone separates the mountains from the Jornada del Muerto Valley, a synclinal structure of Laramide age. The western fault zone separates the mountains from the Cenozoic Rio Grande rift. The Fra Cristobal Mountains are bounded on the north by the San Pascual platform (Thompson, 1955b, p. 156; not shown in fig. 1) and are separated from the Caballo Mountains to the south by the Cutter Sag (fig. 1) also of Laramide age.

Three different Laramide domains with distinct styles of deformation are recognized in the Fra Cristobal Mountains: 1) a thick-skinned domain involving Precambrian crystalline basement rocks along the northwest flank of the mountains; 2) a thin-skinned domain along the southwest flank of the mountains (Nelson and Hunter, 1986); and 3) a combined thick- and thin-skinned domain along the eastern flank of the mountains (Nelson, 1993). Although exposure is limited, the third domain is characterized by an eastward-directed thrust fault with an upper plate of gently southeast-tilted homocl ine of Paleozoic strata and a lower plate of steeply east-dipping Mesozoic and Cenozoic strata (Nelson, 1993, p. 261). The timing of deformation in the three structural domains is not constrained by crosscutting or stratigraphic relations (Nelson, 1993). Previous researchers identified and differentiated the Paleozoic strata involved in the third
Figure 24. Location of uplifts and normal faults marginal to the Rio Grande rift system in New Mexico. Heavy dark solid lines and dash lines show approximate boundary of Rio Grande rift. Uplifts are diagonally lined, normal faults show tick marks on hanging wall. S=Santa Fe; A=Albuquerque; SO=Socorro; T=Truth or Consequences; L=Las Cruces; FRA=Fra Cristobal Mountains; SA=San Andres. Note: FRA includes the Caballo Mountains and Cutter Sag to the south. Modified from Nelson (1986, p. 84).
Figure 25. Tectonic map of the Fra Cristobal Mountains showing the two major bounding fault zones—the Walnut Canyon-West Vein fault zone and the Fra Cristobal fault zone. Major contacts (thin dashed lines) are taken from figure 4. Dot-dashed lines are axial-surface traces of major folds; thrust faults shown with teeth on the upper plate; high angle faults shown with ball on relatively downthrown block. Faults are dashed where approximate or inferred and dotted where covered. Modified from Nelson (1986, p. 88).
structural domain (Nelson, 1993), but specific late Cretaceous strata, also deformed in the third structural domain, were not differentiated (Foulk, 1990; Nelson, 1993). Thus, only a late Cretaceous (Laramide) age could be assigned to the thrusting observed on the southeast flank of the Fra Cristobal Mountains (Nelson, 1993, p. 260-261 and p. 265) and on the west side of the present study area (Plate 1). Other structures in the study area include normal faults and folds.

5.1  
Faults

A thrust fault of Nelson's (1993) third domain was mapped by Foulk (1990). Evidence for thrusting is documented in an outcrop in the western part of Arroyo D where rocks of the Tres Hermanos(?) Formation are overturned and overthrusted by Paleozoic rocks (Plate 1, fig. 26). Assuming all overlying tilted Cretaceous formations above the Tres Hermanos(?) Formation were similarly deformed near this site, indicates that thrusting occurred near or following the end of the Cretaceous.

Normal faults are present in the west and east central part of the study area (Plate 1; figs. 12, 26, 27, and 28). The western normal fault crops out in Arroyo D (fig. 12). It strikes N58°E with a near vertical dip and truncates the lower fossiliferous shell bed of the Gallup Sandstone (Plate 2) about 25 ft along the northeast strike of the fossiliferous bed from the outcrop in Arroyo D. This fault is characterized by about 1 ft of gouge with 7.5 ft of breccia to the east and about 5 ft of breccia to the west of the gouge zone.
Figure 26. Cross section A-A' across the western and eastern normal faults and Cretaceous and Tertiary formations. Horizontal scale is equal to vertical scale. Fine dashed lines represent bedding planes. Heavy solid and dashed lines represent fault traces. See Plate I for explanation of formation symbols and location of cross section line.
Figure 27. Photograph of the eastern normal fault (see Plate 1). View south with rock of the Crevasse Canyon Formation on the upthrown block on the right.
Figure 28. Cross section B-B' across the eastern normal fault and Cretaceous and Tertiary formations. Horizontal scale is equal to vertical scale. Fine dashed lines represent bedding planes. See Plate I for explanation of formation symbols and location of cross section line.
Breccia clast size increases away from the gouge zone in both directions. Displacement is down to the east with younger strata on the east block. This fault trace is covered to the south of Arroyo D and is visible only a few tens of feet to the northeast of the outcrop in Arroyo D. The amount of displacement is not known because the section in the study area is thicker than other sections in the surrounding area and because of the lack of a distinctive marker bed that can be identified on either side of the fault. In the study area, the thickness measured from the top of the cephalopod bearing sandstone of the D-Cross Tongue of the Mancos Shale to the west normal fault trace is about 198 ft. This is a thicker section for the Gallup Sandstone than reported by either Wallin (1983, p. 50) in Mescal Creek (156 ft) or by Mack and Seager (in press) in the Engle quadrangle (100 ft). Therefore, the amount of displacement on this fault is unknown.

The eastern normal fault crops out best in Arroyo D (fig. 27) where it strikes N20°W 54°NE and probably intersects the western normal fault (Plate 1). The fault is characterized by about 3.5 ft of gouge and breccia and juxtaposes strata of the Tertiary Love Ranch Formation in the hanging wall with strata of the Cretaceous Ash Canyon Member of the Crevasse Canyon Formation in the footwall (fig. 27). Although covered, the fault also appears to bring part of the Hall Lake Member of the McRae Formation adjacent to Love Ranch Formation near Arroyo E. The location of the fault trace is indicated (from west to east) by an increase in bedding dip from less than 50° in the underlying Crevasse Canyon Formation to about 61° in the McRae Formation just west of the projected fault location (Plate 1). To the east of the fault trace is the Love Ranch Formation.
Because of the tilted and incomplete Cretaceous section in the study area, the true amount of displacement is not known. However, Mack and Seager (in press) reported a total thickness of about 1127 ft (357 ft of Jose Creek Member plus 770 ft of Hall Lake Member) of an incomplete section of the McRae Formation in the Engle quadrangle and about 1857 ft in the Elephant Butte area. In the study area, there is about 175 ft of exposed Jose Creek Member and only 10 ft of exposed Hall Lake Member. If it is assumed that there is an additional 105 ft of Jose Creek Member and 25 ft more of the Hall Lake Member that are covered between the top of the last exposed bed of the Crevasse Canyon Formation and the predicted fault trace (Plates 1 and 3), then there is at least 315 ft of McRae Formation west of the eastern normal fault trace. Subtracting 315 ft of the McRae Formation in the study area from 1857 ft in the Elephant Butte area indicates that at least 1542 ft of titled McRae Formation has down-dropped an undetermined vertical distance to the east of the eastern normal fault trace in Arroyo E.

In the Engle quadrangle, the Crevasse Canyon Formation has a measured thickness of 2030 ft (Mack and Seager, in press). From the top of the Gallup Sandstone to the west contact with the eastern normal fault in Arroyo D, about 625 ft of the Crevasse Canyon Formation is present (Plate 2). In Arroyo E, another incomplete section of the Crevasse Canyon Formation is about 1028 ft thick (Plate 3). Using the 1857 ft thickness for the McRae Formation plus 1355 ft (the difference between 2030 ft of Mack and Seager (in press) and about 675 ft from from Arroyo D in the study area) thickness for the Crevasse Canyon Formation, suggests that a maximum of 3212 ft of titled upper Cretaceous strata has been down-dropped at the Arroyo D fault site. It should be noted that this maximum does not represent "vertical" displacement, but the approximate missing thickness of the
combined Crevasse Canyon and McRae formations east of the eastern normal fault trace. The amount of "vertical" displacement can only be estimated based on bedding dips.

Bedding dips for Cretaceous strata vary from about 17° to over 60° near the eastern normal fault, whereas bedding dips in the Tertiary Love Ranch Formation vary from 90° (at the eastern normal fault in Arroyo D) to 9° or less farther east of the fault. Assuming that the contact between the Love Ranch Formation and underlying tilted Cretaceous strata marks an angular unconformity, it can be suggested that the minimum amount of vertical separation is about the thickness of a near horizontal Love Ranch Formation (figs. 26 and 28). In the Engle quadrangle, Mack and Seager (in press) estimated that the Love Ranch Formation is about 500 ft thick; however, in the study area, it is about 700 ft thick (Plate 3). Therefore, a minimum of 700 ft of vertical displacement has occurred on the eastern normal fault. Based on dip angles on the west side of the fault, the Cretaceous strata in the down thrown block is also believed to be tilted near the fault and speculated to be horizontal further out into the Jornada del Muerto Valley away from the fault.

Because the youngest strata displaced by the eastern normal fault are assigned to the Love Ranch Formation, the last movement on this fault would have been Eocene or younger. The tilted Cretaceous strata suggests that thrusting continued after the deposition of at least the lower part of the Hall Lake Member of the McRae Formation.

The Love Ranch Formation in the footwall of the eastern normal fault has been removed by erosion. In the hanging wall, the Love Ranch Formation is preserved in part. Therefore, the Love Ranch Formation in the study area is found only to the northeast of the eastern normal fault (Plate 1, and figs. 26 and 28).

At the east end of Arroyo D, a breccia zone in the Love Ranch Formation is about 2 to 3 ft wide and trends roughly east-west. Clasts within the breccia zone are as large as
2 ft in diameter (fig. 29). The south block is down-to-the-south relative to the north block and is rotated upward, bringing a conglomerate bed to the surface at the north side of the arroyo. However, it is not clear if this is a slump block as indicated by the rotated upward toe or a normal fault block.

The sandstone unit to the north of and in contact with the breccia zone is marked by distorted and convoluted bedding, and contains blocks of rotated sandstone within surrounding parallel bedding. The rotated sandstone blocks are of the same texture and composition as the surrounding rock. Both the blocks and distorted bedding within the sandstone indicate soft sediment deformation. It is possible that the distorted bedding and rotated blocks within the sandstone indicate a seismic event that had occurred during the deposition of the upper part of the Love Ranch Formation.

The western normal fault is similar to the northeast-trending Laramide faults described by Mack and Seager (in press) for the Engle quadrangle which have steep dips (50°-70°) with normal displacement. Similarly, the eastern normal fault compares to the Jornada Draw, Antelope, and Ceder Lake normal faults by having the same northwest trend and down-to-the east displacement (fig. 30). However, these later faults displace "gravels" of the Pliocene Palomas Formation and thus have more recent movement than the eastern normal fault in the study area.

5.2 Folds

Folds are identified in Cretaceous strata and in the Love Ranch Formation in the study area. Folds in the Cretaceous strata are attributed to thrusting and are represented by overturned beds in the western part of the study area (fig. 26). Folds in the Love
Figure 29. Photograph of the east trending fault? displacing sandstone of the Love Ranch Formation. Fault located at the east end of Arroyo D (see Plate 1). Scale (lower left) is 19 cm (7.5 in.) in length.
Figure 30. Map showing principal structural features of the Engle Quadrangle. From Mack and Seager (in press).
Ranch Formation are inclined with eastern limbs dipping less than 10° and western limbs
dipping as much as 22° (Plate 1). Mapped fold axial traces and a pi-analysis plot (fig. 31)
show a poorly-defined subhorizontal fold axis that trends to the northeast (Plate 1).
Using an approximate northward plunge direction of about 10° and 700 ft (measured
thickness of the Love Ranch Formation), trigonometric calculation indicates that the
Love Ranch Formation thins southward (Plate 1, figs. 28 and 29). The folds imply that a
component of compressional horizontal stress occurred in the northeast direction, perhaps
related to deformation during the Laramide orogeny with the uplift of the Fra Cristobal
Mountains.

5.3  Tectonic Synthesis

The Laramide orogeny began in southern New Mexico between Campanian and
latest Maastrichtian time during which a sequence of volcanic debris was deposited over
the south central part of New Mexico (Seager and others, 1997, p. 1396). Based on
structural and lithologic evidence in the Cutter Sag and Caballo Mountains area, Seager
and others (1997) believed that two pulses of Laramide deformation followed this
volcanic phase. The first pulse began by lower upper Maastrichtian and was
characterized by a series of symmetrical, open, northwest-trending folds in Upper
Cretaceous sedimentary rocks, a feature not found in the study area. Uplift resulted in
erosion of volcanic rock which supplied detritus for the McRae Formation (Seager and
others, 1997, p. 1397, fig. 32, Time 1). In the study area, the McRae Formation contains
a high percentage of volcanic detritus, and thus supports the conclusion of Seager and
others (1997) that volcanic deposits were once present and that the McRae Formation
Figure 31. Lower hemisphere equal area stereo-plot of poles to bedding planes (dots) of the Love Ranch Formation. $N =$ number of poles; square = fold axis. North direction is to top of page.
Figure 32. A schematic illustrating progressive deformation and uplift of the Fra Cristobal Mountains. Time 1—incipient uplift with deposition of lower part of McRae Formation. Time 2—Continued uplift, deformation, and deposition of McRae Formation. Time 3—Continued uplift with deformation of McRae Formation and deposition of Love Ranch Formation. Time 4—Thrust of Paleozoic over upper Cretaceous formations, overturning of Cretaceous formation, and deposition of lower part of Love Ranch. Time 5 and 6—Erosion of uplift and upper Cretaceous strata, continued deposition of Love Ranch Formation, and followed by normal faulting with erosion of Love Ranch Formation from uplift block.
documents the initial uplift and erosion of those volcanic rocks. With continued uplift in
the study area, the McRae Formation and older Cretaceous strata were tilted eastward
(figs. 26, 28, and 32, Time 2 -- upper Maastrichtian). However, Seager and others (1997)
indicate that the McRae Formation in their study area onlapped the highland area that was
forming, but was not deformed.

The second pulse of Laramide deformation formed the Rio Grande uplift (Seager
and others, 1997) and formed an unconformity between the McRae and the Love Ranch
formations (fig. 32, Time 3 -- lower middle Miocene). Seager and others (1997, p. 1397)
could not determine the significance of this unconformity and speculate that it may
represent an acceleration of Laramide deformation. This unconformity, if present, is
covered in the study area. However, it is speculated to be a low angle (less than 20°) to
underlying, tilted Cretaceous strata. This speculation is based on dips mapped in the
Cretaceous strata west of the eastern normal fault in the Arroyo E area (Plate 1 and figs.
26 and 27). During this second pulse, continued eastward compressional stress placed
Paleozoic strata over Cretaceous strata as mapped in the western part of the study area
(Foulk, 1990). Thus (in the study area), strata of the Cretaceous Tres Hermanos (?)
Formation were overturned and Cretaceous strata of the D-Cross Tongue of the Mancos
Shale, Gallup Sandstone, Crevasse Canyon Formation, and McRae Formation were tilted
eastward 20°-40° (fig. 32). As the (Fra Cristobal Mountains) foreland rose during this
time, it was weathered and the resulting detritus eroded to form the Love Ranch
Formation which covered the McRae Formation and onlapped the highlands (fig. 32,
Time 4 -- upper Miocene). Unroofing of the uplift is documented by the clasts of Upper
Cretaceous, Paleozoic, and Precambrian strata forming the conglomerates of the Love
Ranch Formation. Folds mapped in the Love Ranch Formation exposed in the study area
probably formed during this second pulse of the Laramide deformation. Mack and others (1997) also concluded that similar folds in the Love Ranch Formation formed during this pulse. Other Laramide structures formed in the area include the Jornada del Muerto Valley and the Cutter Sag.

At the beginning of the Oligocene, extensional tectonism began in southern New Mexico (Mack and Seager, 1995, p. 552; fig. 31, Time 5) and eventually superimposed a fault block mountain terrane over the earlier Laramide structures and formed the Rio Grande rift. Normal faults also formed that bounded the Fra Cristobal Mountain block as well as other mountain blocks in south-central New Mexico. The western normal fault in the study area is interpreted to have formed at this time displacing tilted strata of the Gallup Sandstone and Crevasse Canyon Formation. The eastern normal fault formed later with continued uplift of the Fra Cristobal Mountain block displacing the Eocene Love Ranch Formation as well as possibly the western normal fault (figs. 26, 27, 31, and Plate 1). With continued uplift along the eastern normal fault, erosion of the Love Ranch Formation from the upthrown block occurred. The last event is recorded by the deposition of the Palomas Formation over the eroded surface of titled Cretaceous strata and Love Ranch Formation. The Palomas Formation documents the most recent phase of extensional tectonism in the vicinity of Truth or Consequences (Mack and Seager, 1995, p. 552).

The structural style of the Laramide uplifts in Wyoming and Montana are very similar to those of the southern New Mexico foreland in that they are basically of fold-thrust origin. The synorogenic conglomerates of the Beartooth Range in Montana and Wyoming, and of the Madison Range in southwestern Montana are similar to the McRae and Love Ranch Formations of the Fra Cristobal Mountains in that they document the
uplift and unroofing of the forelands (DeCelles and others, 1987; DeCelles and others, 1991a; DeCelles and others, 1991b; Seager and others, 1997). Syndepositional folding of synorogenic strata found in the Beartooth Range (DeCelles and others, 1991a, b) and Sphinx conglomerate of the Madison Range (DeCelles and others, 1987), is similar to that found in the Love Ranch Formation. DeCelles and others (1991a, b) and DeCelles and others (1987) interpreted angular unconformities within synorogenic strata indicate uplift rates of a rising foreland. Similarly, the unconformity between the Love Ranch and McRae Formations is believed to indicate an increased rate of uplift according to Seager and others (1997). However, the Laramide structures in southern New Mexico differ from those in the north due to subsequent segmentation by extensional faulting related to the Rio Grande rift (Seager and others, 1997).
Chapter 6
SUMMARY AND CONCLUSIONS

Detailed mapping, stratigraphic studies, and cross sections have revealed the following important results of this study:

• This study was the first to establish what formations of Cretaceous and Tertiary age are present in the study area. Cretaceous strata correlate to the Fite Ranch Sandstone(?) Member of the Tres Hermanos(?) Formation; D-Cross Tongue of the Mancos Shale, Gallup Sandstone, Lower and Ash Canyon members of the Crevasse Canyon Formation, and Jose Creek and Hall Lake members of the McRae Formation. Strata of Tertiary age include the Love Ranch and the Palomas formations.

• This study found important ammonites that include *Prionocyclus wyomingensis*, *Coiropoceras inflatum*, *Prionocyclus novimexicanus*, and *Scaphites whitfieldi*. These ammonites establish an upper Turonian age for the D-Cross Tongue of the Mancos Shale which represents the last high sea level stand in the study area.

• This study identified two major pulses of Laramide deformation. The first recorded by the thrusting of Paleozoic strata over Upper Cretaceous strata and the syn- to post-tectonic deposition of the McRae Formation. The second pulse is documented by the syn- to post-tectonic deposition and folding of the Love Ranch Formation.
• This study more narrowly constrained the time of Laramide deformation in the study area as Late Maastrichtian to about the end of the Miocene.

• This study mapped normal faults which formed after deposition of the Miocene Love Ranch Formation and which probably formed concurrently with the formation of the Rio Grande rift.

• This study documented the most recent extensional tectonism as represented by the Palomas Formation.
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