



Geology of the Fra Cristobal Mountains, New Mexico

W. John Nelson, Spencer G. Lucas, Karl Krainer, Virginia T. McLemore, and Scott Elrick
2012, pp. 195-210. <https://doi.org/10.56577/FFC-63.195>

in:
Geology of the Warm Springs Region, Lucas, Spencer G.; McLemore, Virginia T.; Lueth, Virgil W.; Spielmann, Justin A.; Krainer, Karl, New Mexico Geological Society 63rd Annual Fall Field Conference Guidebook, 580 p.
<https://doi.org/10.56577/FFC-63>

This is one of many related papers that were included in the 2012 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual [Fall Field Conference](#) that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

GEOLOGY OF THE FRA CRISTOBAL MOUNTAINS, NEW MEXICO

W. JOHN NELSON¹, SPENCER G. LUCAS², KARL KRAINER³, VIRGINIA T. MCLEMORE⁴, AND SCOTT ELRICK¹

¹ Illinois State Geological Survey, 615 East Peabody Drive, Champaign, IL 61820; jnelson@isgs.uiuc.edu

² New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, NM 87104-1375 USA; spencer.lucas@state.nm.us

³ Institute of Geology and Paleontology, Innsbruck University, Innrain 52, Innsbruck, A-6020 AUSTRIA; Karl.Krainer@uibk.ac.at²

⁴ New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro; NM 87801, ginger@gis.nmt.edu

Abstract—The Fra Cristobal Mountains are a small north-trending range situated on the east side of the Rio Grande northeast of Truth or Consequences. The range is an east-tilted horst of Proterozoic granitic rocks overlain by Paleozoic, Mesozoic, and Cenozoic sedimentary formations. Paleozoic rocks comprise the Cambro-Ordovician Bliss Formation, Ordovician El Paso Formation and (locally) Montoya Formation, Pennsylvanian Red House, Gray Mesa, Bar B, and Bursum formations, and Permian Abo Formation, Yeso Group, thin Glorieta Sandstone, and San Andres Formation. Representing the Mesozoic are the Cretaceous Dakota Sandstone, Mancos Shale, and Crevasse Canyon and McRae formations. Mantling the flanks of the range is the Cenozoic Palomas Formation of the Santa Fe Group along with younger, unnamed Quaternary deposits. Flows, cinder cones, and dikes of Upper Pliocene olivine basalt occur in several areas in and near the range. The Fra Cristobals underwent Laramide compressional deformation followed by Cenozoic extensional faulting and uplift related to the Rio Grande rift. Small deposits, chiefly fault-controlled veins, of gold, silver, copper, lead, fluorite, and manganese have been prospected, but no significant mining has taken place in the range.

INTRODUCTION

Thousands of travelers view the Fra Cristobal Mountains every day, but few ever set foot there. Located between the Rio Grande valley to the west and the Jornada del Muerto basin to the east (Fig. 1). The range is about 27 km long north to south, no more than 11 km wide east to west, and the highest elevation in the range is 1,830 m. Nevertheless, this little mountain range contains a more than average share of features of geologic interest. Many aspects of the regional geologic story are illustrated here. Although few geologists are fortunate enough to visit these mountains, many aspects of their geology can be appreciated from distant vantage points along Interstate Highway 25.

The name of the range commemorates Fray Cristóbal de Salazar, a Franciscan friar who accompanied Oñate's 1598 expedition that established the first Spanish settlements in New Mexico. It is believed that Fray Cristóbal died near these mountains on his return trip to Mexico in 1599 (Julyan, 1998).

The most detailed investigations of Fra Cristobal geology are contained in four unpublished graduate theses, Thompson (1955), Jacobs (1956), Cserna (1956), and McCleary (1960). All include geologic maps, but these suffer from a lack of topographic base and, in several cases, from poor cartography and a scarcity of geographic reference points. Stratigraphic descriptions tend to be brief and lack detail, particularly of paleontology. Nevertheless, taken together, they decently describe the various rock types and portray their aerial distribution. They reflect the efforts of students to grasp concepts that have now aged by half a century. Subsequent work in the Fra Cristobal Mountains has concentrated on petrogenesis of basalts (Warren, 1978; Kelly, 1988), Laramide tectonics (Chapin, 1986; Foulk, 1991; Collins, 1999), Paleozoic magnetism (Romano, 1997), and mineral resources (van Allen et al., 1983; Sarkar, 1985; DeLillo, 1991).

For the last Truth or Consequences Region Field Conference, Nelson (1986) wrote a summary article on the geology of the Fra Cristobal Range. This remains the only geologic overview spe-

cifically of these mountains. Nelson's article was well-illustrated and covers all the major points of interest. Its chief shortcoming is lack of a detailed geologic map. Here, we present an updated overview of the geology of the Fra Cristobal Mountains, some of it based on our own recent fieldwork in the range, and our overview contains a detailed geologic map (Fig. 2).

GEOLOGIC SETTING

The Fra Cristobal Range exemplifies Basin-and-Range topography and the structure of New Mexico's Rio Grande rift. Together with the Caballo Mountains to the south, the Fra Cristobals mark

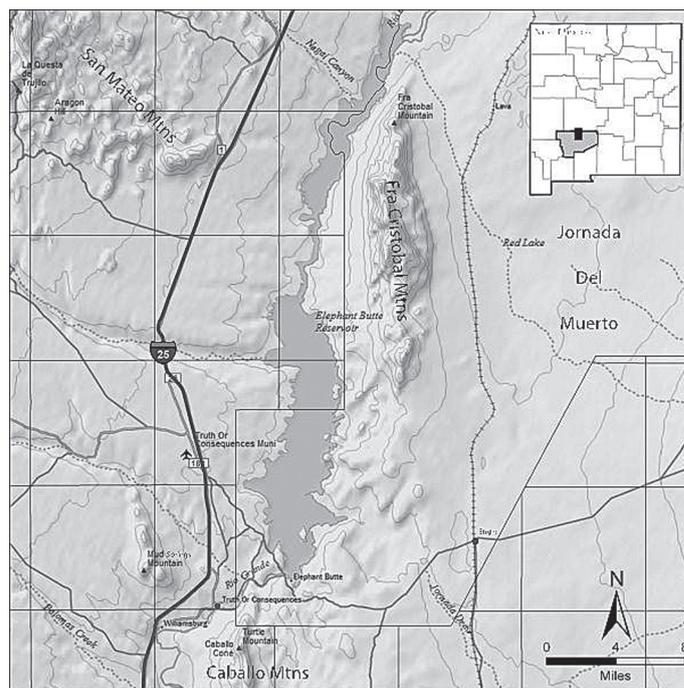


FIGURE 1. Map showing location of Fra Cristobal Range.

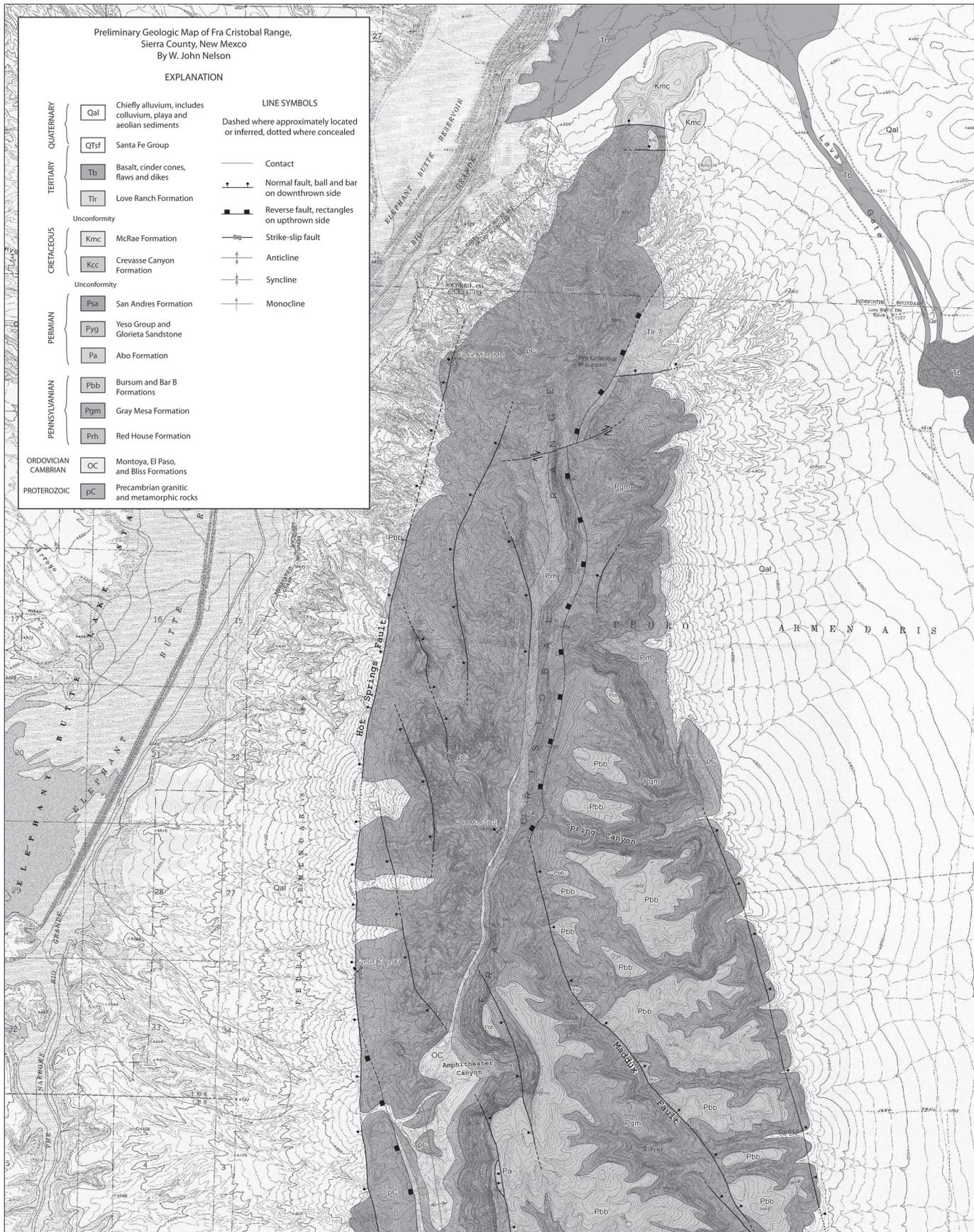


FIGURE 2. North half of a preliminary geologic map of Fra Cristobal Range. See Plate 4 on page 176 for a color version of this half of the map.

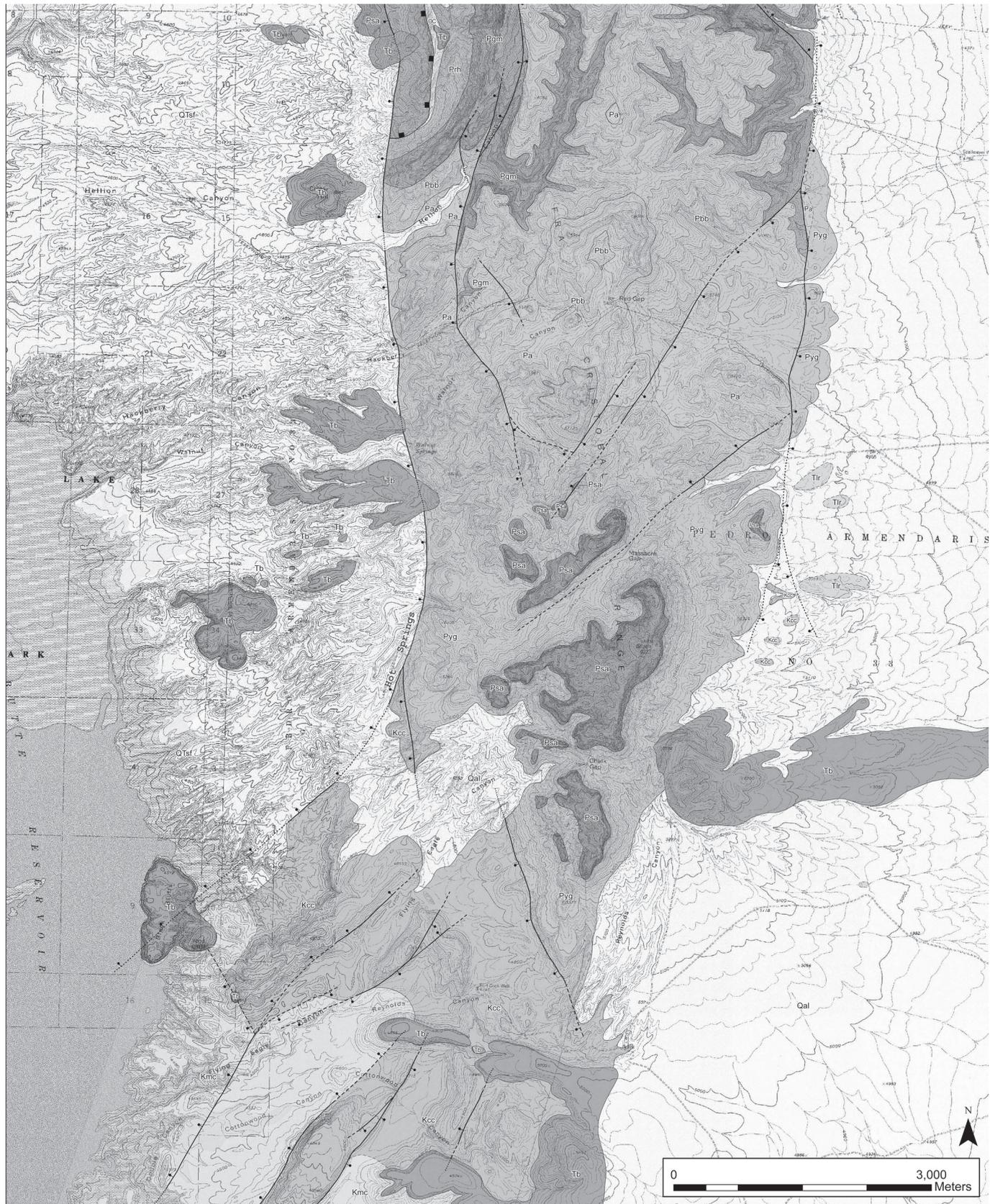


FIGURE 2. - cont. South half of a preliminary geologic map of Fra Cristobal Range. See Plate 4 on page 177 for a color version of this half of the map.

the upturned western limb of a syncline 60 km wide. The San Andres Mountains make up the eastern limb of the trough, while the broad axial zone underlies the Jornada del Muerto.

GEOLOGIC MAP

A preliminary geologic map (Fig. 2) of the Fra Cristobal Range accompanies this article. To create this map, the maps of Thompson (1955) and McCleary (1960) were rescaled and overlaid on a topographic base. Because of distortions in the original maps, exact registration was impossible. Extensive use was made of Google Earth satellite imagery to align contacts, faults, and other features with topography. This imagery provides full color, high-resolution views of the land surface at practically any angle and magnification. In many places, the geology was reinterpreted on the basis of satellite imagery alone. The authors' own field observations, chiefly in the central part of the range, provided further insights. Faults were interpreted conservatively; and complex areas were simplified because of scale issues. We hope to conduct further field work in the Fra Cristobals to provide the basis for a larger scale, more authoritative map.

Overall, the Fra Cristobal Range is a tilted horst. The northern half of the range is tilted eastward. Proterozoic granitic rocks crop out along the western flank, topped by a bold escarpment composed largely of limestone of the Pennsylvanian Gray Mesa Formation (Fig. 3). The eastern flank, largely Pennsylvanian dip slopes, is less precipitous. In the southern half of the range the strata dip gently southward, so that Permian and Cretaceous strata overlap the Pennsylvanian (Fig. 4).

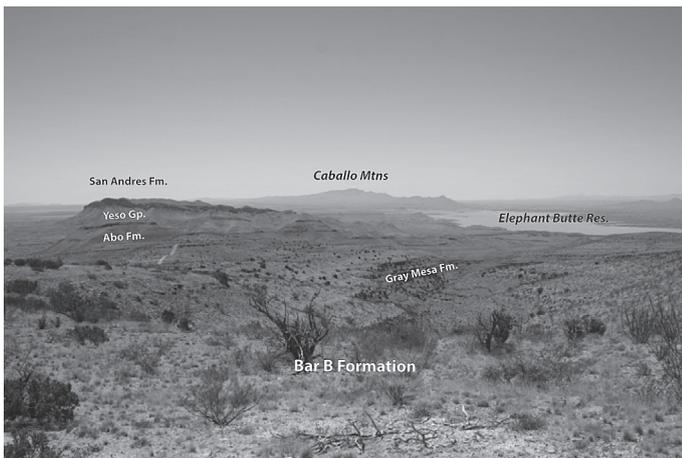


FIGURE 3. View looking southward along crest of the range, with the Caballo Mountains and Elephant Butte Lake in the distance. Photographer stood on Pennsylvanian Bar B Formation, which overlies Gray Mesa Formation along canyon in foreground. Permian Abo Formation forms rounded hills in middle distance. Beyond are light-colored slopes of Yeso Group capped by dark cliffs of San Andres Formation (also Permian).



FIGURE 4. View looking northwest, down the western escarpment at "Amphitheater Canyon". Cliff-forming limestone of the Pennsylvanian Gray Mesa Formation overlies slope-forming Pennsylvanian Red House Formation. Ragged dark hill beyond is Proterozoic granitic rock. The Rio Grande flows along the wooded valley bottom, while the San Mateo Mountains form the skyline.

STRATIGRAPHY

Proterozoic rocks

Proterozoic rocks are exposed along the western face of the Fra Cristobal Mountains from just north of Hellion Canyon to the northern end of the range (Fig. 2). McCleary (1960) also mapped a small exposure just north of Spring Canyon on the east side of the range. None of the previous mapping subdivided the Proterozoic rocks. The oldest rocks in the Fra Cristobal Mountains are metamorphosed amphibolites, chloritic schist, and granitic gneiss (Harley, 1934; McCleary, 1960; van Allen et al., 1984; Sakar, 1985; Nelson, 1986). The Fra Cristobal granitic pluton intruded these rocks and is the predominant Proterozoic lithology in the Fra Cristobal Mountains. Abundant small, irregular granitic dikes and pegmatites intruded the Fra Cristobal pluton (van Allen et al., 1984; Sakar, 1985). Locally the pegmatites grade into white quartz veins (Sakar, 1985; Chapin, 1986).

The Fra Cristobal pluton consists of pink to red to red-brown, medium- to coarse-grained, locally gneissic granite and is typically altered, with mafic minerals replaced by chlorite and hematite (Cserna, 1956; McCleary, 1960; van Allen et al., 1984; Chapin, 1986). Masses of dark green hornblende schist, with foliations striking north, occur within the Fra Cristobal pluton in the vicinity of Contact and Long Canyons (McCleary, 1960; van Allen et al., 1984). Small, metasomatic, brick-red episyenites are found within the Fra Cristobal pluton (van Allen et al., 1984) and are hypothesized to be Cambrian-Ordovician based upon field relationships and similarity to other syenites and episyenites (metasomatized K-feldspar-rich syenites, alkali granite) found in the Caballo Mountains and elsewhere in New Mexico (McLemore et al., 2012, this guidebook).

The age of the Proterozoic rocks in the Fra Cristobal Mountains is uncertain. An altered sample of the Fra Cristobal granitic pluton was dated by K/Ar methods as 850 ± 29 Ma (van Allen et al., 1986), which is likely a minimum age. In the Caballo Mountains, $^{40}\text{Ar}/^{39}\text{Ar}$ ages of granitic rocks similar to the Fra Cristobal pluton yield age gradients between about 900 to 1100 Ma that support cooling during Grenville contraction, similar to granitic rocks throughout central New Mexico (McLemore et al., 2012, this guidebook). In the Caballo Mountains, the metamorphic rocks are ~ 1680 Ma and the granitic rocks are ~ 1480 Ma (Amato and Becker, 2012, this guidebook; McLemore et al., 2012, this guidebook). Presumably the basement rocks of the Fra Cristobal and Caballo Mountains are of similar age and composition, but more study of the Proterozoic rocks in the Fra Cristobal Mountains is needed to confirm this hypothesis.

Cambrian and Ordovician Systems

Bliss Formation

The oldest sedimentary unit in the Fra Cristobal Mountains is the Bliss Formation, which overlies Proterozoic “basement” with a contact that is unconformable but nearly planar. The Bliss is rich in iron and weathers to darker colors than the granitic rocks below or the overlying carbonate rocks. This formation can be divided into two unnamed units of approximately equal thickness. The lower unit is sandstone that is fine to coarse-grained, thin to thick-bedded, and commonly crossbedded. The sandstone contains glauconite and hematitic ooids. Extensively silicified, the sandstone resembles quartzite and commonly forms a cliff. A basal conglomerate containing granitic clasts up to boulder size is locally present. The upper unit of the Bliss Formation consists of interbedded shale, siltstone, fine-grained sandstone, and limestone. Clastic rocks are greenish to brownish gray, calcareous, glauconitic, and thinly layered. Limestone is mostly dark gray and varies from microgranular to sandy and oolitic. These rocks generally erode to a slope and are incompletely exposed.

Aside from a few trace fossils, none of the authors observed any fossils in the Bliss Formation in the Fra Cristobal Mountains. Elsewhere in southern New Mexico, the Bliss contains fossils indicating a Middle Cambrian to Early Ordovician age (e.g., Mack, 2004). Sedimentary structures and fossils indicate regional deposition of the Bliss Formation in a siliciclastic-dominated, tidally influenced, shallow marine setting (Chafetz et al., 1986; Thompson and Potter, 1991; Seager and Mack, 2003; Mack, 2004).

The contact of the Bliss Formation with the overlying El Paso Formation is gradational. Where the El Paso is present, the Bliss reaches a maximum thickness of 49 m (Nelson, 1986). Northward in the Fra Cristobals, the Bliss thins to a feather edge because of pre-Pennsylvanian erosion. Thus, Pennsylvanian rocks rest directly on the Proterozoic basement at the northern end of the mountains and near Spring Canyon on the eastern side.

El Paso Formation or Group

Cserna (1956), Jacobs (1956), and McCleary (1960) all mapped the El Paso Group conformably overlying the Bliss Formation along the central western escarpment of the Fra Cristobals. Following Kelley and Silver (1952), these authors classified the El Paso as a group, divided into Sierrite Limestone (older) and Bat Cave Formation (younger). Considering that both these units occupy narrow outcrop belts, which cannot be discerned while mapping, the Sierrite and Bat Cave might better be classified as members of the El Paso Formation in this mountain range. Furthermore, Hayes (1975a, b) advocated a different regional subdivision of the El Paso Formation in southern New Mexico, dividing it into the (ascending order) Hitt Canyon and McKelligon members, whereas Clemons (1991) and Mack (2004) used a different subdivision of the El Paso Formation into the (ascending) Hitt Canyon, Jose, McKelligon, and Padre members. Further study of the El Paso Formation in the Fra Cristobal Mountains is needed to determine which subdivisions are present and what nomenclature best applies to them. Here, we follow the subdivisions used by the early thesis mappers.

The Sierrite Member attains a maximum thickness of about 40 m and is composed of limestone containing prominent bands of chert. Colors range from light to medium gray to pinkish and purplish gray. The limestone is described as granular to semi-crystalline, and it contains purplish shale partings that yield a corrugated appearance. The Sierrite commonly forms a cliff.

The Bat Cave Member is a unit of interbedded limestone, dolomite, sandstone, and conglomerate. Limestone is similar to that of the Sierrite; dolomite is light to medium gray, crystalline, and thickly bedded. Cserna (1956) reported silicified stromatolites. Sandstone is greenish gray, fine to medium-grained, micaceous, and thickly bedded. Jacobs (1956) reported conglomerate that is light gray to brick-red and “granulitic to pebbly”. The same author reported a Bat Cave Member thickness of 24 m at Amphitheater Canyon.

No fossils diagnostic of age have been recorded in the El Paso Formation in the Fra Cristobal Range. Elsewhere in southern New Mexico and Texas, the El Paso yields an Early Ordovician marine fauna (e. g., Mack, 2004).

Montoya Formation

In the Fra Cristobal Mountains, Nelson (1986) reported exposures as thick as 6 m of the Cable Canyon Sandstone, the basal unit of the Montoya Formation (or Group). The sandstone is described as white to mottled gray and brown, and medium- to coarse-grained with lenses of conglomerate and carbonate cement. None of the thesis mappers mentioned this unit; they may have combined it with the Bat Cave Formation.

Regionally, the Cable Canyon is of Blackriveran (early Late Ordovician) age and rests unconformably on the El Paso Group (Hills and Kottowski 1983; Mack, 2004). A major unconformity separates Pennsylvanian strata from older rocks throughout the Fra Cristobals. Silicified collapse breccia commonly marks this

contact (Nelson, 1986). To the south, in the southern Caballo Mountains, the remainder of the Montoya Formation, the Devonian Percha Formation and (locally) thin remnants of the Mississippian Lake Valley Formation fill in part of the hiatus represented by the unconformity (Kelley and Silver, 1952; Seager and Mack, 2003). In the Fra Cristobal Mountains, the base of the Pennsylvanian section has eroded down into the Ordovician so that it rests on the Cable Canyon Sandstone and older units (Nelson, 1986). North of the Fra Cristobal Mountains, in Socorro County, the Pennsylvanian section sits directly on the Proterozoic basement (Lucas et al., 2009). Kelley and Silver (1952) noted that the disappearance of lower Paleozoic units in central New Mexico is marked by a hingeline that runs from north of the Caballo Mountains to the Oscura Mountains. They argued that the region north of the hingeline was recurrently uplifted during the Paleozoic, which accounts for the thinning and disappearance of lower Paleozoic strata.

Pennsylvanian System

Pennsylvanian rocks make up the high country in the northern Fra Cristobal Range. They are readily divided into three mapping units: the Red House, Gray Mesa (= Nakaye) and Bar B formations of Kelley and Silver (1952). The basal Red House Formation is as much as 73 m thick, dominated by shale with beds of limestone, sandstone and conglomerate. This unit erodes to largely covered slopes punctuated by small ledges along the western foot of the range. Overlying the Red House is the Gray Mesa Formation a unit dominated by gray, cherty limestone, more than 300 m thick, forming the bold western escarpment and the cliffs that wall in many of the canyons (Figs. 4-6). This is capped by a the Bar B Formation, a unit of largely thin-bedded limestone, shale, and mudstone, eroding to step-and-ledge topography along the crest of the range and down the less precipitous



FIGURE 5. View looking north at Pennsylvanian rocks in the upper reaches of Hellion Canyon. Limestone cliffs and steep ledges of the Gray Mesa Formation are capped by low, rounded slopes of the shaly Bar B Formation, with the light-colored bed of dolomite at the top of the canyon walls marking the contact.

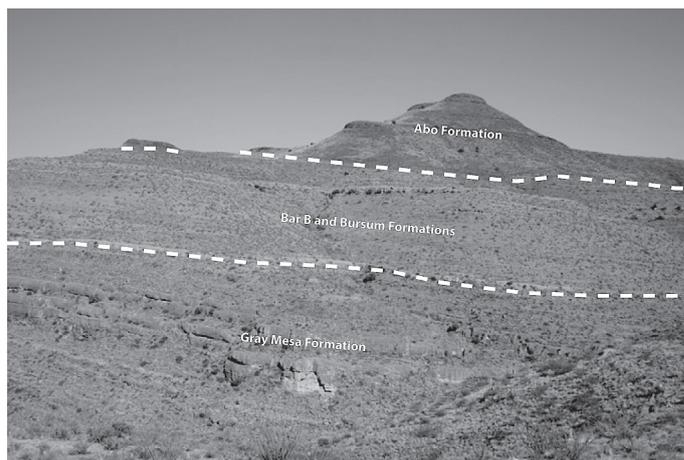


FIGURE 6. View looking east across southern reaches of Hellion Canyon. In ascending order, limestone cliffs and ledges of Gray Mesa Formation, less resistant shale and limestone of Bar B and Bursum Formations with light-colored dolomite bed at base; and slope-forming mudstone and thin sheet sandstone of Lower Permian Abo Formation.

eastern slopes. The Bar B Formation is overlain by a thin (less than 25 m thick) section of Bursum Formation (cf. Krainer and Lucas, 2009). The Bar B and Bursum have been combined on our geologic map (Fig. 2).

Jacobs (1956) covered Pennsylvanian rocks in a cursory fashion. Cserna (1956) provided more details, including measured sections; but these are difficult to reconcile because they are not located on any map. Cserna recognized the three divisions, but did not use formal names. The lower and middle divisions are combined on his geologic map. McCleary (1960) used the stratigraphic terminology that Kelley and Silver (1952) developed in the Caballo Mountains: lower slope-forming Red House Formation, middle cliff-making Nakaye Limestone, and upper step-and-ledge Bar B Formation.

Here, we retain the Red House and Bar B Formations, but use the older name Gray Mesa Formation (Kelley and Wood, 1946) in preference to Nakaye Limestone (see Lucas et al. (2012, in this guidebook) on the Pennsylvanian stratigraphy in Sierra County).

Verville et al. (1986) discussed and illustrated Pennsylvanian fusulinids from the Fra Cristobals. However, their lithostratigraphy is so generalized that formations cannot be identified. In his 377 m thick composite section, Verville et al. (1986) reported 10 m of upper Atokan, 150 m of lower Desmoinesian, 107 m of upper Desmoinesian, 60 m of Missourian, and 50 m of Virgilian. Their youngest fusulinids near the top of the Pennsylvanian were middle Virgilian.

Red House Formation

The Red House Formation is difficult to study in the Fra Cristobals because its outcrop belt is largely mantled by talus from the cliffs above (Fig. 4). The Laramide fold and thrust zone that follows the western escarpment further frustrates the effort to obtain an accurate section. Being mechanically weak, the Red House

is a favored interval for thrust faults. Imbricate thrusts were observed in the Red House near Amphitheater Canyon. However, a measured section of the Red House Formation at Amphitheater Canyon suggests it is about 77 m thick. The lowermost 16 m is composed of intercalated silty shale, crossbedded quartzose sandstone, pebbly sandstone, and conglomerate. Above follows a succession of limestone beds as thick as 1.5 m, alternating with covered intervals believed to be shale. Limestone is mostly lime mudstone and wackestone, with minor packstone and floatstone. Some of the limestone is wavy bedded to nodular. Chert content varies. Fossils include crinoid debris, brachiopods, solitary corals, gastropods, fusulinids, and the trace fossil *Zoophycos* near the top of the Red House.

Cserna (1956) measured a Red House section ~81 m (266 ft) thick in Prospectors Canyon. Approximately ~24 m (79 ft) of this section, including the upper contact, is covered. The exposed portion is approximately 85% shale and 15% limestone, the thickest limestone unit being a little over 3 m thick. The shale is described as greenish to olive-gray and calcareous. McCleary (1960) stated that the Red House is 530 ft (162 m) thick, but his graphic column indicates that more than half of this thickness is thick-bedded, cherty limestone that belongs to the Gray Mesa Formation. Only the lower 55 m of McCleary's column represents the shale-dominated Red House Formation.

Gray Mesa Formation

The Gray Mesa Formation is prominently exposed and easy to map throughout the northern part of the range. Cserna (1956) reported a thickness of ~331 m (1,087 ft). McCleary (1960) reported 213 m (700 ft), but another 107 m (350 ft) of cherty, thick-bedded limestone in his upper Red House should be added, yielding ~320 m (1,050 ft). Our section measured in Hellion Canyon totaled 138 m, with the base covered.

More than 90% of the Gray Mesa is limestone that forms cliffs and ledges (Figs. 4-6). Shale and mudstone intervals are numerous, but poorly exposed outside of deep canyons. The lower part of the measured section is composed of limestone that is mostly wavy bedded to nodular, fossiliferous, and partly cherty, alternating with layers of greenish gray shale. In the middle and upper parts of the section, thick-bedded to massive limestone alternates with thin- to medium-bedded limestone. Chert nodules, lenses, and layers are common. Shale intervals, poorly exposed, range up to 6.6 m thick.

Commonly seen (and noted by McCleary, 1960) is cyclic repetition that seems to record rapid transgression followed by gradual regression or shoaling. A typical cycle begins with shale at the base, changing upward to dense, micritic limestone in thin wavy beds. This in turn grades upward to fossiliferous wackestone, packstone, and grainstone. Bedding thickness and chert content increase upward. The upper parts of some cycles include burrowed and brecciated dolomitic limestone, algal mats, and subaerial crusts. Most cycles are 5 to 10 m thick. However, many departures from the "typical" pattern are evident, and the lateral continuity of cycles has not been addressed.

The Gray Mesa contains an abundant and diverse marine fauna. Brachiopods, bryozoans, crinoids (fragmentary for the most part), solitary corals, rare *Syringopora*, phylloid algae, and foraminiferans (fusulinids) are the most common elements. The trace fossil *Zoophycos* was observed in wavy-bedded limestone near the top of the formation.

Following Cserna (1956), we pick the top of the Gray Mesa at the upper surface of a widespread thick-bedded to massive limestone or dolomite layer. This bed is 3 to 5 m thick in most places and weathers lighter gray than any adjacent bed (Figs. 5-6). It makes an easily traced mapping boundary between the Gray Mesa and Bar B formations along much of the northwestern front of the Fra Cristobal Mountains. The Gray Mesa-Bar B contact appears to be conformable.

Bar B Formation

Kelley and Silver (1952) named this formation for Bar B Draw, which in turn took its name from a ranch (no longer extant) on the east side of the Caballo Mountains. In the Fra Cristobal Range, the Bar B surmounts the northern ridge crest and extends down the east-facing dip slope between the deep canyons carved into the underlying Gray Mesa. Cserna (1956) and McCleary (1960) reported thicknesses of 266 ft (81.0 m) and 258 ft (78.6 m), respectively. We measured thicknesses of 76 and 102 m near Hellion Canyon in the southern part of the outcrop belt. There is no indication of a regional change in thickness within this mountain range.

Because the Bar B occurs high in the landscape, the soil cover is thin, yet large intervals are covered or poorly exposed (Figs. 5-6). The lower part is largely dark gray, dense micritic limestone in thin, wavy to nodular beds separated by layers of olive-gray silty shale. The upper part of the formation consists of poorly exposed, non-fissile mudstone that alternates with ledges of light gray, siliceous limestone. Much of the mudstone is pink to red and loaded with small nodules of gray limestone. Resistant limestone layers vary from massive to nodular, conglomeratic, and brecciated. Some of the limestone is algal. Other fossils include brachiopods, gastropods, crinoids, and fusulinids.

Bursum Formation

The presence of the Upper Pennsylvanian Bursum Formation in the Fra Cristobal Range has not been recognized by previous authors. The Bursum represents mixed marine and nonmarine deposition just before the beginning of Permian time (Krainer and Lucas, 2009). Thickness increases southward, from about 7 m in the northern part of the range to 10-16 m near Hellion Canyon and 24 m near Red Gap. The Bursum is composed of interbedded mudstone, limestone, dolomite, and conglomerate. Non-fissile mudstone, poorly exposed, is green, red, and purple and contains abundant pedogenic nodules. Limestone varieties include: thin micrite beds containing ostracods, wackestone and floatstone containing crinoids, brachiopods, and molluscs; nodular limestone; and conglomerate of carbonate clasts in a mud-

stone matrix. Stromatolitic limestone and dense, microgranular dolomite that weathers orange occur at the top of the Bursum.

Permian System

Rocks of Permian age crop out in the southern half of the Fra Cristobal Range. Four lithostratigraphic units that have regional extent have been identified: Abo Formation (oldest), Yeso Group, Glorieta Sandstone, and San Andres Formation. Less than 10 m thick, the Glorieta has been combined with the San Andres on our geologic map (Fig. 2).

Abo Formation

The Abo Formation is a highly distinctive succession of reddish brown mudstone, siltstone, sandstone, and conglomerate. Because mudstone dominates, the Abo erodes to rounded hills that show occasional ledges of the more resistant lithologies (Figs. 3, 6). The outcrop area extends southward from aptly named Red Gap in the south-central part of the mountains.

Earlier estimates of the thickness of the Abo Formation in the Fra Cristobal Mountains indicated it being less than 150 m thick (Lee, 1909; Darton, 1928; Nelson, 1986). However, Lucas et al. (2012, this guidebook) measured a complete section of the Abo Formation at Red Gap that is ~ 294 m thick. This section is almost entirely mudstone (71% of the measured section) and sandstone (27%). Minor lithologies are shale, siltstone, calcrete, and intraformational conglomerate.

Lucas et al. (2012) recognized in the Fra Cristobals two members of the Abo Formation named in Valencia County to the north. The lower unit, the Scholle Member, is about 40 m thick and dominantly composed of mudstone. The Cañon de Espinosa Member, above, contains numerous sheet-like beds of sandstone. At Red Gap, the Abo Formation rests with sharp contact on color-mottled (pedogenically modified?), nodular, bioclastic marine limestone at the top of the Bursum Formation. Abo red mudstones above the contact contain dispersed calcrete nodules, whereas Bursum red mudstones below the contact do not. A conglomerate low in the Scholle Member contained a vertebra of the reptile *Dimetrodon* (Harris et al., 2011). Sandstone beds high in the Scholle Member yielded the extensive ichnofossil assemblage of arthropod and tetrapod traces documented by Lucas et al. (2005a, b).

In the Red Gap Abo section, the ratio of sandstone to mudstone increases up section. Sandstone bodies in the upper 75 m of the Abo range up to 6 m thick, but most are much thinner. These sandstone bodies are full of climbing ripples. A covered (mudstone?) slope is the uppermost bed of the Abo Formation and is overlain by green, thinly laminated and ripple-laminated sandstone with halite pseudomorphs that is the basal bed of the Arroyo de Alamillo Formation of the Yeso Group.

Yeso Group

The Yeso Group in the Fra Cristobal Mountains is a succession of interbedded claystone, siltstone, sandstone, gypsum, and limestone as much as 400 m thick. The Yeso crops out exten-

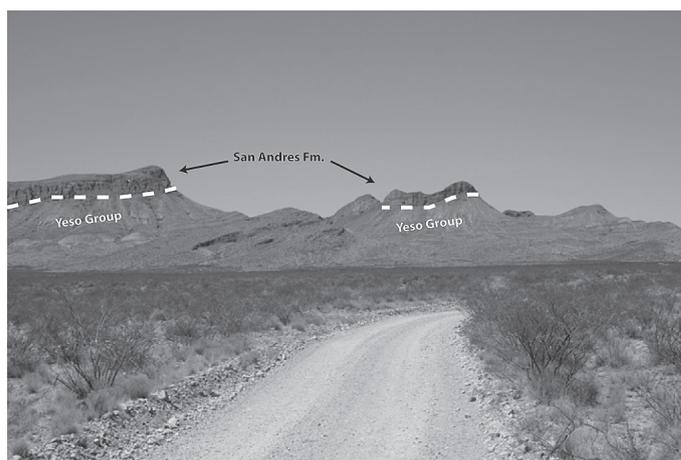


FIGURE 7. View looking west, toward Massacre Gap in the southern part of the range, where Permian strata dip gently southward. These include Abo Formation at base of range, far right, overlain by lighter colored Yeso Group and capped by dark cliffs of San Andres Formation.

sively in the southern part of the range, where it underlies valleys and steep, rounded slopes capped by cliffs of the San Andres (Figs. 3, 7-8).

Nelson (1986) and Nelson and Hunter (1986) divided the Yeso into four members in the report area. Lowest is the Meseta Blanca Member, which is 153 to 183 m thick and consists of siltstone to fine sandstone that is white to reddish and greenish gray, well sorted, and thin- to medium-bedded. Ripple marks and salt crystal casts occur in the lower part. Next is the Los Vallos Member, 92 to 122 m of limestone interbedded with sandstone, gypsum, anhydrite, and salt. Limestone is dense, microgranular, and partly dolomitic; it contains unspecified marine fossils. The overlying Cañas Member consists of gypsum and anhydrite with lesser sandstone and limestone totaling 43 to 49 m thick. The Joyita Member, at the top of the Yeso, consists of light brown to red, fine- to medium-grained sandstone along with minor sandstone, and ranges up to 100 m thick.

In this guidebook, Lucas and Krainer (2012) describe a complete Yeso Group section at Massacre Gap that they assign to the Arroyo de Alamillo and overlying Los Vallos formations. They further divide the Los Vallos into the Torres, Cañas and Joyita members, so these are the same stratigraphic units recognized by Nelson (1986), though the abandoned term Meseta Blanca Member (for the basal clastic interval of the Yeso) is not used. At Massacre Gap, the Arroyo de Alamillo Formation is mostly thinly laminated or ripple-laminated sandstone. The upper part of the Yeso Group at the Massacre Gap section can be divided into the Torres Member of the Los Vallos Formation (~ 134 m), Cañas Member of the Los Vallos Formation (~ 58 m) and Joyita Member of the Los Vallos Formation (~ 42 m). The principal lithologies of the Torres Member are dolomite, gypsiferous siltstone, gypsum and siltstone to fine-grained sandstone. At Massacre Gap, the Cañas Member is mainly composed of gypsum with gypsiferous siltstone beds intercalated in the lower part (each 0.8 m thick). In the middle of the member, a 10-m thick dolomite interval is

developed. The uppermost unit of the Los Vallos Formation is red-bed siliciclastics of the Joyita Member. The lower 20 m of the Joyita Member is massive to indistinctly laminated siltstone to fine-grained sandstone. The upper part consists of horizontally laminated and ripple-laminated red siltstone and some massive red siltstone to fine-grained sandstone.

Glorieta Sandstone

Cserna (1956) described the Glorieta as “white, medium-grained, well-sorted, porous, friable, clean quartz arenite with subrounded grains, weathering to a buff, yellow, or medium tan color.” Locally, the sandstone is crossbedded. The reported thickness does not exceed 9 m. Cserna did not describe the lower contact; the upper was stated to be disconformable. The Glorieta has been combined with the Yeso Group on our geologic map (Fig. 2).

Lucas and Krainer (2012, this guidebook) measured a thin (1.8 m), but complete, section of the Glorieta Sandstone at Massacre Gap, where it has a sharp contact on the underlying Yeso Group sandstones of the Joyita Member. Here, the Glorieta Sandstone is fine grained, with an average grain size of 0.1 and maximum grain size of 0.3 mm. The sandstone is well sorted, and the grains are mostly subangular to subrounded. Compared to the underlying Joyita Member, detrital feldspars are less common and heavy minerals are more abundant, particularly rounded zircon, and also tourmaline, apatite and rutile. The amount of carbonate cement is high (~ 30%), and feldspar grains in particular are replaced by carbonate. The thin Glorieta Sandstone of the Fra Cristobal Mountains is comparable to the thin and locally absent Glorieta Sandstone in the San Andres Mountains to the southeast (Kottlowski et al., 1956); to the south, no Glorieta Sandstone is present in the Caballo Mountains (Seager and Mack, 2003).

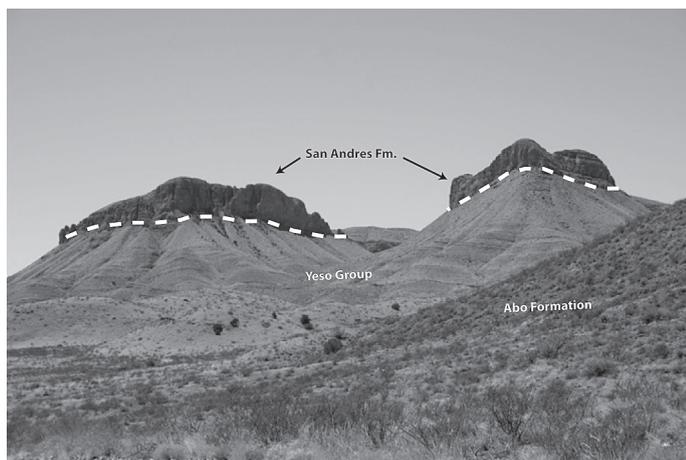


FIGURE 8. Massacre Gap in southern Fra Cristobals, looking south. Slope-forming Permian Yeso Group is overlain by cliff-forming carbonate rock of the Permian San Andres Formation. Glorieta Sandstone, at base of cliffs, is thin and poorly exposed.

San Andres Formation

The San Andres consists of limestone that forms bold cliffs capping a group of buttes around Chalk Gap and Massacre Gap in the southern part of the Fra Cristobal Mountains (Figs. 3, 7-8). These buttes are landmarks, visible from many kilometers away in all directions. Briefly, Cserna (1956) described the limestone as “thin to thick-bedded, dark gray, dense, microcrystalline, locally dolomitic, marine limestone.” The only fossils he reported were “some small gastropods.” Cserna did not mention thickness; using the topographic map, a maximum of 160 m is estimated. The top of the San Andres is eroded at the present ground surface on the buttes, but in one place, Cretaceous rocks overlie San Andres unconformably (Cserna 1956). To our knowledge, no detailed study of the San Andres Formation has been undertaken in the Fra Cristobal Mountains.

Cretaceous System

Cretaceous rocks occupy much of the area between the Fra Cristobal and Caballo Ranges. They are well exposed along the eastern shore of Elephant Butte Lake and beside the road that passes just south of the dam en route from Truth or Consequences to Engle. Geologists who have mapped in this area identified four formations: Dakota Sandstone (oldest), Mancos Shale, Crevasse Canyon Formation, and McRae Formation. Among these names, only McRae is locally derived. Dakota refers to South Dakota, whereas Mancos is a town in southwestern Colorado, and Crevasse Canyon comes from the Gallup area of west-central New Mexico. Except where indicated otherwise, the following unit descriptions are taken from Lozinsky (1985).

Dakota Sandstone

The sandstone at the base of the Cretaceous section ranges from 24 to 75 m in thickness and rests unconformably on Paleozoic rocks. It is largely white to buff, medium to coarse-grained, and medium to thick-bedded. Interbeds of gray shale and lenses of pebbly conglomerate and carbonaceous material are present. The Dakota is resistant to erosion, forming a ridge. No fossils are known from the Dakota Sandstone in the Fra Cristobal Mountains. This unit may contain strata of both later Early Cretaceous (Albian) and early Late Cretaceous (Cenomanian) age (cf. Lucas and Estep, 1998).

Mancos Shale

Poorly exposed, the Mancos is composed of medium gray to black, partly calcareous shale that contains thin interbeds of limestone and siltstone. These rocks are easily eroded and mostly underlie valleys. A thickness of 81 m is reported south of the area of this article at the mouth of Mescal Creek. Regionally, this unit is of Late Cretaceous (Cenomanian-Turonian) age (Moleenaar, 1983). Although Cserna mapped Mancos Shale northeast of Black Bluffs, Thompson stated that this unit does not crop out within the report area. We follow Thompson’s mapping. \

Crevasse Canyon Formation

In the Truth or Consequences area, the Crevasse Canyon Formation (called Mesaverde Formation by early workers) is a complex unit more than 1000 m thick. Briefly, this unit consists of olive-gray to brownish-gray shale, siltstone, and mudstone with lenticular bodies of sandstone and conglomerate. Sandstone is mostly buff to brown, fine- to medium-grained, and commonly crossbedded. Conglomerate contains pebbles of chert, quartz, and petrified wood. Fossils in the Crevasse Canyon include oysters, leaves, and silicified wood. Little study of this unit has been undertaken in Sierra County, but regionally it is of Late Cretaceous (primarily Coniacian-Santonian) age (Molenaar, 1983). Extensive outcrops occur in the area of Cottonwood, Flying Eagle, and Reynolds Canyons in the southern part of our map area (Fig. 2).

McRae Formation

Named by Kelley and Silver (1952), the McRae Formation approaches a thickness of 975 m. The type area is in badlands east of Elephant Butte Lake near the site of 19th-century Fort McRae. In this area, the formation consists of mudstone, siltstone, sandstone, and conglomerate containing clasts up to boulder size, and beds of silicified volcanic ash. A Late Cretaceous (Lancian = late Maastrichtian) age is based on dinosaur bones along with fossil plants of known Cretaceous affinity (Wolberg et al., 1986; Gillette et al., 1986; Lucas et al., 1998; Upchurch and Mack, 1998).

McCleary (1960) mapped the Jose Creek Member of the McRae Formation in an area of about 1 square km at the northern end of the range. He stated that the McRae lies in direct depositional contact with Proterozoic rocks. However, his geologic map shows a fault contact, and questionably drawn contacts that appear to place Proterozoic rocks above Cretaceous. This area needs further field work.

Tertiary and Quaternary Systems

Love Ranch Formation

Coarse red conglomerate believed to belong to the Love Ranch Formation crops out east of the mountain front in the vicinity of Massacre Gap. Overlooked by the thesis mappers, these deposits erode to low, rounded outcrops. Another area of possible Love Ranch straddles the Sierra-Socorro County line near the northern end of the range. McCleary (1960) mapped this area as Abo Formation, but as viewed in satellite imagery, the rocks lack the uniform red-brown color and resistant layers characteristic of the Abo. Regionally, the Love Ranch is interpreted as alluvial-fan deposits of probable Eocene age, deposited in tectonically active Laramide basins (Seager and Mack, 2003; Krainer and Lucas, 2012).

Santa Fe Group

Miocene to Pleistocene alluvial deposits along the greater Rio Grande Valley are referred to the Santa Fe Group. Students who

mapped in the Fra Cristobal Range described these sediments in a cursory manner. Lozinsky (1985) provides a thorough description of Santa Fe deposits in the Elephant Butte area, just south of the mountains, where the exposed strata are assigned to the Plio-Pleistocene Palomas Formation (Lozinsky and Hawley, 1986a, b; Morgan et al., 2011).

Briefly, the Palomas Formation is composed of stratified clay, silt, sand and gravel that is poorly sorted and weakly lithified or unlithified. In the Engle basin (west of the Fra Cristobal Mountains) coarser piedmont and finer axial facies can be delineated. Ages range from early Pliocene to middle Pleistocene, based primarily on mammalian biochronology and limited magnetostratigraphy and radioisotopic ages (see Morgan et al., 2011 for the latest synthesis). Although Lozinsky (1985) reported a maximum thickness of 180 m, the map of Harrison et al. (1993) shows a well 17 km NNW of Truth or Consequences that penetrated 1989 m of Santa Fe Group without reaching the bottom.

Basalt

Extensive flows of olivine basalt, together with cinder cones and small dikes, are present in the vicinity of the Fra Cristobal Mountains. The southwest edge of lava flows that cover some 250 square km is located at the northeast corner of the mapped area. These flows evidently were erupted from a cone on the Jornada about 20 km east-northeast of the northern end of the range. Smaller flows and associated cinder cones occur west, south, and southeast of the range. Several cones are situated close to or in line with large faults, which probably served as conduits.

Cserna (1956) described the rock as “vesicular olivine basalt, which is scoriaceous locally.” Composition (apparently based on petrographic study) included 13% olivine, 17% augite, 49% labradorite, and 21% glass matrix, with a few phenocrysts of olivine and augite plus iddingsite along fractures. Concerning outcrops south of the mountains, Lozinsky (1985) wrote, “The basalt is usually scoriaceous and typically exhibits a porphyritic texture with olivine and plagioclase phenocrysts.”

Basalt from two localities near the Fra Cristobals yielded late Pliocene K-Ar dates. Specifically, the dates are 2.1 ± 0.4 Ma from a cinder cone 6 km southwest of Engle and 2.9 ± 0.3 Ma from a lava flow at Mitchell Point, on the Rio Grande west of Hellion Canyon. The latter flow is interbedded with alluvium, helping to constrain the history of regional drainage development (Bachman and Mehnert 1978).

Younger Quaternary Sediments

Mentioned in passing and not differentiated in these are Pleistocene and Holocene sediments younger than the Santa Fe Group. These include alluvium and terrace deposits of the Rio Grande and tributary arroyos, small areas of wind-blown sand, and playa deposits on the Jornada del Muerto. Lozinsky (1985) mapped multiple sets of pediment and terrace deposits in the Elephant Butte area, south of the mountains.

STRUCTURAL GEOLOGY

In simplest terms, the Fra Cristobal Range is a horst of Proterozoic and Paleozoic bedrock that has been elevated relative to the flanking alluvial basins. It exemplifies the basin-and-range topography that characterizes the Rio Grande Valley in central and southern New Mexico. The Fra Cristobals lie close to the axis of the Rio Grande rift, part of the much larger region of the southwestern U.S. and adjacent Mexico where extensional tectonics have dominated since middle Cenozoic time.

Also well displayed here is a belt of compressional deformation that is a product of the Late Cretaceous-Paleogene Laramide orogeny. Both thick-skinned (involving Proterozoic basement) and thin-skinned structures are present. This compressive belt continues southward into the Caballo Mountains and has direct counterparts northward into the Socorro area, and beyond. Because they are older, the compressional features will be described first.

Laramide Compressional Structures

A zone of east-verging compressional structures extends from the northern end of the Fra Cristobals down the western flank of the range as far south as Walnut Canyon. Mapped structures include west-dipping high-angle reverse and low-angle thrust faults, bedding-plane faults, and sharp folds on which the eastern limb is commonly overturned (Fig. 9). Although some of these structures are detached within the sedimentary cover, the crystalline basement has been both folded and faulted (Nelson 1986, 1993, Nelson and Hunter 1986, Chapin and Nelson, 1986).

The master fault is a west-dipping reverse fault in the Proterozoic basement. Although slightly sinuous, it has an overall strike of N 15° E and dips 50° to 63° west (McCleary, 1960). In the northern part of the range, this fault juxtaposes Proterozoic granitic rocks against various Paleozoic formations. South of Prospectors Canyon, the fault has not been mapped continuously, being more difficult to recognize where crystalline rocks lie along both sides. Evidently, the master fault disappears under the western valley fill near Hellion Canyon. The master fault closely parallels and in places probably coincides with the Hot Springs fault, which is the principal Cenozoic normal fault of the region (Seager and Mack, 2003). The same belt of Laramide compressional structures resurfaces more than 25 km south in the northern Caballo Range.

Overtaken anticlines and synclines parallel the east side of the master reverse fault (Fig. 9). These folds represent the footwall of a large fault-propagation fold, the hanging-wall of which has been eroded. As Chapin and Nelson (1986) explained, the character of the fold zone changes markedly within short distances. Hellion Canyon is probably the best place to appreciate the intensity of deformation. At the mouth of the canyon, the fold belt curves to the west and plunges steeply, passing under the valley fill.

Previous authors reported detached folds, thrusts, and bedding-plane faults east and south of the basement faults. Several klippen have been mapped, in which Proterozoic granite and

lower Paleozoic rocks have been thrust over younger Paleozoic strata. Incompetent shale layers in the Bliss Formation commonly served as glide planes. Farther south, intricate sets of folds, thrust faults, and horizontal shears occur in the vicinity of Hackberry and Walnut Canyons. These are largely confined to the Permian Yeso Group, which contains many incompetent layers of claystone, gypsum, and salt. On the east flank of the range near Masseur Gap, Yeso Group reportedly has been thrust over Upper Cretaceous McRae Formation, indicating that the age of the thrusting is post-Cretaceous (Cserna, 1956; Nelson and Hunter, 1986). Because of scale problems, difficulties registering geology with topography, and conflicting interpretations, we have not depicted any of the thin-skinned deformation on our geologic map (Fig. 2).

Cenozoic Extensional Structures

Faults related to the Rio Grande rift are vertical to steeply dipping normal faults that exhibit a variety of trends, but most of them strike more or less north. Most of these faults displace the Santa Fe Group and all older units, but some have fresh scarps that indicate they are still active.

The largest of these structures is the Hot Springs fault, which marks the western flank of the range. This fault continues south-southwest across Elephant Butte Reservoir, cutting across the northern end of the Caballo Mountains before passing beneath the waters of Caballo Reservoir. Along most of its extent in the Fra Cristobals, the Hot Springs fault juxtaposes Santa Fe Group on the west with Proterozoic and Paleozoic rocks on the east. From this evidence alone, the amount of slip is difficult to judge, because the Santa Fe was deposited while the mountains were rising. However, San Andres Formation crops out west of the fault near Amphitheater Canyon, and Bar B Formation is west of the fault about 8 km north. The San Andres outcrop indicates a minimum throw of 1100 m.

McCleary (1960) reported that the Hot Springs fault consistently dips 65° to 75° west. The fault zone is heavily silicified



FIGURE 9. Laramide deformation at mouth of Hellion Canyon, with a partly overturned section of Pennsylvanian Gray Mesa and Bar B formations.

with jasper, which has been brecciated and cemented by crystalline quartz. Without specifying a location, Cserna (1956, p. 52) stated “small hanging valleys, 2 to 3 ft (0.6 to 0.9 m) high, along the silicified fault scarp suggest that subsidence of the Rio Grande trough is still in progress.” North of Amphitheater Canyon, a much higher scarp of the Hot Springs fault is plainly evident on the topographic map and also on the Google Earth satellite image, which was taken with the sun low in the east.

Along the eastern flank of the range, the Fra Cristobal fault of McCleary (1960) is mostly concealed by Quaternary alluvium. The best evidence is east of Massacre Gap, where arroyos reveal tilted Cretaceous strata east of the fault near the elevation of the Abo-Yeso contact west of the fault. A throw of not less than 350 m is indicated. Smaller parallel faults that dip 50° to 70° east displace Pennsylvanian rocks near the east margin of the mountains.

Many lesser normal faults have been mapped within Paleozoic rocks in the Fra Cristobals. Most notable of these is the Maddux fault, which crosses the north-central part of the range on a heading of N 40° W. Throw decreases northward from 150 m at the southeast end. The northern part of the fault is thoroughly silicified and bears galena (McCleary, 1960).

Tectonic Summary

The Laramide orogeny produced a zone of east-verging, high-angle reverse faults in Proterozoic crystalline basement, accompanied by partially overturned folds in the sedimentary cover. Thin-skinned deformation took place east of these structures, particularly in the incompetent layers of the Permian Yeso Group. Timing of Laramide deformation in the Fra Cristobals is poorly constrained but regionally, this activity spanned Late Cretaceous through Eocene time (Seager and Mack, 2003).

Around Miocene time, the regional stress field changed from compression to east-west crustal extension. Although many new normal faults developed, the greatest displacements took place along the Hot Springs fault. This fracture zone closely parallels and in places directly coincides with the pre-existing Laramide reverse fault. As the Engle basin west of the fault sank, the Fra Cristobals rose. Thus, the range lies on the western limb of a broad syncline having the San Andres Mountains on the eastern limb. The trough between is the basin of the Jornada del Muerto.

There is also evidence for large-scale Laramide strike-slip movement along the Hot Springs fault. This fault is part of the larger Hot Springs fault system, over 160 km long and as much as 15 km wide. Isopach mapping of four Paleozoic intervals indicates approximately 26 km of dextral offset – west side moved northward (Cather and Harrison 2002). Obliquely crossing Laramide structures, along with gravity and magnetic gradients, are offset in similar fashion (Harrison and Cather 2004). The McRae Formation may be syntectonic, filling a transpressional basin that developed during Late Cretaceous and Early Tertiary time. Wrench faulting along the Hot Springs fault system apparently accommodated northward motion of the Colorado Plateau during the Laramide orogeny (Harrison and Cather 2004).

MINERAL DEPOSITS

Sporadic efforts at prospecting and mining have been made in the Fra Cristobals over the past three centuries. No sustained mineral production has yet taken place. A report on the most recent mineral evaluation of the range, made by Tenneco Minerals, is available at the Library of the University of Wyoming in Laramie (van Allen et al., 1983).

The first mining claim in New Mexico was filed in the northern Fra Cristobal Mountains by Pedro de Abalos on March 26, 1685. Although the exact location is unknown, the claim is believed to be in the vicinity of the Sunset Ridge or Old Mine deposit (Table 1; File and Northrop, 1966). Rio Grande Rift fluorite-barite and epithermal manganese deposits are found in the Proterozoic granite (Table 1) and carbonate-hosted Au-Ag and epithermal manganese deposits are found in carbonate rocks; gypsum deposits also are found in the Yeso Formation. The Blackie or Black Pete manganese mine first produced in 1957 when a jig mill was erected. Less than 50 long tons of manganese concentrates were produced from open pits and an adit (Farnham, 1961). Placer gold and rare earth elements (REE) vein deposits may occur in the area.

Rare earth elements (REE)-Th-U veins in Metasomatic episyenite

Small, brick-red, metasomatic episyenites in the Caballo Mountains are associated with REE (rare earth elements)-Th-U and Nb veins (McLemore, 1986; McLemore et al., 2012, this guidebook). Similar deposits are found in the Fra Cristobal pluton (van Allen et al., 1984) and should be examined for their REE and Nb potential.

Rio Grande Rift fluorite-barite deposits

Rio Grande Rift fluorite-barite deposits are found as fissure veins along the north-trending, steeply dipping West Vein fault in Proterozoic granite at Sunset Ridge (Table 1; Jacobs, 1956; Van Allen et al., 1984). The mineralized zone is 1.5-40 m thick, 120 m long, dips steeply to the west, and samples assayed 37.6–62.5% CaF₂ (Van Allen et al., 1984). Gangue minerals include quartz, calcite, barite, pyrite, trace malachite, and iron oxides. Three drill holes encountered fluorite at depths of 100 m. Silicification and brecciation of the host granitic rocks are common. Assays as high as 7.8% Fe, 6% Ba, and 0.45% Mn are reported (Van Allen et al., 1984). Fluid inclusion studies indicated temperatures of homogenization of fluorite from the drill holes at Sunset Ridge ranged from 176° to 252°C with low salinities (0.53–5.85 eq. wt.% NaCl; Sarkar, 1985).

Carbonate-hosted Au-Ag deposits

Jasperoids at the Jornada Vista prospect form narrow (0.1-1 m wide) discordant to concordant irregular veins and pods within limestones of the Magdalena Group (DeLillo, 1991). Most jasperoids are associated with faults and fracture zones. Brecciation is locally common. Many jasperoids are zoned with central quartz

surrounded by pods of barite and gray jasperoid. Red jasperoid typically forms the outermost zone (DeLillo, 1991). Assays of jasperoids range as high as 2 ppm Ag, 0.4 ppm Au, 85.3 ppm As, <1.0 to <0.1 to 6.8 ppm Hg, 0.56 to 1188 ppm Pb, and <0.1 to 1.9 ppm Cd (DeLillo, 1991).

Jasperoids also are found in the San Andres, Glorieta, and Yeso formations in the Walnut Canyon area and along the eastern flank of the Fra Cristobal Mountains (Foulk, 1991), but no chemical analyses of these outcrops are available to determine if they are mineralized.

Epithermal manganese vein deposits

Epithermal manganese vein deposits are found along faults, joints, shear zones, and fracture zones within Proterozoic granite and schist, and along contact zones between Proterozoic granite and schist at the Blackie or Black Pete mine near the northern end of the range (Farnham, 1961; Sarkar, 1985). Romanechite is the predominant manganese mineral along with a gangue of quartz, chalcedony, calcite, and iron oxides. The manganese is found as fracture fillings, encrustations, and stockwork veins. Brecciation and silicification are common. The granitic host rocks were altered to kaolinite, illite, and iron oxides. The mineralized zone is approximately 366 m long and up to 61 m wide (Farnham, 1961). Two samples assayed 9.1% and 15.5% Mn, but intergrown, fine-grained quartz hampers concentration of the material (Farnham, 1961).

Manganese oxides are found in stringers and thin veins within sandstone and limestone underlying a basalt cap at the Bolander deposit in sections 3, 4, 9, 12, T12S, R3W (Farnham, 1961). The deposit is less than 15 m long.

Sandstone uranium deposits

Uranium minerals with minor amounts of malachite, chalcocite, and azurite are found in small deposits in sandstones of the Abo Formation in the southern Fra Cristobal Mountains (Table 1).

Gypsum deposits

Abundant bedded gypsum occurs in the southern part of the range in the Yeso Group, particularly in the Cañas Member in the upper part of the group. Purity of this material and suitability for industrial use has not been evaluated.

Placer gold deposits

Placer gold deposits are found in many arroyos draining the Proterozoic rocks in the Caballo Mountains (McLemore et al, 2012, this guidebook). Since the geology is similar in the Fra Cristobal Mountains to the Caballo Mountains and some of the jasperoids contain gold (Table 1), it is possible that placer gold deposits could occur in the arroyos draining these rocks in the Fra

TABLE 1. Mineral prospects and mines in the Fra Cristobal Mountains (from McCleary, 1960; Farnham, 1961; Templain and Dotterrer, 1978; McLemore, 1983; van Allen et al., 1984; Sarkar, 1985; DeLillo, 1991). Mine Id number is from the New Mexico Mines Database (McLemore et al., 2005a, b).

Mine Id	Mine Name (Alias)	Location	Latitude	Longitude	Commodities	Development	Type of Deposit	HOST
NMSI0259	Blackie (Black mine, Black Pete, Pedro de Abalos?)	1, 10 10S 3W	33.470272	-107.11216	Mn, Cu, F	trenches	epithermal manganese	Proterozoic granite
NMSI0260	Bolander (Ruth B., Ada Gayle, Ina B.)	3,4,9,10 12S 3W	33.296742	-107.12654	Mn	pits	epithermal manganese	Tertiary Santa Fe Group
NMSI0261	Jornada Vista	6 10S 4W	33.470206	-107.08883	Au, Ag, F, U, Cu	drill holes	Carbonate-hosted Au	Proterozoic granite, Penn Magdalena Group
NMSI0262	Sunset Ridge (Old Mine, Portland)	26, 35 10S 3W	33.406343	-107.12363	F, Cu, Ag	drill holes	Rio Grande Rift	Proterozoic granite
NMSI0264	unknown	1 13S 3W	33.459344	-107.0835	U	none	sandstone uranium	Tertiary McRae Formation
NMSI0263	unknown	23 12S 3W	33.271306	-107.12197	U	none	sandstone uranium	Cretaceous Mesaverde Formation
NMSI0265	unknown	33 12S 3W	33.253556	-107.10763	U	none	sandstone uranium	Cretaceous Mesaverde Formation
NMSI0266	unknown	6 10S 2W	33.466898	-107.08996	U, Cu	none	sandstone uranium	Permian Abo Formation
NMSI0882	Black Pete	1, 2, 3, 10 10S 3W	33.470272	-107.12654	Mn	pits	epithermal manganese	Proterozoic granite

Cristobal Mountains (Harley, 1934). During fluvial events, large volumes of sediment containing free gold are transported and deposited in relatively poorly-sorted alluvial and stream deposits. The gold concentrates by gravity in incised stream valleys and alluvial fans in deeply weathered highlands. Stream-sediment sampling is required to test this hypothesis.

Mineral resource potential

A variety of mineral deposits are found in the Fra Cristobal Mountains, but most of these mineral deposits are small, low grade, and uneconomic. However, there is potential for placer gold deposits and REE-U-Th veins in possible Cambrian-Ordovician syenites and associated metasomatic episyenites; but additional sampling and mapping are required to determine the mineral resource potential.

ACKNOWLEDGMENTS

We thank the management of the Armendaris Ranch, and particularly Ted Turner and Tom Waddell, for property access to the Fra Cristobal Range. Justin Spielmann assisted in the field. Andrew Louchios of the Illinois State Geological Survey performed the digital cartography for the geologic map. Justin Spielmann, New Mexico Museum of Natural History and Science, and Steve Cather, NMBGMR, provided reviews.

REFERENCES

- Amato, J.M. and Becker, T., 2012, Proterozoic rocks of the Caballo Mountains and Kingston mining district: U-Pb geochronology and correlations within the Mazatzal province of Southern New Mexico: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.
- Bachman, G.O. and Mehnert, H.H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, no. 2, p. 283-292.
- Cather, S.M. and Harrison, R.W., 2002, Lower Paleozoic isopach maps of southern New Mexico and their implications for Laramide and Ancestral Rocky Mountain tectonism: New Mexico Geological Society, 53rd Field Conference, Geology of White Sands, p. 85-101.
- Chafetz, H. S., Meredith, J. C. and Kocurek, G., 1986, The Cambro-Ordovician Bliss Formation, southwestern New Mexico, U. S. A.—progradational sequences on a mixed siliciclastic and carbonate shelf: Sedimentary Geology, v. 49, p. 201-221.
- Chapin, M.A., 1986, Analysis of Laramide basement-involved deformation, Fra Cristobal Range, New Mexico: M.S. thesis, Colorado School of Mines, Golden, CO, 92 p.
- Chapin, M.A. and Nelson, E.P., 1986, Laramide basement-involved deformation in the Fra Cristobal Range, south-central New Mexico: New Mexico Geological Society, 37th Field Conference Guidebook, p. 107-114.
- Clemons, R. E., 1991, Petrography and depositional environments of the Lower Ordovician El Paso Formation: New Mexico Bureau of Mines and Mineral Resources, Bulletin 125, 66 p.
- Collins, D.S., 1999, Laramide and post-Laramide stratigraphy and tectonism on the southeast flank of the Fra Cristobal Mountains, New Mexico: M.S. thesis, Colorado School of Mines, Golden, CO, 116 p.
- Cserna, E.G., 1956, Structural geology and stratigraphy of the Fra Cristobal quadrangle, Sierra County, New Mexico: Ph. D. thesis, Columbia University, New York, 104 p. and 1 plate.
- Darton, N. H., 1928, "Redbeds" and associated formations in New Mexico: U.S. Geological Survey, Bulletin 794, 356 p.
- DeLillo, N.J., 1991, Geology and geochemistry of gold mineralization in the Jornada Vista prospect, Fra Cristobal Range, New Mexico: M.S. thesis, Colorado School of Mines, Golden, 97 p.
- Farnham, L.L., 1961, Manganese deposits of New Mexico: U.S. Bureau of Mines, Information Circular IC-8030, 176 p.
- File, L., and Northrop, S.A., 1966, County township, and range locations of New Mexico's mining districts: New Mexico Bureau of Mines and Mineral Resources, Circular 84, 66 p.
- Foull, L.S., 1991, Characteristics and origin of structural features of the central eastern flank and the Walnut Canyon area in the Fra Cristobal Range, south-central New Mexico: M.S. thesis, Colorado School of Mines, Golden, CO, 93 p.
- Gillette, D.D., Wolberg, D.L., and Hunt, A.P., 1986, *Tyrannosaurus rex* from the McRae Formation (Lancian, Upper Cretaceous), Elephant Butte Reservoir, Sierra County, New Mexico: New Mexico Geological Society, 37th Field Conference Guidebook, p. 235-238.
- Harley, G.T., 1934, The geology and ore deposits of Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 10, 220 p.
- Harris, S. K., Lucas, S. G. and Rinehart, L. F., 2011, The euelycosaur *Dime-trodon* from the Lower Permian Abo Formation, Fra Cristobal Mountains, Sierra County, New Mexico: New Mexico Geology, v. 33, p. 47.
- Harrison, R.W. and Cather, S.M., 2004, The Hot Springs fault system of south-central New Mexico – evidence for northward translation of the Colorado Plateau during the Laramide orogeny: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, p. 161- 179.
- Harrison, R.W., Lozinsky, R.P., Eggleston, T.L., and McIntosh, W.C., 1993, Geologic map of the Truth or Consequences 30 X 60-minute quadrangle (1:100,000 scale): New Mexico Bureau of Geology and Mineral Resources, Open File Report 390, 19 p. and 1 sheet.
- Hayes, P.T., 1975a, Cambrian and Ordovician rocks of southern Arizona and New Mexico and westernmost Texas: U.S. Geological Survey, Professional Paper 873, 98 pp.
- Hayes, P.T., 1975b, Selected stratigraphic sections of Cambrian and Ordovician rocks in Arizona, New Mexico, and western Texas: U.S. Geological Survey, Open-File Report 75-178, 51 pp.
- Hills, J.M. and Kottlowski, F.E., 1983, Southwest/southwest Mid-Continent region: Correlation of Stratigraphic Units of North America (COSUNA) Project: American Association of Petroleum Geologists, Tulsa, 1 sheet.
- Jacobs, R.C., 1956, Geology of the central front of the Fra Cristobal Mountains, Sierra County, New Mexico: M.S. thesis, University of New Mexico, 47 p. and 2 plates.
- Julyan, R., 1998, The place names of New Mexico (revised edition): University of New Mexico Press, Albuquerque, 385 p.
- Kelley, V.C. and Silver, C., 1952, Geology of the Caballo Mountains: University of New Mexico Publications in Geology, No. 4, 286 p.
- Kelley, V.C. and Wood, G.H., 1946, Lucero uplift, Valencia, Socorro, and Bernalillo Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations, Preliminary Map 47, 1 sheet.
- Kelly, J.C., 1988, Petrology and petrogenesis of alkali basalts and their associated inclusions from Elephant Butte area, Sierra County, New Mexico: M.S. thesis, Albuquerque, University of New Mexico, 172 p.
- Kottlowski, F. E., Flower, R. H., Thompson, M. L., and Foster, R. W., 1956, Stratigraphic studies of the San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 1, 132 p.
- Krainer, K. and Lucas, S. G., 2009, Cyclic sedimentation of the Upper Pennsylvanian Olower Wolfcampian) Bursum Formation, central New Mexico: Tectonics vs. eustasy: New Mexico Geological Society, 60th Field Conference Guidebook, p. 167-182.
- Lee, W. T., 1909, The Manzano group of the Rio Grande valley, New Mexico. Stratigraphy of the Manzano Group: U.S. Geological Survey, Bulletin 389, p. 5-40.
- Lozinsky, R.P., 1985, Geology and late Cenozoic history of the Elephant Butte area, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 187, 40 p.
- Lozinsky, R. P. and Hawley, J. W., 1986a, The Palomas Formation of south-central New Mexico — a formal definition: New Mexico Geology, v. 8, p. 73-78, 82.
- Lozinsky, R. P. and Hawley, J. W., 1986b, Upper Cenozoic Palomas Formation of south-central New Mexico: New Mexico Geological Society, 37th Field Conference Guidebook, p. 239-247.

- Lucas, S. G., and Estep, J. W., 1998, Cretaceous stratigraphy and biostratigraphy in the southern San Andres Mountains, Doña Ana County, New Mexico: New Mexico Geological Society, 49th Field Conference Guidebook, p. 187-196.
- Lucas, S.G. and Krainer, K. 2012, The Lower Permian Yeso Group in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.
- Lucas, S. G., Krainer, K., and Barrick, J. E., 2009, Pennsylvanian stratigraphy and conodont biostratigraphy in the Cerros de Amado, Socorro County, New Mexico: New Mexico Geological Society Guidebook, 60th Field Conference Guidebook, p. 183-212.
- Lucas, S. G., Krainer, K., Chaney, D.S., Dimichele, W.A., Voigt, S., Berman, D.S., and Henrici, A.C., 2012, The Lower Permian Abo Formation in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.
- Lucas, S. G., Krainer, K. and Colpitts, R. M., Jr., 2005a, Abo-Yeso (Lower Permian) stratigraphy in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 31, p. 101-117.
- Lucas, S. G., Mack, G. H. and Estep, J. W., 1998, The ceratopsian dinosaur *Torosaurus* from the Upper Cretaceous McRae Formation, Sierra County, New Mexico: New Mexico Geological Society, 49th Field Conference Guidebook, p. 223-227.
- Lucas, S. G., Minter, N. J., Spielmann, J. A., Hunt, A. P., and Braddy, S. J., 2005b, Early Permian ichnofossil assemblage from the Fra Cristobal Mountains, southern New Mexico: New Mexico Museum of Natural History and Science Bulletin, 31, 140-150.
- Mack, G. H., 2004, The Cambro-Ordovician Bliss and Lower Ordovician El Paso formations, southwestern New Mexico and West Texas; in Mack, G. H. and Giles, K. A., eds., The geology of New Mexico—A geologic history: New Mexico Geological Society, Special Publication 11, p. 35-44.
- McCleary, J.T., 1960, Geology of the northern part of the Fra Cristobal Range, Sierra and Socorro Counties, New Mexico: M.S. thesis, University of New Mexico, 59 p. and 1 sheet.
- McLemore, V. T., 1983, Uranium and thorium occurrences in New Mexico: distribution, geology, production, and resources; with selected bibliography: New Mexico Bureau of Mines and Mineral Resources, Open-file Report OF-183, 950 pp., also; U.S. Department of Energy Report GJBX-11 (83).
- McLemore, V.T., 1986, Geology, geochemistry, and mineralization of syenites in the Red Hills, southern Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, 37th Field Conference Guidebook, p. 151-159.
- McLemore, V.T., Hoffman, G., Smith, M., Mansell, M., and Wilks, M., 2005a, Mining districts of New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 494, CD-ROM.
- McLemore, V. T., Krueger, C. B., Johnson, P., Raugust, J. S., Jones, G.E., Hoffman, G.K. and Wilks, M., 2005b, New Mexico Mines Database: Society of Mining, Exploration, and Metallurgy, Mining Engineering, February, p. 42-47.
- McLemore, V.T., Rämö, O.T., Heizler, M., and Heinonen, A.P., 2012, Intermittent Proterozoic and Possible Cambrian-Ordovician plutonic magmatism in the Caballo Mountains, Sierra County, New Mexico; preliminary results: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.
- Molenaar, C. M., 1983, Major depositional cycles and regional correlations of Upper Cretaceous rocks, southern Colorado Plateau and adjacent areas; in Reynolds, M. W. and Dolly, E. D., eds., Mesozoic paleogeography of the west-central United States: Denver, RMS-SEPM, p. 201-224.
- Morgan, G. S., Sealey, P. L., and Lucas, S. G., 2011, Pliocene and early Pleistocene (Blancan) vertebrates from the Palomas Formation in the vicinity of Elephant Butte Lake and Caballo Lake, Sierra County, southwestern New Mexico: New Mexico Museum of Natural History and Science, Bulletin 53, p. 664-736.
- Nelson, E.P., 1986, Geology of the Fra Cristobal Range, south-central New Mexico: New Mexico Geological Society, 37th Annual Field Conference Guidebook, p. 83-92.
- Nelson, E.P., 1993, Thick- and thin-skinned Laramide deformation, Fra Cristobal Range, south-central New Mexico: Geological Society of America, Special Paper 280, p. 257-270.
- Nelson, E.P. and Hunter, J.C., 1986, Laramide thin-skinned deformation in Permian rocks, Fra Cristobal Range, south-central New Mexico: New Mexico Geological Society, 37th Annual Field Conference Guidebook, p. 115-122.
- Romano, E.M., 1997, Late Paleozoic remagnetization of the Bliss Formation in the Fra Cristobal Range and Caballo Mountains, Sierra County, New Mexico: M.S. thesis, University New Mexico, Albuquerque, NM, 186 p.
- Sarkar, G.P., 1985, Late Cenozoic epithermal tungsten-bearing romanechite veins at the Blackie mine area, and selected localities in central and southwestern New Mexico, U.S.A.: Ph.D. dissertation, University of New Mexico, Albuquerque, 194 p.
- Seager, W.R. and Mack, G.H., 2003, Geology of the Caballo Mountains, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Memoir 49, 135 p.
- Templain, C.J., and Dotterrer, F.E., 1978, Jornada del Muerto Basin and adjacent areas, south-central New Mexico: U.S. Department of Energy, Report GJBX-80(78), 22 p.
- Thompson, M.L., 1942, Pennsylvanian System in New Mexico: New Mexico Bureau of mines and Mineral resources, Bulletin 17, 92 p.
- Thompson, Samuel, III, 1955, Geology of the southern part of the Fra Cristobal Range, Sierra County, New Mexico: M.S. thesis, University of New Mexico, 67 p.
- Thompson, S. III and Potter, P. E, 1981, Paleocurrents of Bliss Sandstone (Cambro-Ordovician), southwestern New Mexico and western Texas: New Mexico Bureau of Mines and Mineral Resources, Annual Report for the Fiscal Year July 1, 1979 to June 30, 1980, p. 36-51.
- Upchurch, G. R., Jr. and Mack, G. H., 1998, Latest Cretaceous leaf megafloras from the Jose Creek Member, McRae Formation of New Mexico: New Mexico Geological Society, 49th Field Conference Guidebook, p. 209-222.
- Van Allen, B.R., Gill, R.D., and Emmons, D.L., 1983, Minerals reconnaissance of the Pedro Armendaris Grants nos. 33 and 34 and adjacent areas, Sierra and Socorro Counties, New Mexico: Tenneco Minerals Company report available at Library of the University of Wyoming in Laramie.
- Van Allen, B.R., Wilson, J.L., and Hunter, J.C., 1984, Sunset Ridge fluorite deposit, Fra Cristobal Range, Sierra County, New Mexico: New Mexico Geology, v. 6, no. 1, p. 1-5, 12.
- Verlille, G.J., Sanderson, G.A., and Madsen, M.E., 1986, Pennsylvanian fusulinids from the Fra Cristobal Range, Sierra County, New Mexico: New Mexico Geological Society, 37th Field Conference Guidebook, p. 215-224.
- Warren, R.G., 1978, Characterization of the lower crust-upper mantle of the Engle basin, Rio Grande rift, from a petrochemical and field geologic study of basalts and their inclusions: M.S. thesis, Albuquerque, University of New Mexico, 156 p.
- Wolberg, D.L., Lozinsky, R.P., and Hunt, A.P., 1986, Late Cretaceous (Maastrichtian-Lancian) vertebrate paleontology of the McRae Formation, Elephant Butte area, Sierra County, New Mexico: New Mexico Geological Society, 37th Annual Field Conference Guidebook, p. 227-234.



A freight team, near Winston New Mexico, ca 1890.