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

Cretaceous stratigraphy, paleontology, petrography, depositional environments, and cycle stratigraphy at Cerro de Cristo Rey, Doña Ana County, New Mexico

Spencer G. Lucas, New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, New Mexico 87104, spencer.lucas@state.nm.us; *Karl Krainer*, Institute of Geology and Paleontology, Innsbruck University, Innrain 52, Innsbruck, A-6020 Austria, Karl.Krainer@uibk.ac.at; *Justin A. Spielmann*, New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, New Mexico 87104, justin.spielmann1@state.nm.us; *Kevin Durney*, 11212 Jockey Bluff Drive, Austin, Texas 78748

Abstract

Cretaceous marine and nonmarine strata of late Albian–middle Cenomanian age are exposed around the Cerro de Cristo Rey uplift in southern Doña Ana County, New Mexico. These strata comprise a section approximately 350 m thick and are assigned to the (ascending order) Finlay, Del Norte, Smeltertown, Muleros, Mesilla Valley, Mojado (="Anapra"), Del Rio, Buda, and Mancos (="Boquillas") Formations. Macrofossils and microfossils from these strata indicate that the Finlay, Del Norte, Smeltertown, Muleros, and Mesilla Valley Formations are of late Albian age, whereas the Del Rio, Buda, and Mancos Formations are of Cenomanian age. The base of the Cenomanian is most likely at a trangressive surface within the uppermost Mojado Formation. The late Albian (*Manuaniceras powelli* Zone) to early Cenomanian (*Neophlycticeras hyatti* Zone) sedimentary succession at Cerro de Cristo Rey consists of alternating fossiliferous limestone, shale with limestone and sandstone intercalations, and sandstone. Muddy limestone types are commonly wavy to nodular and represent deposits of an open-marine shelf environment below wave base. Intercalated coquina beds rich in mollusc shells are interpreted as storm layers. Shale was deposited in an open-shelf environment below or near wave base during periods of increased siliciclastic influx. Intercalated thin limestone and sandstone beds are inferred to be storm layers. The siliciclastic Mojado Formation is a regressive-transgressive succession formed in depositional environments ranging from lower shoreface to upper shoreface and even fluvial, again overlain by shallow-marine siliciclastics. Although the Washita Group section at Cerro de Cristo Rey is much thicker and displays some differences in facies, the succession shows similar transgressive and regressive trends compared to the Washita Group of north Texas. Thus, we recognize eight unconformity-bounded depositional cycles in the Cretaceous section at Cerro de Cristo Rey, the upper Finlay Formation (youngest cycle of the Fredericksburg Group), lower Mancos Formation (base of Greenhorn cycle), and six Washita Group cycles: WA1=Del Norte Formation, WA2=Smeltertown Formation, WA3=Muleros Formation, WA4=most of Mesilla Valley Formation, WA5=uppermost Mesilla Valley Formation and most of Mojado Formation, and WA6=uppermost Mojado and Del Rio and Buda Formations. The persistence of cycles from the tectonically passive, open-marine margin of the Gulf of Mexico into the tectonically active Chihuahua trough suggests that regional if not global eustasy, not local tectonism, drove late Early to early Late Cretaceous sedimentation at Cerro de Cristo Rey.

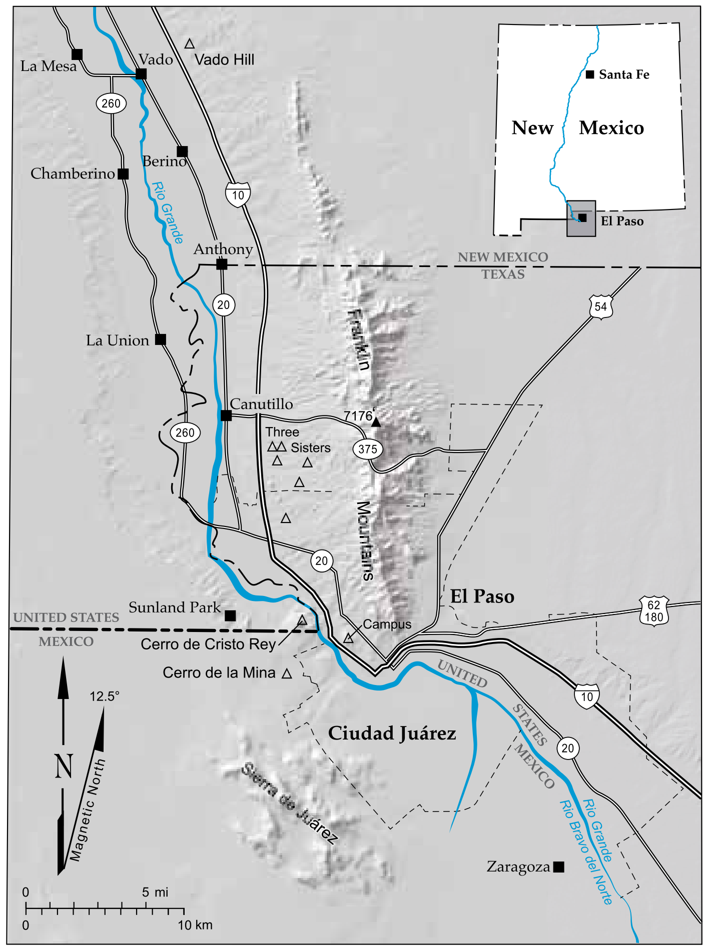

FIGURE 1—Location of Cerro de Cristo Rey in southern Doña Ana County, New Mexico (after Lovejoy 1976). ∆ indicates Eocene igneous intrusions—Cerro de Cristo Rey, Cerro de la Mina, Campus Andesite, the Three Sisters, and Vado Hill.

Introduction

Cerro de Cristo Rey is a prominent peak in Doña Ana County, New Mexico, just north of the U.S.–Mexican border and just west of the city of El Paso, Texas (Fig. 1). The mountain was long referred to as the Cerro de Muleros, but was renamed Cerro de Cristo Rey ("Sierra" de Cristo Rey of Hook 2008 and Cobban et al. 2008, also appears on the U.S. Geological Survey topographic map of the area) in recognition of the large statue of Christ on the cross at its crest. The mountain has an elevation of 1,425 m (4,675 ft) (Lovejoy 1976; Hook 2008).

The core of Cerro de Cristo Rey is an andesite laccolith, the Muleros Andesite of Eocene age (Fig. 2). The laccolith is surrounded by "an annulus of…faulted Cretaceous marine strata, locally strongly deformed by gravity-glide structures triggered by andesite intrusion" (Lovejoy 1976, p. 24). The Cretaceous strata, a section approximately 350 m thick, include rocks of Early Cretaceous (late Albian) and Late Cretaceous (early–middle Cenomanian) age (Figs. 3–4). These rocks have been studied for more than a century, most notably by Böse (1910) and Strain (1976). Here, we present the first detailed lithostratigraphy and sedimentary petrography of the Cretaceous strata exposed around the New Mexican periphery of the Cerro de Cristo Rey uplift. We combine these data with paleontology and regional correlations to present the first detailed interpretation of the depositional environments and cycle stratigraphy of the Cretaceous section.

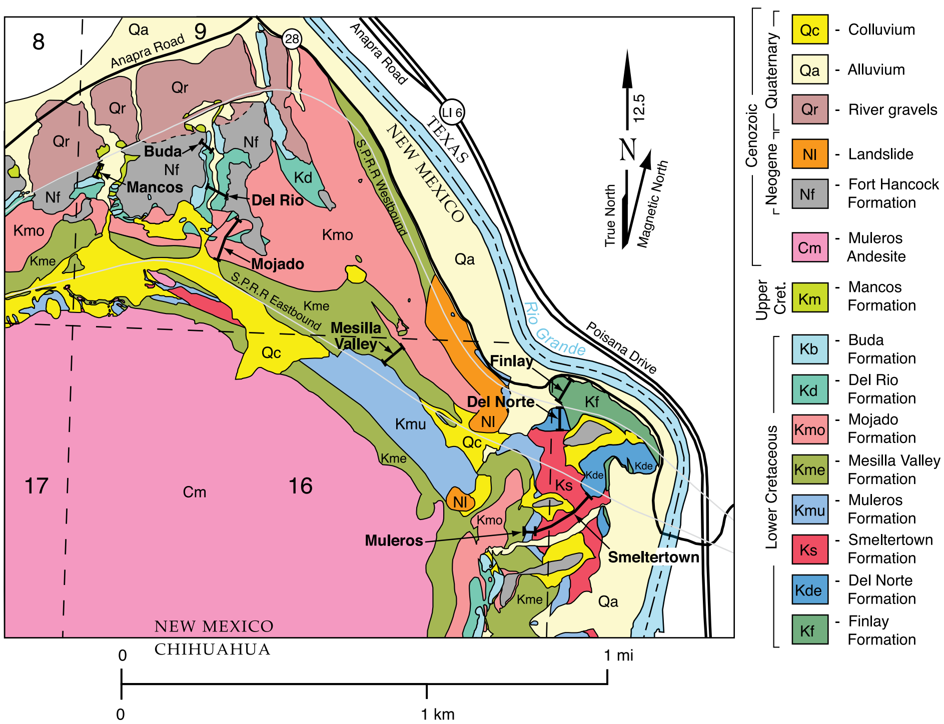

FIGURE 2—Geologic map of part of the New Mexican portion of the Cerro de Cristo Rey uplift (from Lovejoy 1976) showing locations of measured stratigraphic sections in this study. See Appendix for map coordinates of the measured sections.

the Cretaceous invertebrate macrofossils he collected at Cerro de Cristo Rey.

Adkins (1932) and Imlay (1944) subsequently applied Texas stratigraphic names to the section Böse (1910) delineated at Cerro de Cristo Rey (Fig. 3). Córdoba (1968, 1969a,b) proposed a formal lithostratigraphic nomenclature for the Cretaceous section in northeastern Chihuahua, Mexico. He mapped these units as far north as the international border, so he assigned Cretaceous strata along the southern flank of Cerro de Cristo Rey in Chihuahua to strata of his Ojinaga Group. Córdoba (1969a) makes clear the equivalence between his stratigraphic names and those introduced at Cerro de Cristo Rey by Strain (1968, 1976).

The lithostratigraphic names long applied to Cretaceous strata at Cerro de Cristo Rey were briefly introduced by Strain (1968) and elaborated on by Strain (1976) and Lovejoy (1976). Thus, four stratigraphic names from farther east, in Texas (Finlay, Del Rio, Buda, and Boquillas), are applied, whereas Strain introduced five local lithostratigraphic names—Del Norte, Smeltertown, Muleros, Mesilla Valley, and Anapra (Figs. 3–4).

Subsequent workers (e.g., LeMone and Simpson 1983; Maudlin 1985; Cornell and LeMone 1987; Cornell et al. 1991; Cornell 1997; Lucas and Estep 1998b, 2000; Scott et al. 2001, 2003; Turnšek et al. 2003) have employed the lithostratigraphy of Strain (1976). The only previously suggested modification is that of Lucas and Estep (1998b, 2000), who argued that the Anapra Sandstone is part of the same lithosome as the Mojado Formation to the west. They therefore abandoned the name Anapra Sandstone and replaced it with the term Mojado Formation. Here, we employ the lithostratigraphic nomenclature of Strain (1968, 1976) with two modifications, the use of Mojado Formation instead of Anapra Sandstone and the use of Mancos Formation instead of Boquillas Formation (Fig. 4). These modifications are justified below.

Located on the northern margin of the Chihuahua trough, the Cretaceous section at Cerro de Cristo Rey is between Bisbee Group sections to the west and Washita Group sections to the east. It thus provides a pivotal reference section for regional correlation and testing concepts of Washita Group cycle stratigraphy.

Previous studies

Emory (1857), Stanton and Vaughan (1896), and Richardson (1909) first reported on the Cretaceous rocks exposed around Cerro de Cristo Rey (Fig. 3). However, the real starting point for understanding the stratigraphy and paleontology of these strata was the monograph of Böse (1910). He informally divided the Cretaceous section at Cerro de Cristo Rey into 11 stratigraphic units, many characterized by a distinctive fossil assemblage (Fig. 3). Although Böse (1910) explicitly correlated these units to formally named units of the Fredericksburg and Washita Groups and overlying Eagle Ford Shale of Texas (as had Stanton and Vaughan [1896] and was later done by Adkins [1932]), he applied no formal lithostratigraphic nomenclature to the Cretaceous section at Cerro de Cristo Rey. Most significantly, Böse (1910) provided a monographic description of

Series	Provincial Series	Central Texas Group	SGCS	Stanton and Vaughan (1896)				Böse (1910)	Adkins (1932)		Imlay (1944)	Strain (1968)		Cordoba (1969a, b)		Strain (1976)				This paper
Upper Cretaceous	Gulfian	Eagle Ford	Cenomanian			Tur-onian		11 Eagle Ford *Inoceramus labiatus* horizon	11 Eagle Ford	Cenomanian Stage	11 Eagle Ford (or Colorado Shale)	10 Boquillas (= bed 11 of Böse)	La Mina Fm.	Ojinaga	Turonian	10 Boquillas (= bed 11 of Böse)	Cenomanian	Cenomanian	X	Mancos Formation
				10 (7) Sandstone White, yellow, brown		Cenomanian upper		10 Woodbine sandstone	10 Woodbine Ss.		10 Woodbine Ss.									
Lower Cretaceous	Comanchean	Washita		9 (8) Clay shale			Washita upper	9 Hemiaster calvini horizon (9–8)	9 Buda		9 Buda	9 Buda	Juarez Fm.	Buda	Cenomanian	9 Buda Ls.			Washita Group	Buda Fm.
				8 (9) Hard limestone				8 Buda	8 Del Rio		8 Del Rio	8 Del Rio		Del Rio		8 Del Rio Clay				Del Rio Fm.
			Albian upper	7 Sandstone White or brown	Washita			7 Red sandstone w/ *Exogyra whitneyi*	7 Main Street	Albian Stage	7 Main Street	7 Anapra	Arroyo Colorado Fm.	Anapra		7 Anapra Ss.		Albian		Mojado Fm.
				6 Clay shale and sandy flagstone		lower	middle and lower	6–4 Del Rio *Schloenbachia trinodosa* horizon	6 Weno-Pawpaw		6 Pawpaw-Weno equiv.	6 Mesilla Valley		Mesilla Valley		6 Mesilla Valley Sh.	Albian			Mesilla Valley Fm.
				5 Flaggy argillaceous limestone with shale					5 Fort Worth-Denton		5 Denton-Fort Worth equiv.	5 Muleros		Muleros		5 Muleros Fm.				Muleros Fm.
		Fredericksburg		4 Clay shale, calcareous bands					4 Duck Creek		4 Duck Creek equivalents	4 Smeltertown		Smeltertown (Vraconian)		4 Smeltertown Fm.				Smeltertown Fm.
				3 Ledges of hard limestone	Fredericksburg	Vraconian	Fredericksburg	3–1 *Exogyra texana* horizon	3–2 Kiamichi		3 Kiamichi	3–2 Del Norte		Del Norte	Albian	3–2 Del Norte Fm.				Del Norte Fm.
				2 Alternations of clay and soft argillaceous limestone ledges							2 Edwards (Finlay Ls.)									
				1 Argillaceous limestone in thick ledges, weathering to nodular masses surrounded by clay					1 Edwards		1 Sandstone, Unnamed	1 Courchesne		Courchesne		1 Finlay Ls.			Fredericks-burg Grp.	Finlay Fm.

SGCS= Standard Global Chronostratigraphic Scale, the current standard of the International Commission on Stratigraphy.

FIGURE 3—Evolution of Cretaceous lithostratigraphic nomenclature at Cerro de Cristo Rey. Modified from Strain (1976).

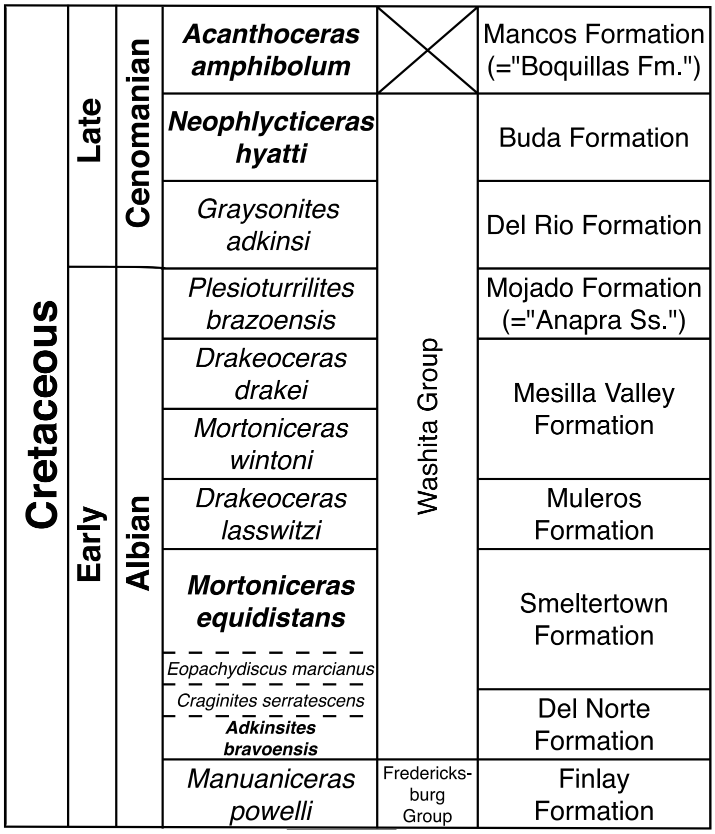

FIGURE 4—Summary of stratigraphic section and age assignments of Cretaceous strata at Cerro de Cristo Rey (modified from Lucas and Estep 1998b, 2000). Only ammonoid zone names in boldface are known from ammonoid fossils collected at Cerro de Cristo Rey; presence of other zones is inferred.

Overview

Below, we present a brief summary of the lithostratigraphy of the Cretaceous rocks exposed at Cerro de Cristo Rey (Fig. 4), based primarily on the stratigraphic sections we measured (Figs. 5–15) and on data in Strain (1976) and Lovejoy (1976). More detailed lithologic information on some of the rock units is presented below in the sections on sedimentary petrography (Figs. 16–24). Note that we refer to all the Cretaceous formation rank units exposed at Cerro de Cristo Rey with the suffix "formation," instead of using the lithic terms limestone, shale, or sandstone.

Böse (1910) published most of what is known of the Cretaceous paleontology of Cerro de Cristo Rey. We have extensive macrofossil collections from Cerro de Cristo Rey that we will document elsewhere. Here, we provide brief summaries of the paleontology, mostly of relevance to interpreting the age and depositional environments of the Cretaceous strata exposed at Cerro de Cristo Rey. We also present a sedimentary petrography of the Cretaceous section at Cerro de Cristo Rey, and we briefly summarize the depositional environments of the Cretaceous formations. The final section of this article brings these data and analyses together to present an interpretation of the cycle stratigraphy of the Cretaceous strata exposed at Cerro de Cristo Rey.

Finlay Formation

Lithostratigraphy

The Finlay Formation is the stratigraphically lowest unit of the Cretaceous section exposed in the New Mexico outcrops at Cerro de Cristo Rey, but its base is not exposed. Lovejoy (1976) reported a thickness of 40 m, and total exposed thickness of our measured section of the Finlay Formation is approximately 41 m (Figs. 5A, 6). The only outcrop of the Finlay Formation on the New Mexico flank of the uplift is located at our measured section (Fig. 2).

Finlay Formation strata are a conspicuous ledge- and cliff-forming interval of interbedded light-gray and white limestone and nodular limestone in a marly matrix (Figs. 5A, 6). The succession is thus composed of alternating fossiliferous limestone ledges and slope-forming nodular limestone in shale. Limestone ledges are 0.4–5.3 m thick and composed of bioclastic wackestone to packstone and some rare grainstone.

Paleontology

Bivalves and gastropods are the most common fossils in the Finlay Formation, but foraminiferans (especially *Dictyoconus walnutensis*: Figs. 16D–F, 25R–S), corals, ammonoids, spatangoid echinoderms, and serpulids are also present (Böse 1910; Strain 1976; Turnšek et al. 2003; Kollmann et al. 2003). In addition, our thin sections (see below) demonstrate that calcareous algae, ostracods, and rare calcisponges are present. Kollmann et al. (2003) recently analyzed the gastropod fossil assemblage of the Finlay Formation at Cerro de Cristo Rey, identifying the following taxa: Aporrhaidae, *Diozoptyxis*, *Drepanocheilus*, *Eunerinea aquiline*, Naticoidea, *Nerinella* n. sp., *Otostoma elpasensis*, *Plesioptyxis texanus*, *Rostroptygmatis kervillensis*, *Turritella*, and *Tylostoma*.

Sedimentary petrography (Figs. 6, 16)

Finlay Formation limestone beds at Cerro de Cristo Rey are mostly bioclastic wackestone that is fine-grained and commonly bioturbated. Fossils include small mollusc fragments (bivalves, gastropods), ostracods, calcareous algae, a few echinoderms, echinoid spines, and many foraminiferans embedded in a pelmicritic matrix (Fig. 16A–C). Rare calcisponges are present. Locally, the wackestone grades into packstone and rarely into washed grainstone containing calcite cement (Fig. 16D–F). Many bioclasts are recrystallized. Common foraminiferans are *Dictyoconus* (particularly in units 2 and 8; Fig. 16D–F) and miliolids, *Nummoloculina, Cornuspira*, and *Ophthalmidium*. Most algae are dasycladacean algae (*Permocalculus*) and aciculariaceans (*Acicularia* or *Terquemella*). This facies corresponds to Facies F (bioclastic dasycladacean wackestone) of Kollmann et al. (2003).

In the Finlay Formation, beds of intercalated nodular limestone are 0.2–5 m thick and composed of limestone nodules embedded in shale. The limestone nodules consist of bioturbated mudstone containing a few larger mollusc shell fragments (bivalves, gastropods) and small bioclasts derived from molluscs, ostracods, rare echinoderms, echinoid spines, and smaller foraminiferans.

Depositional environments

The Finlay Formation section exposed at Cerro de Cristo Rey is very similar to the upper part of the Finlay Formation at its stratotype section in Hudspeth County, Texas (Steinhoff 2003). Thus, the Finlay Formation strata at Cristo Rey are limestones and nodular limestones largely devoid of coarse siliciclastic material. Thin-shelled bivalves and spatangoid echinoids dominate the macrofossil assemblage, and the benthic foraminiferan *Dictyoconus walnutensis* is particularly abundant. Deposition clearly took place on a shallow-marine platform in a relatively restricted circulation shelf environment, and this fits the regional picture of upper Finlay deposition (Scott and Kidson 1977; Reaser and Malott 1985; Steinhoff 2003).

Microfacies and the diverse biota, including broken mollusc fragments in the wackestone to packstone of the massive limestone

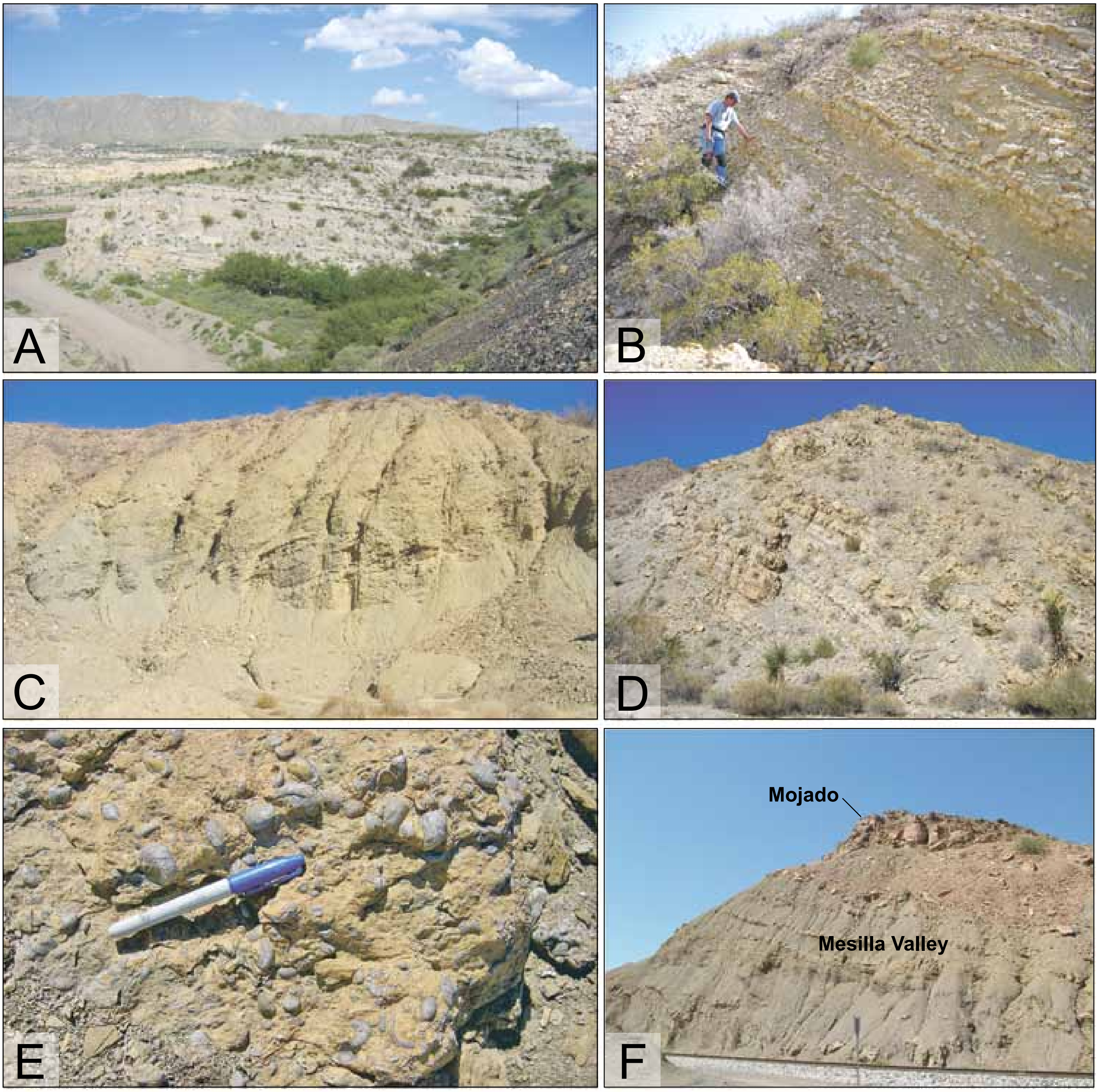

FIGURE 5—Photos of selected Cretaceous outcrops at Cerro de Cristo Rey. **A**—Overview of Finlay Formation section (Fig. 6). **B**—Overview of part of lower member of Del Norte Formation (Fig. 7). **C**—Overview of middle part of Smeltertown Formation (Fig. 8). **D**—Overview of characteristic outcrop of Muleros Formation (Fig. 9). **E**—*Texigryphaea* packstone in lower part of Muleros Formation. **F**—Overview of shale slope formed by Mesilla Valley Formation capped by sandstone at base of Mojado Formation (Fig. 10).

ledges, indicate deposition in an open-shelf setting with moderate energy. The presence of dasycladacean algae points to deposition within the photic zone. Intercalated grainstone suggests periodically high-energy conditions. The wavy to nodular bedded limestone, composed mainly of bioturbated mudstone with a less diverse fauna, suggest deposition in a low-energy, shallow-marine shelf environment.

The facies of the massive and wavy to nodular limestone is very similar to that of the stratotype section of the Finlay Formation, although some differences exist. According to Steinhoff (2003), at the stratotype the lower part of the Finlay Formation is composed of nodular to massive-bedded limestone (bioclastic wackestone to packstone) interbedded with marl and clay. In the upper part of the Finlay Formation massive-bedded limestone (bioclastic wackestone to packstone with a slightly different fauna) is abundant. Rudists, which are common in the stratotype section, particularly in the upper part regionally (e.g., Steinhoff 2003), are absent at Cristo Rey. The lower Finlay Formation of the stratotype is composed of deposits formed on a carbonate ramp in a shallow open-marine shelf environment, whereas the upper Finlay Formation represents deposits of a restricted circulation shelf environment (Steinhoff 2003). Such a trend from a carbonate ramp in the lower Finlay to a restricted shelf environment in the upper Finlay is not evident at Cristo Rey, although some shallowing occurred.

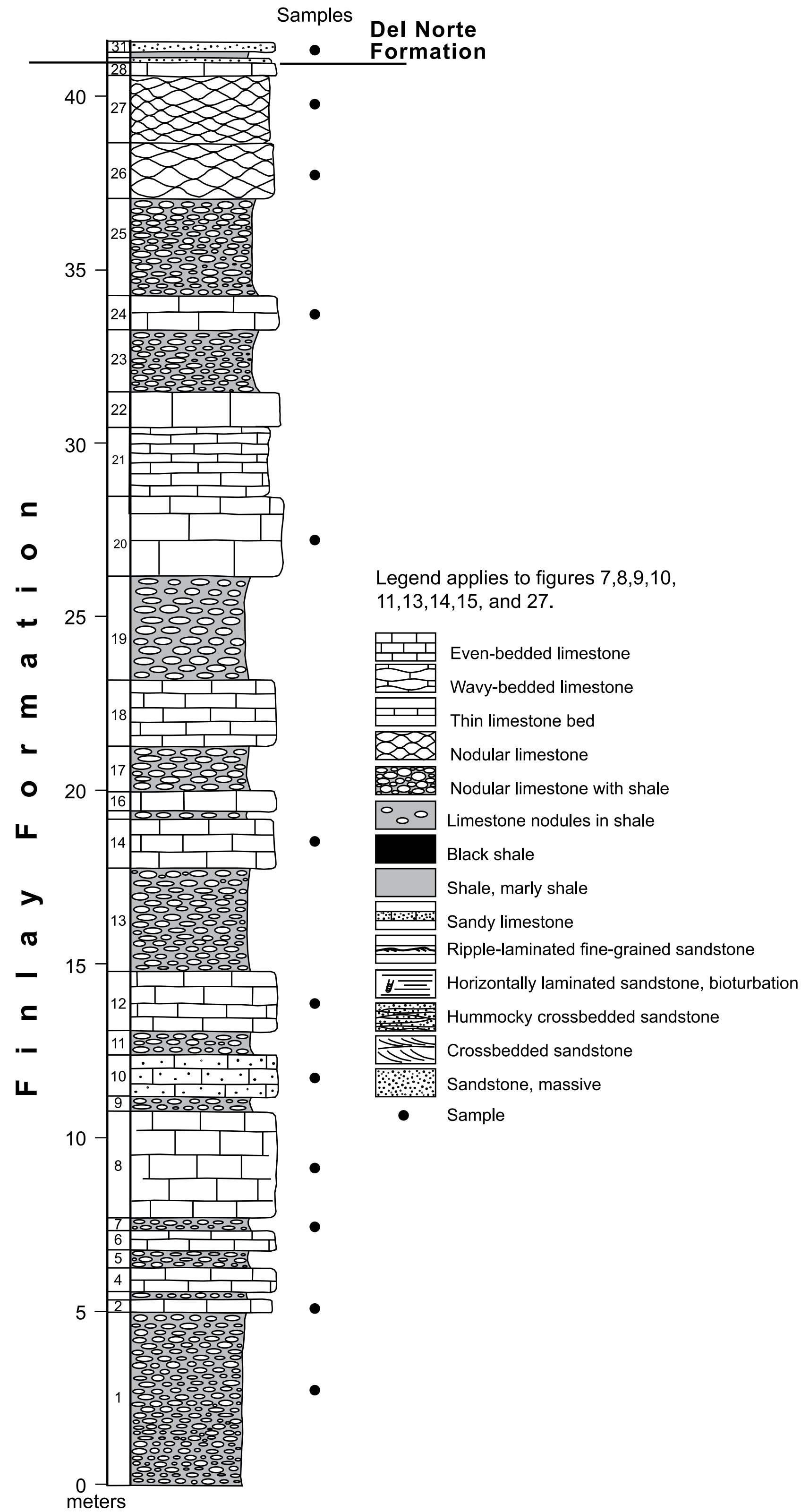

FIGURE 6—Measured stratigraphic section of Finlay Formation. See Figure 2 and Appendix for location of section.

Kollmann et al. (2003, fig. 9) interpreted the facies succession of the exposed Finlay Formation at Cerro de Cristo Rey as that of a shelf lagoon intercalated, near the top of the Finlay, with a bioherm fringe facies represented by "*Orbitolina* wackestone." According to Kollmann et al. (2003), this bioherm fringe facies is approximately 8–15 m below the top of the Finlay, so it corresponds to units 20–24 of our measured section of the Finlay Formation (Fig. 6). However, we did not observe this "*Orbitolina* wackestone" facies. "*Orbitolina*" (we take this to refer to *Dictyoconus*) is present throughout the section and is abundant also in the lower part (particularly in units 2 and 8).

The cyclic alternation of massive and wavy to nodular limestone evident in the Finlay Formation section at Cerro de Cristo Rey (Fig. 6) is also recognized at the Finlay Formation stratotype, where Steinhoff (2003) described nine transgressive-regressive high-frequency cycles in the lower high-frequency sequence 1, and 18 cycles in the overlying high-frequency sequence 2. The stratotype section of the Finlay Formation at the Rimrock escarpment, west Texas, is approximately 52 m thick, although the thickness of the Finlay Formation varies from less than 15 m to approximately 800 m and more in the deeper parts of its depositional basin, the Chihuahua trough (Steinhoff 2003).

Del Norte Formation

Lithostratigraphy

At Cerro de Cristo Rey, the Del Norte Formation of Strain (1968, 1976) rests with sharp contact on the Finlay Formation (Figs. 6–7). It is subdivisions 2 and 3 of Böse (1910), which he estimated to be 20–30 m thick. Our measured section of the Del Norte Formation is the type section of Strain (1976, table 8), where he reported the formation as approximately 17 m thick. However, our section of the Del Norte Formation is 24 m thick and, following Strain (1976), can be divided into a lower (clay) member (approximately 20 m of shale with interbedded sandstone and limestone) and an upper (calcareous) member (3–4 m of limestone) (Fig. 7).

The basal bed of the Del Norte Formation is a prominent, 0.1-m-thick ferruginous sandstone bed that rests with sharp contact on underlying lime mudstone of the Finlay Formation (Figs. 6–7). Above this bed, the lower member ("Brick Plant Member" of Strain 1968) of the Del Norte Formation forms a slope above the Finlay Formation (Fig. 5B) and is composed of alternating beds of limestone, siltstone to fine-grained sandstone, and shale. Limestone beds are thin (0.2–0.6 m thick) and form ledges (Fig. 5B). The lower two limestone beds are nodular. Intercalated beds of calcareous siltstone to fine-grained sandstone in the lower member are 0.3 m thick (Fig. 7, unit 8) and 2.1 m thick (Fig. 7, unit 16). The lower member is capped by the cuesta- and ridge-forming upper member ("Refinery Member" of Strain 1968) of the Del Norte Formation, which is 3.5 m thick. A 0.6-m-thick sandy and shelly limestone ledge (Fig. 7, unit 19) forms its base.

Strain (1976, p. 78) stated that the "Lower Clay Member [of the Del Norte Formation] is conformable with the Finlay Limestone below." However, we agree with Scott et al. (2001, 2003) and Turnšek et al. (2003) that the base of the Del Norte Formation at Cerro de Cristo Rey marks the basal unconformity of the Washita Group (see section on cycle stratigraphy, page 127).

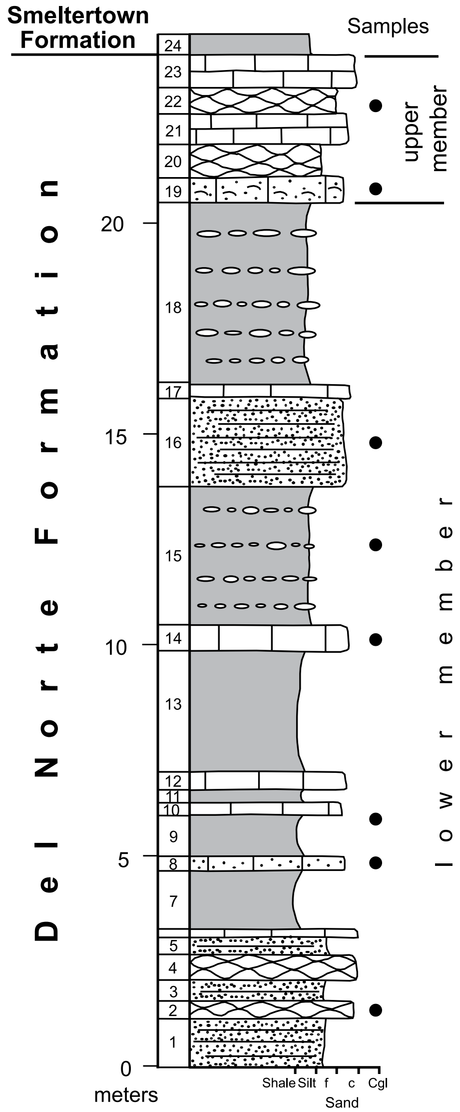

FIGURE 7—Measured stratigraphic section of Del Norte Formation. See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend.

Paleontology

The Del Norte Formation has a diverse fossil assemblage of bivalves (especially gryphaeids, exogyrids, pectens, and oysters), gastropods, spatangoid echinoderms, ammonoids, corals, sponges, and serpulids (Böse 1910; Strain 1976; Turnšek et al. 2003). In thin section, we observed dasycladacean algae, ostracods, foraminiferans, echinoderms, and serpulid worms (see below). Ammonites of the upper Albian *Adkinsites bravoensis* Zone (of Young 1966) are present in the lower member of the Del Norte Formation, in units 15–18 of our measured section (Fig. 7), which indicates correlation with the Kiamichi Formation in north-central Texas. No fossils diagnostic of the *Eopachydiscus marcianus* or *Craginites serratescens* ammonite zones are present at Cerro de Cristo Rey, so their presence (Fig. 4) can only be inferred in the upper Del Norte Formation or lower Smeltertown Formation or missing at an unconformity.

Sedimentary petrography (Figs. 7, 17)

The basal sandstone of the Del Norte Formation (Fig. 7) is fine-grained, mixed siliciclastic and carbonate in composition, containing abundant angular quartz grains, a few micas, and (probably) some detrital feldspars. Carbonate grains are abundant. A few fossil fragments such as shell debris, ostracods, echinoderms, and dasycladacean algae are present. The sandstone is well sorted and laminated.

Nodular limestone of the Del Norte Formation is fine-grained, poorly sorted, bioturbated bioclastic wackestone (Fig. 17A, F) containing abundant fragments of calcareous algae (Aciculariacea, Gymnocodiacea, ?*Permocalculus).* Mollusc shell fragments (gastropods, bivalves), ostracods, foraminiferans, and echinoid spines embedded in gray, micritic, locally pelmicritic matrix are subordinate. Algae and molluscs are very greatly fragmented and recrystallized. Rarely, small voids (?fossils) filled with calcite spar are present.

Limestone of the Del Norte Formation is fine- to coarse-grained, poorly sorted, and commonly bioturbated wackestone to packstone (Fig. 17C, E). A few large mollusc fragments several cm in size float in the wackestone. Mollusc fragments (bivalves, gastropods) and echinoderms are abundant. Echinoid spines, ostracods, foraminiferans (including some large, agglutinated forms), and bryozoans(?) are subordinate. Fossils, particularly molluscs, are commonly recrystallized and strongly fragmented. Lithoclasts include small detrital quartz grains that are mostly 0.1–0.5 mm in diameter (rarely to 1 mm), constituting as much as about 20% of the rock, and a few peloids and micritic intraclasts. Rare glauconite grains are present. The matrix is micrite.

Siltstone to fine-grained sandstone of the Del Norte Formation is commonly nonlaminated and bioturbated, and locally indistinctly laminated (Fig. 17B, D). The composition is mixed siliciclastic-carbonate with as much as about 40% angular detrital quartz grains that are mostly 0.1–0.2 mm in diameter. Other lithoclasts are peloids, micritic intraclasts, and local fecal pellets with diameters from 0.3 to 0.5 mm. The most common fossil fragments are derived from bivalves and gastropods, which are rarely encrusted by bryozoans(?) and annelid worms (serpulid worm tubes). Less abundant are echinoderms, ostracods, foraminiferans (including rare agglutinated forms), echinoid spines, and bryozoans(?).

The basal limestone ledge of the upper member of the Del Norte Formation (Fig. 7, unit 19) is composed of poorly sorted bioclastic wackestone to rudstone containing large, broken fragments of bivalves. Other skeletons are echinoderms, gastropods, ostracods, foraminiferans (including agglutinated forms), echinoid spines, and dasycladacean algae. A few intraclasts and many detrital quartz grains are present. Locally, the grains are densely packed, grading into packstone. The matrix is micrite.

This basal limestone is overlain by two nodular limestone beds (Fig. 7, units 20, 22, forming recessed notches) alternating with limestone ledges. The microfacies is similar to that of the basal limestone ledge: poorly sorted wackestone to packstone and, in part, floatstone containing fragmented and abraded skeletons. Most abundant are mollusc shell fragments derived from bivalves, gastropods, and echinoderms. Echinoid spines, ostracods, foraminiferans (including some agglutinated forms), and bryozoans are subordinate. Angular to rounded detrital quartz grains, mostly 0.2–0.5 mm in diameter and rarely to 1 mm, and a few micritic intraclasts are present. The grains are embedded in micritic matrix.

Depositional environments

Fossils and sediments of the Del Norte Formation indicate deposition in a shallow, open-marine environment with periodically strong siliciclastic influx. The presence of calcareous algae suggests deposition within the photic zone. Sandstone beds in the lower part displaying horizontal lamination and current ripples are interpreted to represent storm layers. Thin sandstone interbeds displaying horizontal lamination and ripple lamination intercalated in shale of a shallow-marine shelf setting have commonly been attributed to storm activity. Thus, Scott et al. (1975) described similar siltstone to fine-grained sandstone beds 1–10 cm thick in the Washita Group of Texas, which they interpreted as density currents formed by storms, tides, rip flow, or floods. Hobday and Morton (1984) interpreted similar thin sandstone intercalations in the Lower Cretaceous Grayson Formation (Texas) as deposits of strong bottom currents below the storm wave base generated by large-scale, storm-generated, bottom-return flow.

Nodular limestone, which is commonly bioturbated and contains micritic to pelmicitic matrix, formed in a low-energy environment, whereas intercalated limestone beds containing strongly fragmented, locally densely packed mollusc fragments (coquina) indicate deposition under high-energy conditions and may represent storm layers. The sharp contact with the underlying Finlay Formation is interpreted as a transgressive surface, which was followed by deepening upward and a regressive trend in the upper member of the Del Norte Formation, which resulted in the deposition of limestone with abundant coquina storm layers.

Smeltertown Formation

Lithostratigraphy

The Smeltertown Formation of Strain (1976) is mostly gray shale with limestone nodules that forms a relatively thick slope (approximately

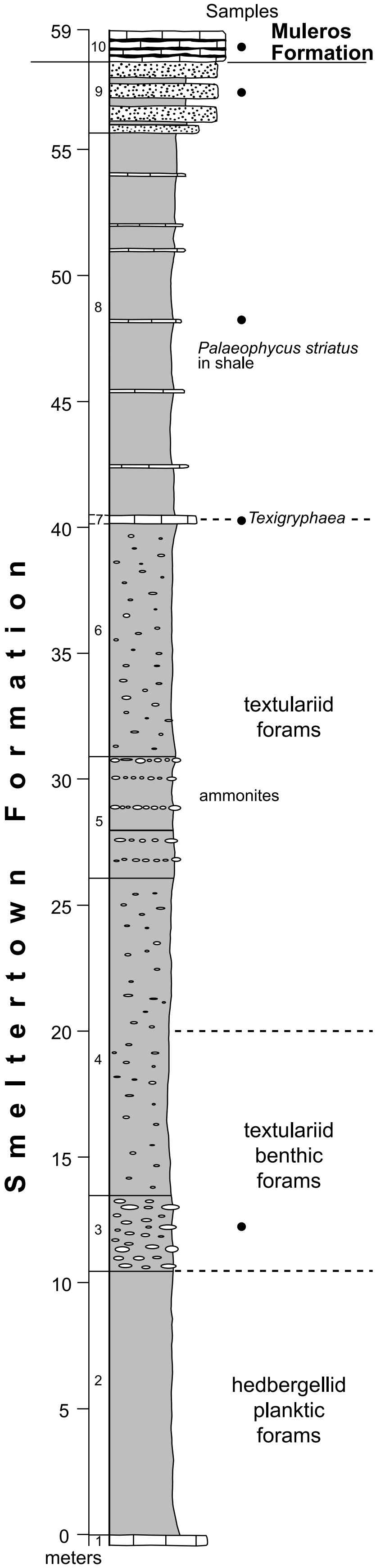

FIGURE 8—Measured stratigraphic section of Smeltertown Formation. See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend. Dashed lines identify the three zones of Bullock and Cornell (1986).

60 m) above the upper member of the Del Norte Formation (Figs. 5C, 8). Our measured section of the Smeltertown Formation (Fig. 8) is the type section of Strain (1976, table 9), which he reported to be approximately 61 m thick. The Smeltertown Formation is subdivision 4 of Böse (1910), which he estimated as 30–50 m thick.

The base of the Smeltertown Formation is dark-colored shale that sits directly on limestone at the top of the Del Norte Formation (Figs. 7–8). In the lower part of the Smeltertown Formation (Fig. 8, unit 3), limestone nodules as much as 20 cm in diameter are in a 3-m-thick shale interval. Sparse limestone nodules are also in shale units 4 and 6. Shale unit 5 contains thin ledges of limestone nodules and a pebbly agate zone near the top. This unit also contains many ammonites, especially specimens of *Mortoniceras equidistans*. The limestone ledge of unit 7 yields many shells of *Texigryphaea*. In unit 8, thin limestone ledges are intercalated in shale. A 2.3-m-thick interval of sandstone ledges, mostly full of abundant tests of the large, arenaceous foraminiferan *Cribratina texana* and intercalated with shale beds (with many horizontal grazing traces of *Palaeophycus striatus*), forms the top of the Smeltertown Formation (Fig. 8). Limestone at the basal Muleros Formation rests with sharp contact on sandstone at the top of the Smeltertown Formation.

Paleontology

The Smeltertown Formation yields fossils of foraminiferans, bivalves, gastropods, ammonoids, bryozoans, crustaceans, ophiuroids, echinoids, brachiopods, and corals (Böse 1910; Strain 1976; Nye and LeMone 1978; Bullock 1985; Bullock and Cornell 1986; Cornell et al. 1991; Turnšek et al. 2003). The foraminiferans establish a robust correlation of the Smeltertown Formation with the Duck Creek Formation of north-central Texas (Bullock and Cornell 1986). Ammonites of the *Mortoniceras equidistans* Zone (present in unit 5 of our measured section; Fig. 8) also correlate the Smeltertown Formation to the lower part of the Mojado Formation (Fryingpan Spring Member) in the Cooke's Range of Luna County, New Mexico (Böse 1910; Cobban 1987; Lucas et al. 1988; Lucas and Estep 1998b, 2000).

Sedimentary petrography (Figs. 8, 18, 19A–D)

Unit 3 in our measured section of the Smeltertown Formation (Fig. 8) is a mixed siliciclastic-carbonate siltstone that is partly laminated and partly bioturbated (Fig. 18A). The siltstone contains as much as 30% detrital quartz grains, abundant carbonate grains, rare glauconite, and micrite. A few large mollusc fragments (bivalves and gastropods) float in the siltstone. Other fossils present are ostracods, a few smaller foraminiferans, rare echinoderms, and echinoid spines.

The nodular limestone ledges of unit 5 of the Smeltertown Formation section (Fig. 8) are composed of bioclastic, mixed siliciclastic-carbonate siltstone, which is partly laminated and partly bioturbated. A few large mollusc shell fragments of bivalves and gastropods float in silty matrix. The siltstone consists of as much as 30% quartz grains, small carbonate grains, a few glauconite grains, and micrite. Bioclasts include abundant ostracods, a few smaller foraminiferans, rare echinoderms, echinoid spines, and shell debris.

The microfacies of the unit 7 limestone ledge (Fig. 8) is fine-grained, bioturbated mixed siliciclastic-carbonate sandstone (Fig. 18B). The sandstone contains abundant detrital quartz grains, mostly 0.2–0.5 mm in diameter, rarely to 1 mm. Most common is monocrystalline quartz, and polycrystalline quartz is subordinate. Rare chert and glauconite grains are present. Quartz grains are surrounded by thin carbonate cement rims. A few micritic intraclasts are present, too. Bioclasts include bivalves, gastropods, echinoderms, ostracods, foraminiferans, and rare worm tubes(?). Litho- and bioclasts float in a micritic matrix.

Thin limestone beds of the uppermost Smeltertown Formation (Fig. 8, unit 8) consist of bioturbated mudstone (Fig. 18C) containing a few siliciclastic grains (mostly quartz, rare chert, and glauconite grains) and bioclasts (mostly ostracods, rare bivalve shells, and echinoderm fragments; probably other skeletons). Siliciclastic grains and bioclasts constitute less than 10% of the rock, and they are locally concentrated due to bioturbation.

The top siltstone to sandstone of the Smeltertown Formation (Fig. 8, unit 9) is fine grained, laminated, and locally bioturbated (Fig. 19A–D). Siliciclastic grains constitute about 50–70% of the rock. Most abundant is detrital quartz, and rare are grains of glauconite, opaque minerals, and micas. A few micritic intraclasts are present. Bioclasts, such as shell fragments, echinoderms, and ostracods, are rare. This facies grades into bioclastic wackestone that contains agglutinated foraminiferans, bivalve fragments, and some other bioclasts embedded in silty, partly peloidal matrix with a few small quartz grains (Fig. 18D–F).

Depositional environments

Dark-colored shale of the Smeltertown Formation is indicative of a muddy marine sea bottom (cf. Scott 1970). From shales of the Smeltertown Formation, Bullock and Cornell (1986) identified 73 species of foraminiferans that belong to the suborders Texturlariina, Miliolina, and Rotaliina and provided some information on the depositional environment. Within the formation they distinguished three zones characterized by distinct assemblages of foraminiferans. Zone 1 (lower 13 m), which correlates with unit 1 of Strain (1976) and with units

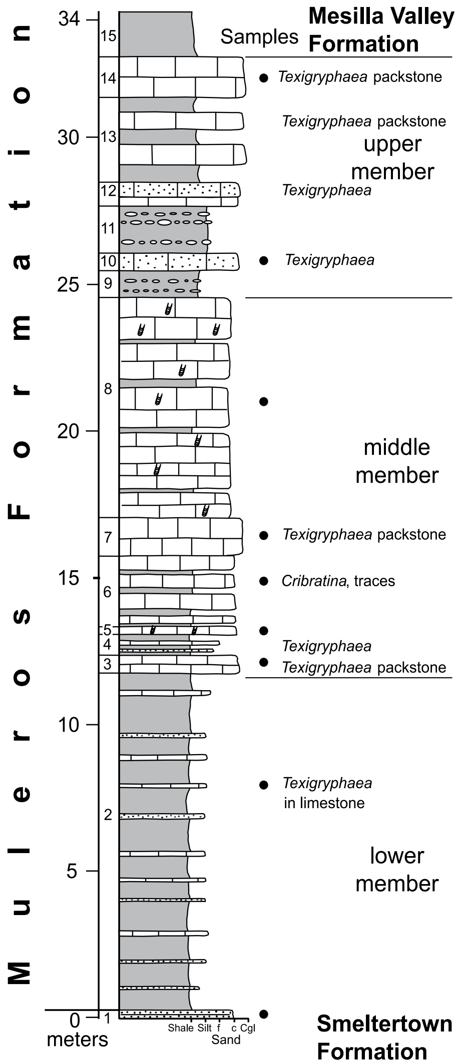

FIGURE 9—Measured stratigraphic section of Muleros Formation. See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend.

1 and 2 of our section (Fig. 8), is characterized by a high abundance of "*Hedbergella" planispira* and the dominance of rotaliine forms, which constitute 45–90% of the individuals. This assemblage indicates deposition in an open, inner-shelf environment with water depths of 50 m or less (Bullock and Cornell 1986).

Zone 2, including unit 2 and the lower 9 m of unit 3 of Strain (1976), which is our unit 3 and part of unit 4 (Fig. 8), is characterized by textulariine forms, which constitute 55–95% of all individuals, with *Cribratina texana* being the most abundant species. The presence of *Ammobaculites* and *Trochammina* is indicative of a shallow, nearshore environment. Bullock and Cornell (1986) concluded that during sedimentation of this interval some shallowing occurred, causing restriction of circulation.

In zone 3, encompassing the upper 24 m of the section (upper 22 m of unit 3 and unit 4 of Strain 1976; upper part of our unit 4 and all of units 5–6; Fig. 8), planktonic foraminiferans are absent, and other rotaliine forms are less abundant than in the underlying strata. Textulariine forms constitute 70% of the tests. Individuals of *Cribratina texana* comprise 60–99% of the specimens, indicating an extremely restricted environment, probably a hypersaline marsh according to Bullock and Cornell (1986), or a shallow, nearshore shelf with possibly lower than normal salinity (R. W. Scott, written comm. 2010).

The foraminiferal assemblages of the shales thus indicate that the Smeltertown Formation represents an upward-shallowing succession from a deeper, open shelf with water depths of approximately 50 m to a shallow restricted shelf environment with increased salinity. Interbedded siltstone, sandstone, and limestone beds in the upper part of the succession may represent storm layers similar to those of the Del Norte Formation.

Muleros Formation

Lithostratigraphy

Our measured section of the Muleros Formation (Fig. 9) is the type section of the formation (Strain 1976, table 10). The Muleros Formation is subdivision 5 of Böse (1910), which he reported as 30–50 m thick; Strain (1976) reported a thickness of 32 m for the formation type section. Our measured section of the Muleros Formation is approximately 33 m thick. The formation generally forms cliffs and ledgy slopes (Fig. 5D), and many of the limestone beds of the middle and upper units are *Texigryphaea* packstones (Figs. 5E and 9).

Following Strain (1976), the Muleros Formation can be divided into three members (Fig. 9). The lower 11–12 m is light-colored shale with some thin, intercalated beds of bioturbated sandstone and limestone with abundant *Texigryphaea*. The limestone is nodules embedded in brownish silty matrix and micrite. The middle part of the Muleros Formation (from 11.5 to 24.3 m) is composed of bioturbated micritic limestone intercalated with thin shale and, in the lower part, thin bioturbated sandstone. The limestone contains *Texigryphaea* and *Cribratina* and is bioturbated. Horizontal, meniscate backfilled burrows are present in unit 5 (Fig. 9). The upper third of the section (approximately 9 m thick) is composed of alternating limestone ledges and shale. Limestone intervals are 0.6–1.4 m thick and consist of floatstone/rudstone and packstone containing *Texigryphaea*. Shale intervals in the upper part are as much as 1.6 m thick. The lower two intercalated shale intervals contain limestone nodules. The base of the Mesilla Valley Formation is a sharp contact of silty shale on *Texigryphaea* packstone at the top of the Muleros Formation (Fig. 9).

Paleontology

The Muleros Formation is very fossiliferous, primarily because of the packstones of the gryphaeid bivalve *Texigryphaea washitaensis* it contains (Böse 1910; Kues 1989). It also yields other bivalves, gastropods, rare ammonoids, common spatangoid echinoderms, foraminiferans (especially the large, arenaceous form *Cribratina texana*), corals, sponge borings, bryozoans, ostracods, and serpulids (Böse 1910; Strain 1976; Kues 1989; Turnšek et al. 2003). Correlation of the Muleros Formation with the Denton and Fort Worth Formations of north-central Texas is supported by stratigraphic position but lacks a robust ammonite biostratigraphic basis (Scott et al. 2003).

Sedimentary petrography (Figs. 9, 19E–F, 20, 21)

The uppermost bed of the Smeltertown Formation (Fig. 8, unit 9) is a quartzose siltstone to fine-grained sandstone that is heavily bioturbated and partly laminated. Most abundant are monocrystalline quartz grains; chert, carbonate grains, opaque minerals, and glauconite are rare. Small bioclasts including shell debris, ostracods, echinoderms, and a few large bivalve shells float in siltstone to fine-grained sandstone. The rock is cemented by quartz overgrowths, rarely by calcite cement.

The limestone beds in the lower part of the Muleros Formation (Fig. 9, unit 2) are gray, bioturbated, fine grained, and composed of abundant peloids, a few detrital quartz grains, and bioclasts such as echinoderms, echinoid spines, ostracods, and a few smaller foraminiferans. The matrix is micrite. The limestone in the middle part of the Muleros Formation (Fig. 9, units 3–8) is mainly composed of bioclastic wackestone to packstone (Fig. 20D), and subordinately mudstone and floatstone to rudstone.

The bioclastic wackestone is fine to coarse grained, poorly sorted, commonly bioturbated, and locally laminated. Abundant fossils are large gryphaeid bivalve shells, subordinate gastropods, echinoderms, corals, smaller foraminiferans (including large agglutinated forms), ostracods, and echinoid spines. A few glauconite grains are present. Locally, peloids and detrital quartz grains are present (Fig. 19E, F; Fig. 20A, B, F).

The bioclastic mudstone is bioturbated and contains as much as about 5% detrital quartz grains and rare glauconite (Fig. 20E). Fossils such as smaller foraminiferans (including rare, larger agglutinated forms), rare ostracods, echinoderms, echinoid spines, and other skeletons are floating in micrite. The following foraminiferans are present in the limestone: *Ammobaculites*, Ataxophragmiidae, and *Nodosaria*.

The bioclastic siltstone to mudstone (Fig. 9, unit 4) is nonlaminated and bioturbated (Fig. 20C). Many small and a few larger bioclasts (echinoderms, ostracods, bivalve shell fragments, rare smaller foraminiferans,

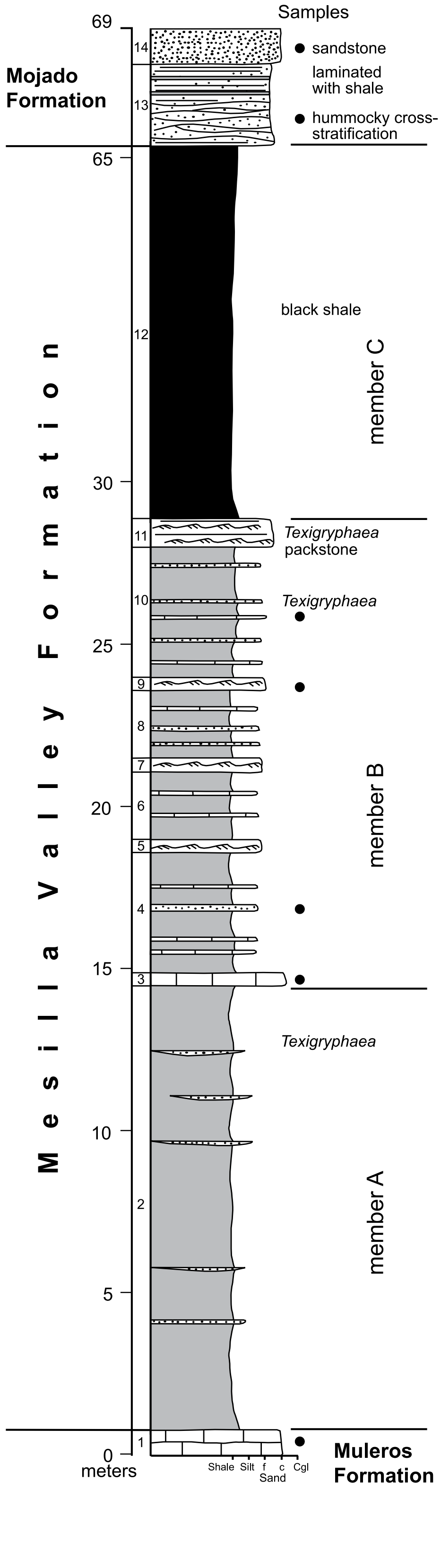

FIGURE 10—Measured stratigraphic section of Mesilla Valley Formation. See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend.

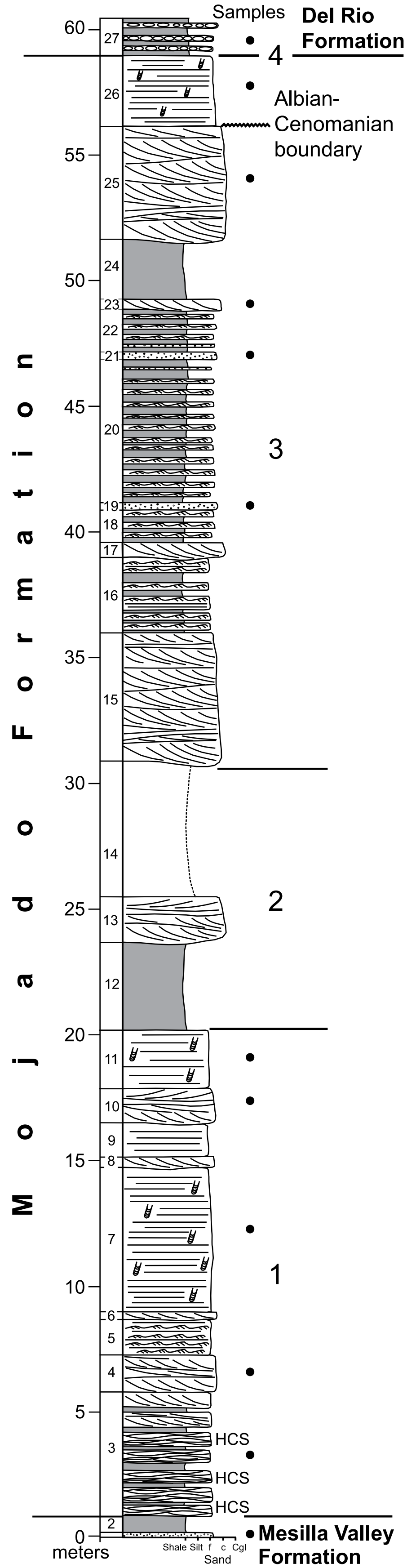

FIGURE 11—Measured stratigraphic section of Mojado Formation ("Anapra Sandstone"). See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend. HCS=hummocky cross-stratification.

corals, and bryozoans) float in a silty to micritic matrix. Peloids (fecal pellets?) are locally present, as are small quartz grains (< 5%).

The floatstone to rudstone (Fig. 9, unit 7) is nonlaminated, poorly sorted, and contains abundant shell fragments of gryphaeids and gastropods (Fig. 21A–B). Many large agglutinated foraminiferans are also present. These foraminiferans include rare agglutinated smaller foraminiferans. Echinoderm fragments, ostracods, smaller foraminiferans, and shell debris are subordinate. A few mollusc shell fragments are encrusted by worm tubes. The matrix is gray peloidal micrite containing a few small quartz grains.

The limestone of unit 8 (Fig. 9) is fine-grained, bioturbated wackestone (Fig. 21C) containing abundant small bioclasts such as ostracods, echinoderms, smaller foraminiferans, mollusc shell debris, and rare larger skeletons of gastropods, echinoderms, and bivalves. The matrix is peloidal micrite containing a few quartz grains and rare glauconite.

Unit 10 of our Muleros Formation section (Fig. 9) is a bioturbated floatstone-rudstone, containing abundant bivalve (*Texigryphaea*) and gastropod shell fragments, many agglutinated foraminiferans, echinoderms, and rare corals (Fig. 21D–E). Smaller foraminiferans, ostracods, and echinoid spines are subordinate. A few skeletons are encrusted by worm tubes. The micritic matrix contains a few angular quartz grains and rare glauconite.

The uppermost limestone interval of the Muleros Formation (Fig. 9, units 13–14) is a packstone–rudstone (Fig. 21F) composed of densely packed bivalve shell fragments that are oriented more or less parallel to the bedding plane. Other bioclasts, such as echinoderms, ostracods, and smaller foraminiferans, are rare. The matrix is siltstone containing abundant angular quartz grains and rare glauconite grains. Locally, some calcite cement is present ("umbrella" porosity). The peloidal wackestone (pelmicrite; Fig. 9, unit 14) is laminated and consists of abundant small peloids, mostly around 0.05 mm in size and a few peloids as large as 0.25 mm in diameter. Bioclasts such as ostracods and foraminiferans are rare. The floatstone–rudstone of the upper part is poorly sorted, nonlaminated, partly bioturbated, and contains abundant large gryphaeid and gastropod shell fragments. A few shells display borings and are encrusted by annelid worms (serpulid worm tubes). Other bioclasts include echinoderms, echinoid spines, ostracods, foraminiferans (*Lenticulina*), rare corals, and bryozoans(?). Locally, agglutinated foraminiferans are common. The rock contains many detrital angular quartz grains and a few glauconite grains. The matrix is micrite.

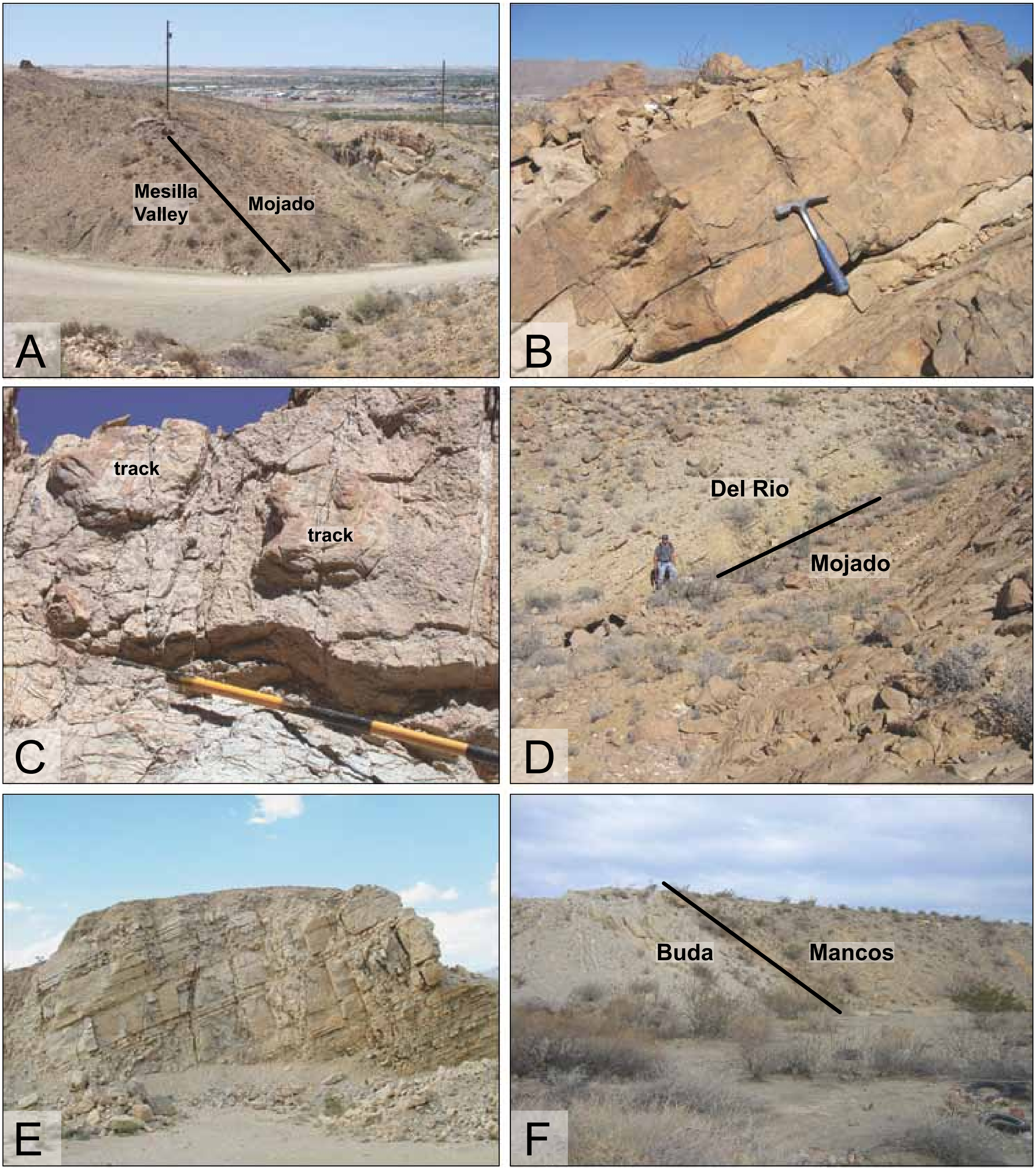

FIGURE 12—Photos of Cretaceous outcrops at Cerro de Cristo Rey. **A**—Outcrops of Mojado Formation overlying Mesilla Valley Formation (Fig. 10). **B**—Characteristic crossbedded sandstone of Mojado Formation. **C**—Dinosaur footprints (ornithopod tracks) in Mojado Formation. Divisions of measuring stick = 0.25 m. **D**—Base of Del Rio Formation on Mojado Formation (Figs. 11 and 13). **E**—Overview of Buda Formation measured section (Fig. 14). **F**—Contact of Buda and Mancos Formations at measured section (Fig. 15).

Depositional environments

Muleros strata also demonstrate an apparent upward-shallowing trend. Thus, lower, shale-dominated strata are relatively deeper marine deposits (though still shallow), whereas *Texigryphaea* packstones and intercalated bioturbated limestones and sandy limestone of the middle-upper Muleros (Fig. 9) suggest shallow, carbonate shelf deposition with some coarse clastic influx (cf. Turnšek et al. 2003).

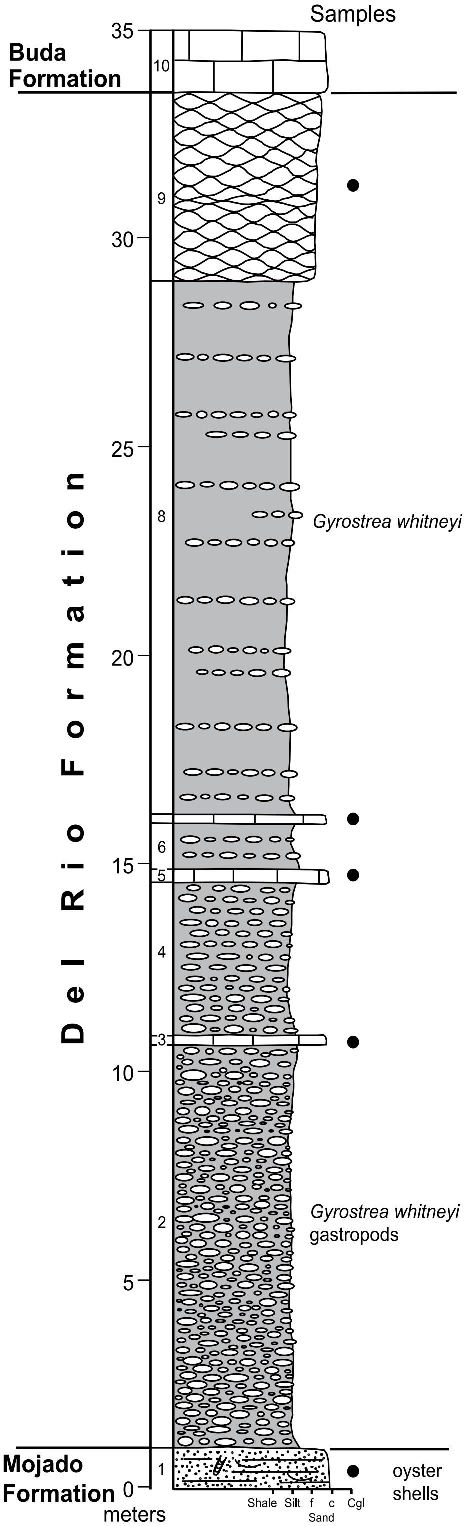

FIGURE 13—Measured stratigraphic section of Del Rio Formation. See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend.

The lower part of the Muleros Formation is mainly composed of shale that accumulated on the shelf in areas deeper than storm-induced currents. Intercalated thin sandstone beds probably formed during storms that resulted in the remobilization of coarser material and their basinward transport and deposition as density current deposits (cf. Scott et al. 1975; Hobday and Morton 1984).

The middle part of the Muleros Formation (Fig. 9, units 3–8) is dominated by different types of limestone containing a fossil assemblage suggesting a shallow-marine setting. Micritic types such as mudstone and wackestone accumulated in shallow, quiet water, where currents were not strong enough to remove the mud. Intercalated floatstone to rudstone, commonly developed as coquinas containing abundant complete and broken gryphaeid bivalve shells, are interpreted to represent storm deposits. Such storm layers with abundant gryphaeid shells are also present in the upper third of the formation, where they are intercalated with fossiliferous shale deposited under low-energy conditions. Deposition of the upper part of the Muleros thus was also in a shallow-marine setting, but one with more storm deposits than in the middle member.

The Muleros Formation succession thus indicates an outer-shelf environment with dominantly shale during deposition of the lower part, followed by some shallowing and deposition of dominantly limestone in an inner-shelf environment periodically affected by storms, and again some deepening resulting in increased deposition of shale with intercalated storm layers in the upper part.

Mesilla Valley Formation

Lithostratigraphy

The Mesilla Valley Formation is a slope-forming, shale-dominated unit approximately 65 m thick at our measured section (Figs. 5F, 10). This is subdivision 6 of Böse (1910), who indicated it is more than 20 m thick. Our measured section is the type section of the Mesilla Valley Shale of Strain (1976, table 11), who indicated it is 64 m thick.

Strain (1976) divided the Mesilla Valley Formation into two units, a lower shale (59–60 m thick) and an upper sandstone and shale (4–5 m thick). However, like the underlying Muleros Formation, we divide the Mesilla Valley Formation into three informal members (Fig. 10). The lower member (member A) is 13.7 m thick and consists of gray shale with some very thin sandstone lenses. The middle member (member B) is 14.4 m thick. Its base is a 0.4-m-thick ledge-forming limestone that contains *Texigryphaea*. The limestone bed is overlain by olive shale with thin, fine-grained sandstone ledges and three thicker, siltstone-sandstone intervals (each 0.4 m thick) that display ripple lamination. Locally, the sandstone contains shell debris and serpulids, and the thin sandstone beds contain *Texigryphaea* (upper part). The upper member (member C) is black shale forming a thick slope (36.5 m). The black shale is sharply overlain by coarse clastic sediments (sandstone) at the base of the Mojado Formation ("Anapra Sandstone" of Strain).

Paleontology

Böse (1910) referred to the Mesilla Valley Formation as the "capas con [beds with] *Ostrea quadriplicata* [now *Peilinia quadriplicata*: Kues 1997]," and most (or all?) fossils of this taxon appear to derive from member B of the Mesilla Valley Formation (Fig. 10). The Mesilla Valley Formation yields a profuse assemblage of gryphaeid bivalves (*Texigryphaea*) as well as other bivalves, gastropods, ammonoids, brachiopods, foraminiferans (particularly *Cribratina texana*), dinoflagellates, echinoids, serpulid worms, corals, ostracods, echinoderms, calcareous algae, and some terrestrial plant fragments (Böse 1910; Strain 1976; Cornell 1982; Kues 1989, 1997; Turnšek et al. 2003). Correlation of the Mesilla Valley Formation with the Weno and Pawpaw Formations (Scott et al. 2003) is based more on stratigraphic position than on precise biostratigraphy, although the presence of the bivalve *Peilinia quadriplicata* in the Mesilla Valley Formation, also known from the Denton–Main Street interval in north-central Texas (Scott et al. 2003, p. 315), does support the Weno–Pawpaw correlation.

Sedimentary petrography (Figs. 10, 22)

The lower part of the Mesilla Valley Formation (member A) is gray shale with a few thin sandy lenses. The microfacies of the limestone at the base of member B (Fig. 10, unit 3) is bioclastic rudstone–packstone (Fig. 22A–B) composed mainly of large, broken bivalve fragments. Subordinate large agglutinated foraminiferans (Fig. 22C), echinoderms, ostracods, and rare smaller foraminiferans are present. The matrix is silty and contains abundant small, angular quartz grains. The large shell fragments are randomly oriented parallel to the bedding plane.

The siltstone of unit 4 at the base of member B (Fig. 10) is laminated, mixed siliciclastic-carbonate and contains rare bioclasts. The most abundant grain type is quartz, and carbonate grains are also present. Bioclasts include ostracods, echinoderms, foraminiferans, and shell debris. Glauconite grains are common.

In member B, the ripple-laminated siltstone of unit 9 (Fig. 10) is partly bioturbated and contains small and some larger bioclasts floating in the silty matrix. Larger bioclasts are bivalve shell fragments, agglutinated foraminiferans, and rare solitary corals (Fig. 22D). Small bioclasts include ostracods, gastropods, small foraminiferans, shell debris, and rare phosphatic fragments. The silty matrix is composed of 70–80% small angular quartz grains, about 2% glauconite, and a few micas in micritic matrix.

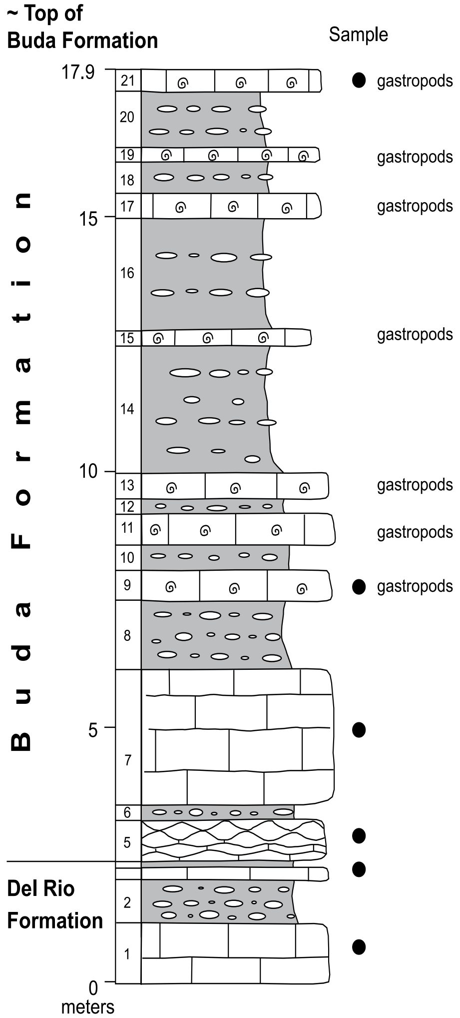

FIGURE 14—Measured stratigraphic section of Buda Formation. See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend.

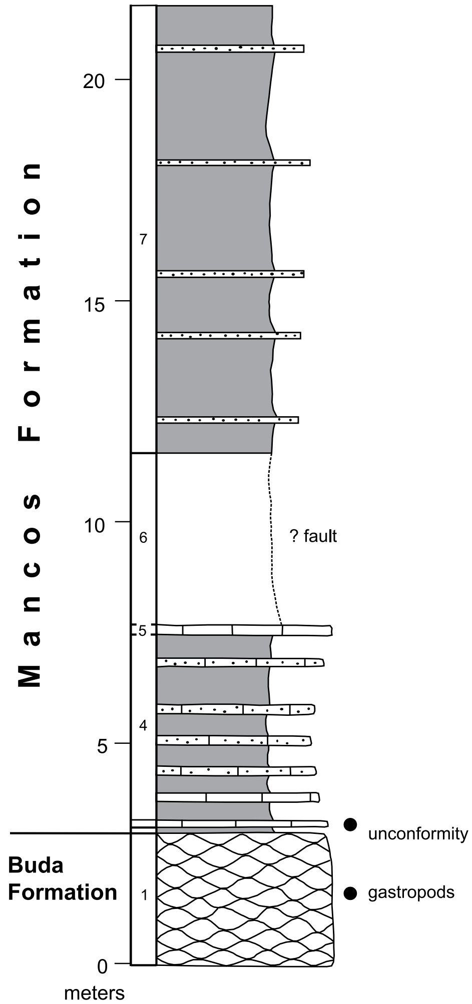

FIGURE 15—Measured stratigraphic section of Mancos Formation ("Boquillas Formation"). See Figure 2 and Appendix for location of section, and Figure 6 for lithology legend.

A thin limestone bed intercalated in unit 10 (Fig. 10) is bioturbated bioclastic wackestone containing a few larger and many small bioclasts floating in micritic matrix (Fig. 22E). Bioclasts include mollusc shell debris (bivalves, gastropods), calcareous algae, worm tubes (Fig. 22F), ostracods, echinoderms, smaller foraminiferans, agglutinated foraminiferans, and echinoid spines. The matrix is micrite and pelmicrite. The top of member B (Fig. 10, unit 11) is formed by a fine-grained sandstone interval 0.9 m thick displaying ripple lamination and containing *Texigryphaea* (packstone). Member C is black shale with no obvious fossil content.

Depositional environments

The shale-dominated Mesilla Valley Formation (Fig. 10) mostly represents deposition on muddy marine sea bottoms below wave base. The lower part of the formation (member A, Fig. 10) is mostly shale with a few thin sandstone lenses, and this appears to represent relatively deep water. The dark shale with intercalated thin sandstone lenses of the lower member is interpreted to record deposition in an outer-shelf environment, which was only rarely affected by storms. The thin intercalated sandstones may represent distal storm layers. Intercalated rudstone to packstone beds (shell coquinas) and ripple-laminated sandstone beds containing fossils such as *Texigryphaea* represent typical storm deposits.

Overlying shale with interbedded *Texigryphaea* packstones and ripple-laminated sandstones (member B) indicate a distinct shallowing. Storm layers are more abundant in member B than in the members below and above, indicating that some shallowing occurred during deposition of the middle member (Fig. 10).

The upper part of the formation (member C) is black shale, which we interpret as relatively offshore marine deposits. Deposition of the organic-rich black shale of member C apparently occurred in a poorly oxygenated environment, which may indicate relatively deep water.

Mojado Formation

Lithostratigraphy

Our measured section of the Mojado Formation (Figs. 11, 12A–D) is the type section of the Anapra Sandstone of Strain (1976, table 12), which he reported as approximately 53 m thick. Here, the Mojado Formation is a sandstone-dominated unit as much as 58 m thick (Figs. 5F, 11, 12A–D). It rests with sharp contact on shale at the top of the Mesilla Valley Formation (Figs. 5F, 11, 12A) and is sharply overlain by shale and nodular limestone at the base of the Del Rio Formation (Fig. 12D).

The topmost bed of the Mesilla Valley Formation at our Mojado Formation section (Fig. 11) is reddish-brown shale/siltstone containing abundant quartz, some chert grains, and rare glauconite. The matrix (or cement) is dark brown (iron stained). Strain (1976, p. 81) stated that "the base of the Anapra [Mojado] is the lowest sandstone stratum 30 cm thick or more just above the thinly bedded sandstone beds at the top of the Mesilla Valley Shale." Thus, he included our basal beds of the Mojado Formation (Fig. 10, unit 13; Fig. 11, unit 3) in the Mesilla Valley Formation. Instead, we draw the base of the Mojado Formation at the base of the first traceable sandstone bed of typical Mojado lithology.

The Mojado Formation is entirely siliciclastic, being composed of different types of sandstone with intercalated gray and black (locally lignitic) shale. A covered interval (5.4 m) is in the middle of the succession. Sandstone intervals are as much as 5.7 m thick, and shale intervals are as much as 3.5 m thick. The following lithofacies are recognized: (1) thin, fine-grained sandstone beds displaying hummocky cross-stratification form the lowermost 4.9 m of the succession (lower ¾ of unit 3); the sandstone beds are interbedded with green shale; (2) iron-mottled, hackly sandstone, which is bioturbated and has Liesegang banding (units 7, 11); (3) thin, fine-grained sandstone with ripple lamination (units 16–22); (4) thin, medium-grained sandstone with trough crossbedding (units 4, 6, 8, 10, 17); and (5) thicker, multistoried sandstone beds with larger-scale trough crossbedding (units 13, 15, 25).

Trough crossbedded sandstone intervals are characterized by erosive lower contacts (e.g., Fig. 12B). Several upward-fining and thinning cycles are developed. Each cycle starts with trough crossbedded sandstone, grading into fine-grained, ripple-laminated sandstone with shale interbeds, and the tops of a few cycles are formed by shale. Hummocky cross-stratification is only observed in the lowermost sandstone beds. Nevertheless, marine fossils and marine bioturbation

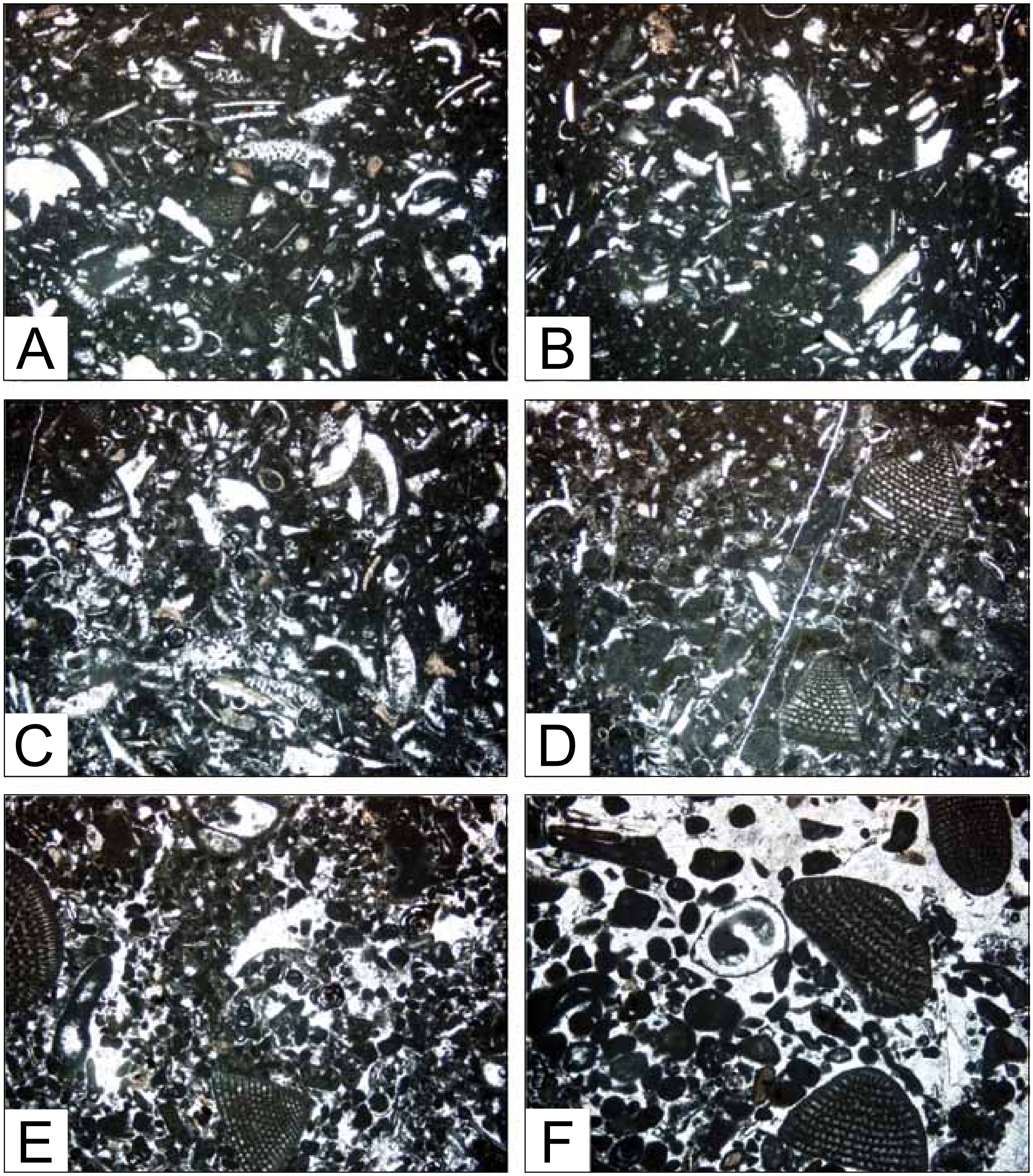

FIGURE 16—Thin section photographs of microfacies of the Finlay Formation at Cerro de Cristo Rey (Fig. 6). Sample numbers correspond to unit numbers in Figure 6. **A**—Bioclastic wackestone containing abundant broken fragments of recrystallized calcareous algae, molluscs, some echinoderm fragments, and foraminiferans in micritic matrix. Sample A24. **B**—Bioclastic wackestone containing abundant fragments of dasycladacean algae, mollusc (bivalve) fragments, and some echinoderms floating in micritic matrix. Sample A27. **C**—Fine-grained bioclastic wackestone–packstone with abundant fragments of recrystallized dasycladacean algae, molluscs, echinoderms, and a few foraminiferans. Matrix is gray micrite. Sample A26. **D**—Packstone containing abundant peloids, smaller foraminiferans including dictyoconid forms, fragments of dasycladacean algae, and molluscs and some micritic matrix. Sample A10. **E**—Packstone–grainstone containing abundant peloids, some orbitolinoid foraminiferans (*Dictyoconus*), and mollusc shell debris cemented by calcite. Sample A10. **F**—Grainstone composed of abundant peloids, some orbitolinoid foraminiferans (*Dictyoconus),* and other bioclasts including gastropods and echinoderms, cemented by calcite. Sample A10. Width of photographs is 6.3 mm.

are present in the upper few meters of the Mojado Formation, and we identify a clear break (transgressive surface) approximately 3 m below its top (base of unit 26, Fig. 11).

Strain (1976) divided the Mojado (his "Anapra") Formation into four units, and Lovejoy (1976) recognized five units. We believe our measured section can be readily divided into at least four intervals: (1) lower beds with marine bioturbation and intercalated shale (Fig. 11, units 3–11), (2) middle, slope-forming interval of mostly siltstone and shale (Fig. 11, units 12–14); (3) upper interval of crossbedded sandstones (Fig. 11, units 15–25); and (4) uppermost interval with marine fossils and bioturbation (Fig. 11, unit 26). However, more subdivisions are possible, though they are of little stratigraphic significance.

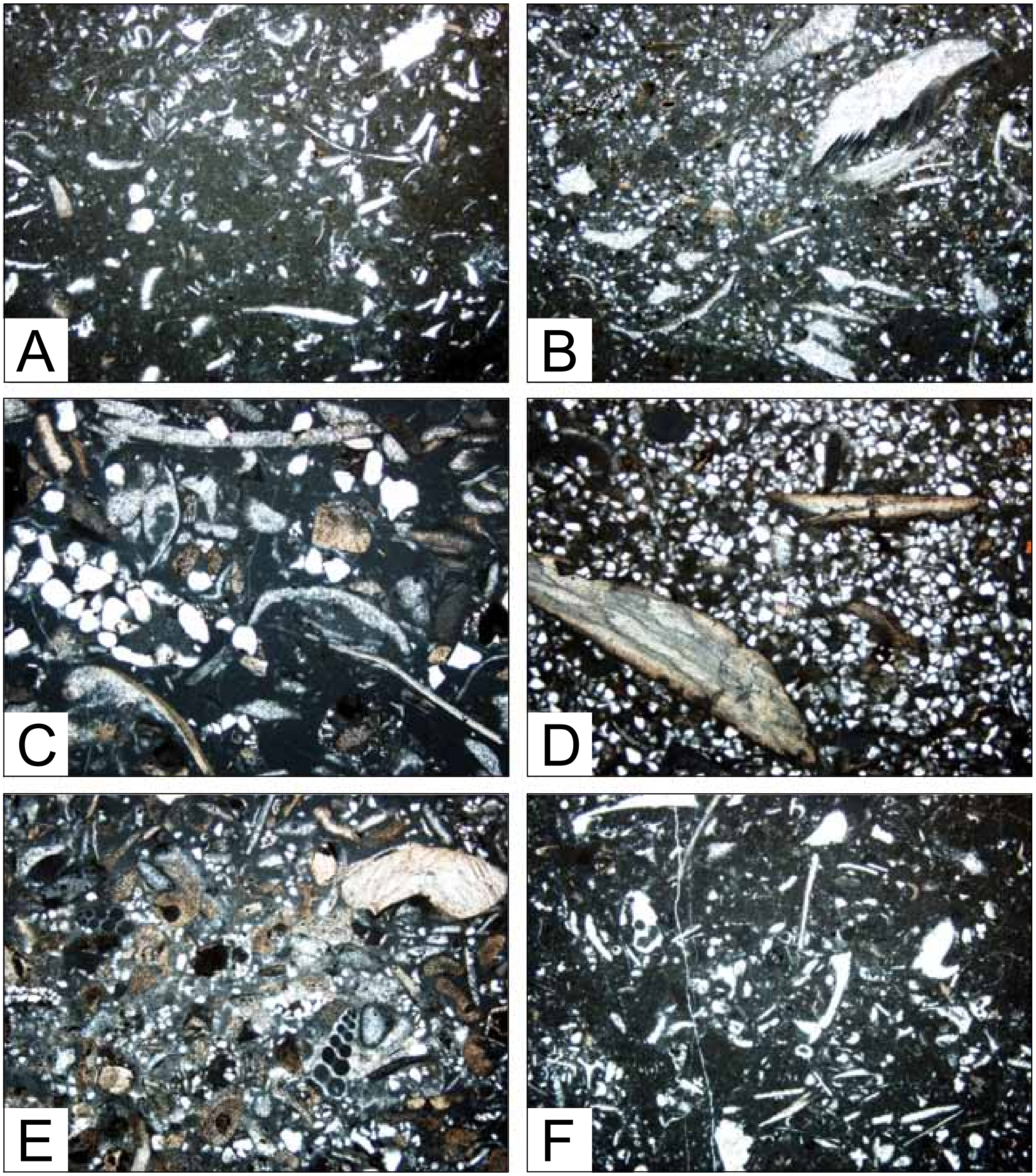

FIGURE 17—Thin section photographs of microfacies of the Del Norte Formation at Cerro de Cristo Rey (Fig. 7). Sample numbers correspond to unit numbers in Figure 7. **A**—Bioclastic wackestone containing abundant algal fragments and mollusc (bivalve) shell debris, a few foraminiferans, and echinoderms in gray micrite. Sample B2. **B**—Mixed carbonate-siliciclastic siltstone containing abundant angular quartz grains and bioclasts such as recrystallized bivalve shell fragments (?oysters), some echinoderms, and micrite. Sample B8. **C**—Wackestone–packstone composed of echinoderms, mollusc shell fragments, and quartz grains floating in micrite. Sample B9. **D**—Mixed siliciclastic-carbonate fossiliferous siltstone containing a few mollusc shell fragments and rare echinoderms. Sample B16. **E**—Bioclastic wackestone–packstone containing abundant mollusc (bivalve) shell fragments (mainly derived from bivalves), subordinate echinoderms, small quartz grains, and a few micritic intraclasts in micritic matrix. Sample B22. **F**—Fine-grained bioclastic wackestone with many mollusc (bivalve) shell fragments and dasycladacean algae, with subordinate echinoderms in micritic, partly peloidal matrix. Sample B19. Width of photographs is 6.3 mm, but for Fig. C is 3.2 mm.

We propose that at Cerro de Cristo Rey the name Anapra Formation be replaced by Mojado Formation. To the west and northwest of Cerro de Cristo Rey, rocks that straddle the Albian–Cenomanian boundary are assigned to the Mojado Formation of Zeller (1965). At the type section, in the Big Hatchet Mountains of Hidalgo County, New Mexico, the Mojado Formation is approximately 1,500 m of sandstone, shale, and minor limestone that overlies the Aptian–Albian U-Bar Formation (Zeller 1965). In the Cooke's Range of Luna County, approximately 120 km northwest of Cerro de Cristo Rey, the Mojado Formation is divided into three members (Lucas and Estep 1998b): (1) Fryingpan Spring Member, approximately 22 m of sandstone, siltstone, shale, and nodular limestone that includes fossils of the ammonoid *Mortoniceras equidistans* (Cragin) (Cobban 1987; Lucas et al. 1988); (2) Sarten Member,

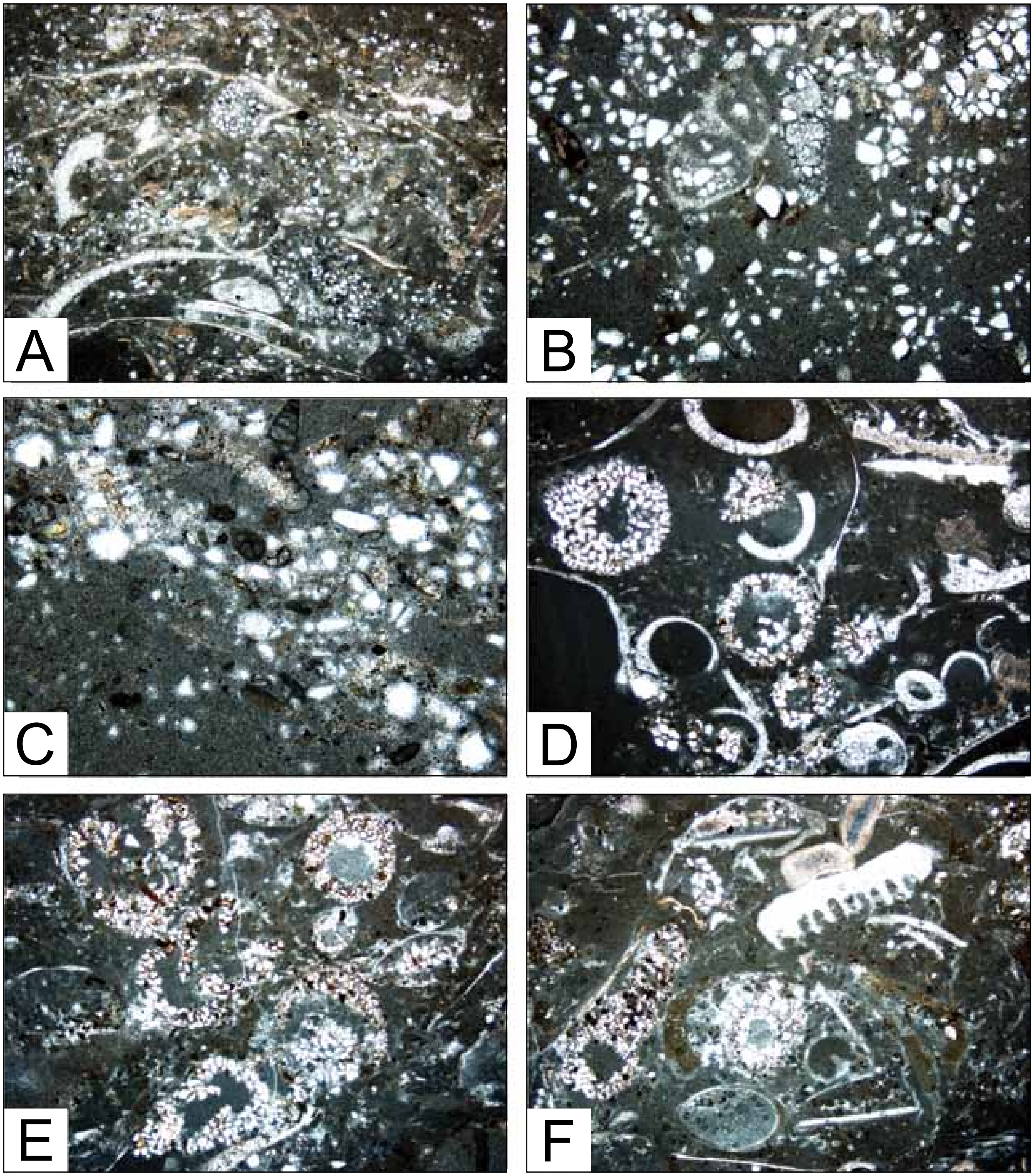

FIGURE 18—Thin section photographs of microfacies of the Smeltertown Formation at Cerro de Cristo Rey (Fig. 8). Sample numbers correspond to unit numbers in Figure 8. **A**—Mixed fossiliferous carbonate-siliciclastic siltstone containing some large mollusc (bivalve) fragments, a few ostracods and foraminiferans, and as much as 30% detrital quartz grains. Sample E3. **B**—Fine-grained, mixed siliciclastic-carbonate sandstone composed of detrital quartz grains, a few glauconite grains, and a few bioclasts (bivalves, gastropods, echinoderms, foraminiferans) floating in micrite. Sample E7. **C**—Mudstone containing some quartz grains and few bioclasts. Sample E8. **D**–**F**—Bioclastic wackestone containing agglutinated foraminiferans (*Cribratina*) and bivalve fragments, and, subordinately, other bioclasts such as ostracods embedded in silty, partly peloidal matrix containing a few small quartz grains. Sample E9. Width of photograph C is 3.2 mm, and of all other photographs is 6.3 mm.

approximately 58 m of sandstone and siltstone of nonmarine origin; and (3) Rattlesnake Ridge Member, approximately 6 m of silty sandstone, siltstone, and nodular limestone that yields a bivalve fauna of earliest Cenomanian age (Lucas et al. 1988). Sandstone and siltstone of the Sarten Member are lithologically very similar to the "Anapra Sandstone," and the biostratigraphy supports a reasonably close correlation (Fryingpan Spring Member correlates to the Smeltertown Formation, and Rattlesnake Ridge Member correlates to the Del Rio Formation; Lucas et al. 1988). Thus, the "Anapra Sandstone" is seen by us as a tongue of the Bisbee Group (Mojado Formation) present in the Cretaceous section of Cerro de Cristo Rey. We therefore abandon the local name Anapra (of Strain 1968, 1976) in favor of the older name of a more regional stratigraphic unit (Mojado of Zeller 1965).

Paleontology

The Mojado Formation ("Anapra Sandstone") at Cerro de Cristo Rey contains dinosaur footprints and plant debris in its

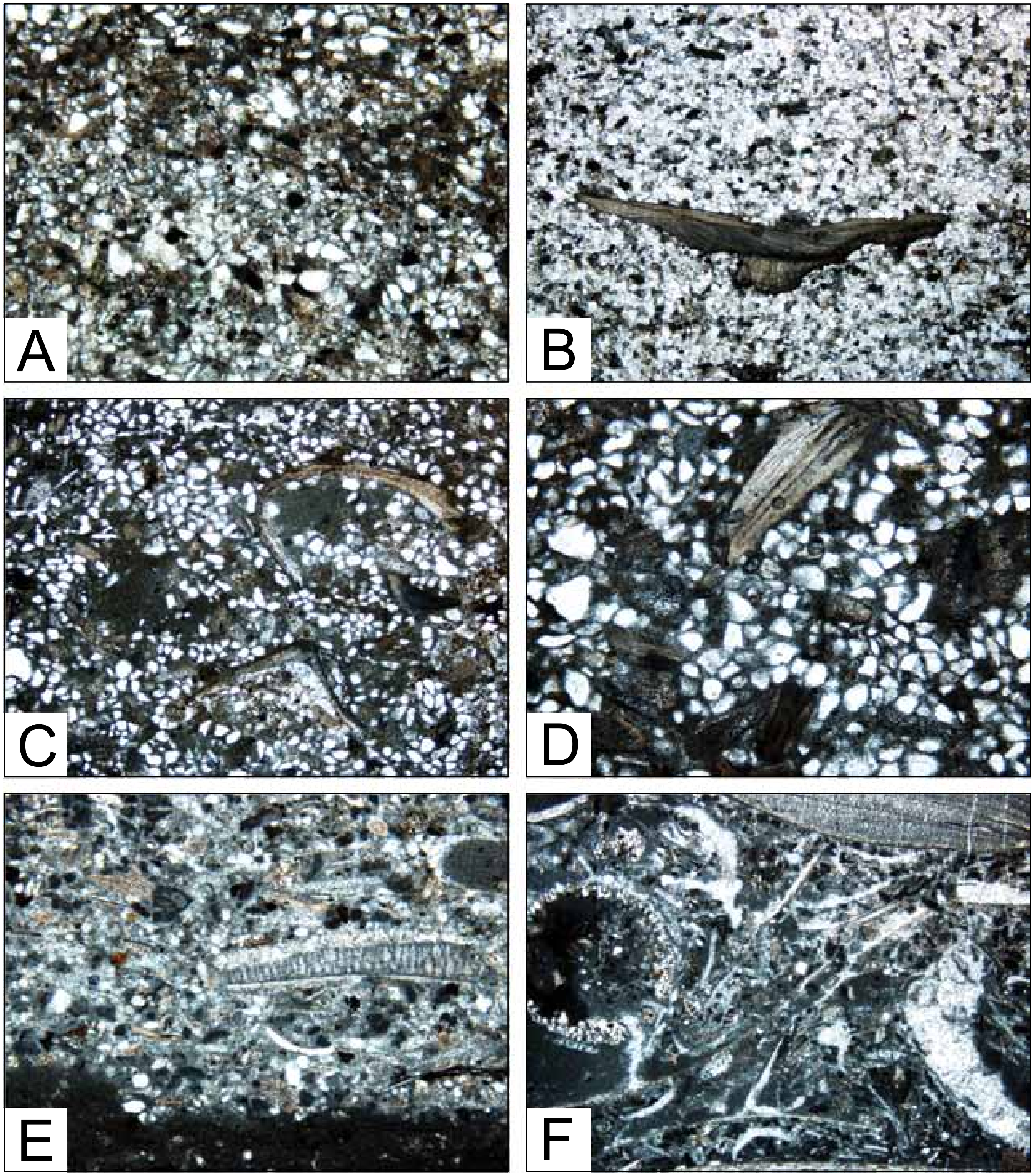

FIGURE 19—Thin section photographs of microfacies of the Smeltertown Formation (A–D) and Muleros Formation (E–F) at Cerro de Cristo Rey (Figs. 8–9). Sample numbers correspond to unit numbers in Figures 8 and 9. **A**—Mixed siliciclastic-carbonate siltstone containing a few glauconite grains and rare bioclasts such as ostracods and echinoderms. Sample E9. **B**—Quartzose siltstone with a few carbonate grains, rare glauconite, and few large bivalve fragments. The siltstone is cemented by quartz (authigenic overgrowths) and rare calcite cement. Sample E10. **C**–**D**—Mixed siliciclastic-carbonate siltstone to fine-grained sandstone containing some bivalve shell fragments and echinoderms. Sample F1. **E**—Fine-grained bioclastic wackestone–packstone overlying gray mudstone. Wackestone–packstone contains bivalve shell fragments, echinoderms, ostracods, a few smaller foraminiferans, peloids, and a few small quartz grains. Sample F2. **F**—Coarse-grained bioclastic wackestone, partly floatstone, containing abundant bivalve shell fragments (*Texigryphaea*), subordinate gastropods, echinoderms, foraminiferans, few peloids, and quartz grains in micritic matrix. Sample F3. Width of photograph D is 3.2 mm, and of all other photographs is 6.3 mm.

lower to middle portions, as well as some marine fossil fragments and tests of the large arenaceous foraminiferan *Cribratina texana*. The dinosaur tracks are primarily those of ornithopods and theropods (Fig. 12C; e.g., Kappus et al. 2003; Kappus 2007) and provide strong evidence of subaerial, terrestrial conditions during deposition of part of the Mojado Formation, but are not of precise biostratigraphic significance. The upper 3 m of the Mojado (unit 26) contain fossils of the large exogyrid bivalve *Gyrostrea whitneyi* (known from the Del Rio Formation in north-central Texas) as well as echinoids and agglutinated foraminiferans (Böse 1910; Strain 1976; Turnšek et al. 2003). We also observed dasycladacean algae, foraminiferans, echinoderms, and ostracods in thin section (Fig. 23E).

Strain (1976) placed the base of the Cenomanian at the base of the "Anapra

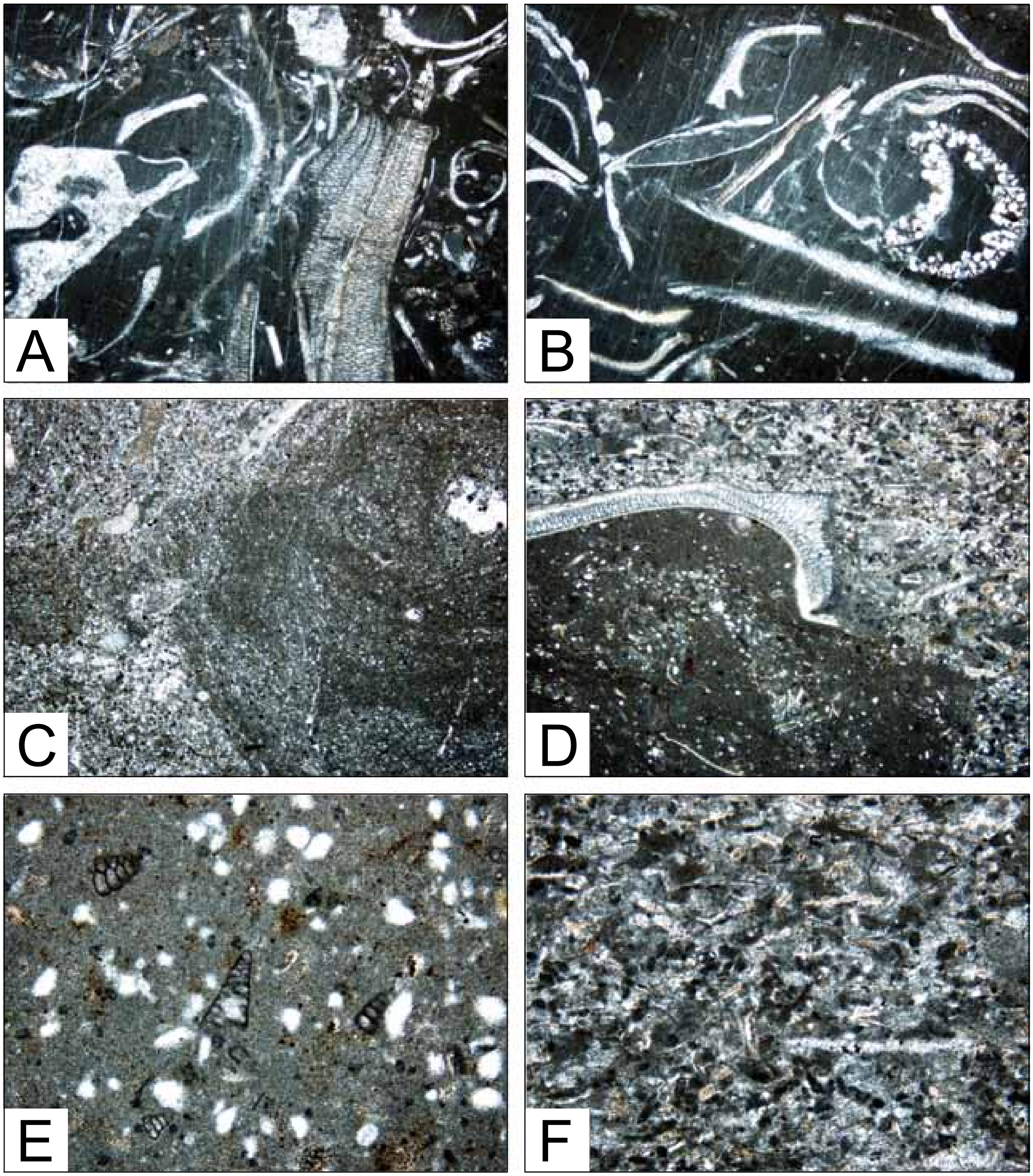

FIGURE 20—Thin section photographs of microfacies of the Muleros Formation at Cerro de Cristo Rey (Fig. 9). Sample numbers correspond to unit numbers in Figure 9. **A–B**—Bioclastic wackestone to floatstone containing abundant bivalve shell fragments (*Texigryphaea*), subordinate gastropods, echinoderms, and foraminiferans, including large agglutinated forms in micritic matrix. Sample F3. **C**—Bioturbated siltstone–mudstone containing a few bioclasts (bivalve shell fragments, echinoderms, ostracods) that float in matrix. Sample F3. **D**—Fine-grained wackestone–packstone with a few large bivalve fragments and many small bioclasts, peloids, and some detrital angular quartz grains in micritic matrix. Sample D5. **E**—Mudstone containing quartz grains and smaller textulariid foraminiferans floating in micrite. Sample F5. **F**—Fine-grained wackestone–packstone containing abundant peloids, a few detrital quartz grains, shell debris, echinoderms, smaller foraminiferans, and ostracods. Sample F6. Width of photographs A–D is 6.3 mm, and of E–F is 3.2 mm.

Sandstone," and Lucas and Estep (1998b, 2000) placed it at the base of the Del Rio Formation. Given that in the regional Washita Group section, the base of the Cenomanian is a sequence boundary at the base of the WA6 cycle of deposition, the Albian–Cenomanian boundary is most likely at the marine transgressive surface that is approximately 3 m below the Mojado–Del Rio contact (Turnšek et al. 2003; Scott et al. 2003) (Fig. 11).

Sedimentary petrography (Figs. 11, 23C–F)

Sandstone of the Mojado Formation is fine- (0.1–0.3 mm) to medium-grained (0.2–0.5 mm) quartz arenite, nonlaminated, and well sorted (Fig. 23C–D). Grains are mostly subrounded to rounded, although many grains display authigenic overgrowths that are not always easy to recognize. The most common grain type is monocrystalline quartz. Subordinate chert grains are present, perhaps of volcanic origin. Polycrystalline quartz of metamorphic origin including stretched metamorphic grains is rare. Detrital feldspars are very rare

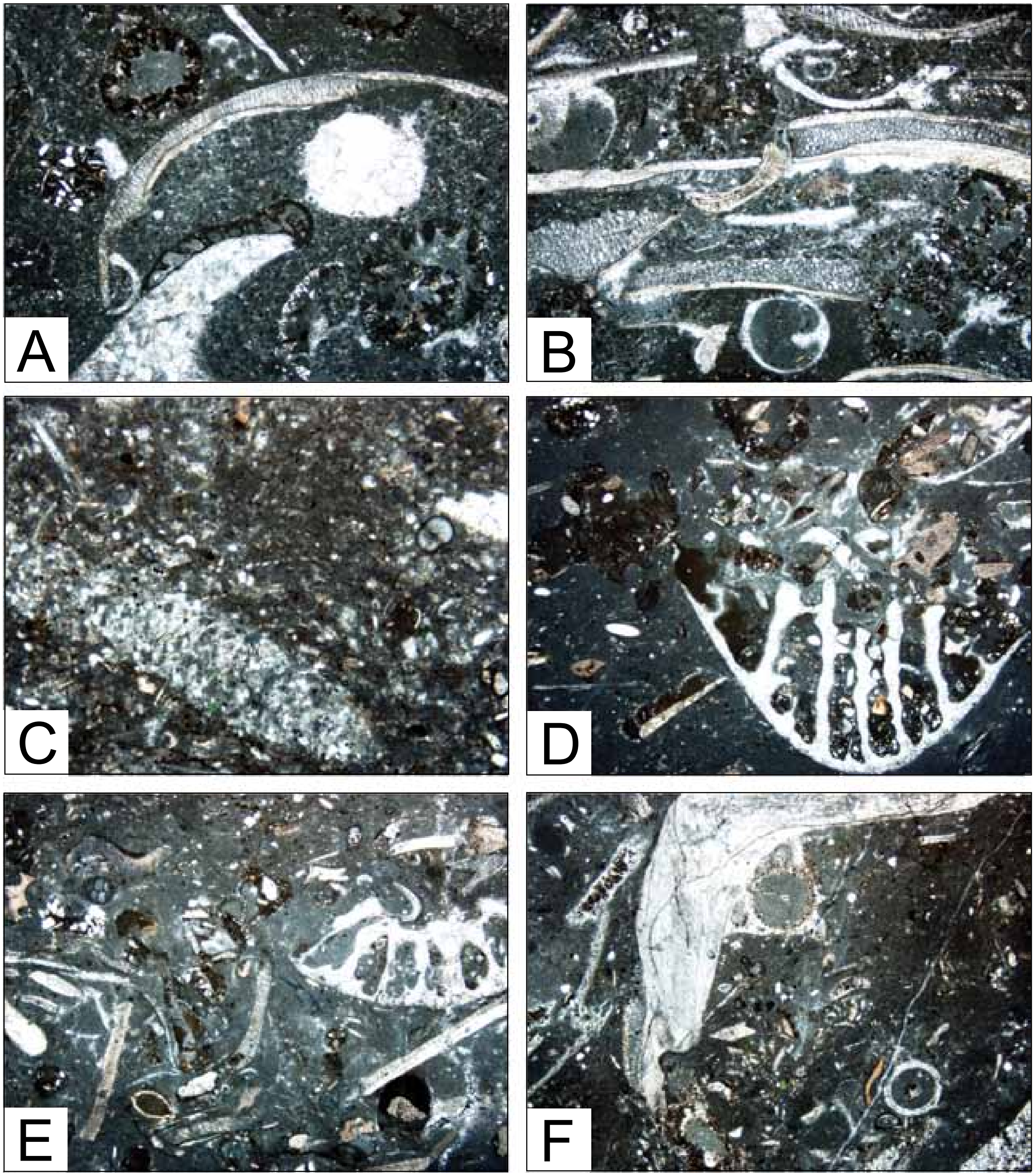

FIGURE 21—Thin section photographs of microfacies of the Muleros Formation at Cerro de Cristo Rey (Fig. 9). Sample numbers correspond to unit numbers in Figure 9. **A**—Floatstone containing gryphaeid shell fragments, some encrusted by balanids, and agglutinated foraminiferans embedded in micritic, partly peloidal matrix. Sample F7. **B**—Wackestone–rudstone with abundant gryphaeid shell fragments, some gastropods, agglutinated foraminiferans, and other bioclasts floating in micritic matrix. Sample F7. **C**—Fine-grained bioturbated wackestone composed of abundant peloidal and small bioclasts (ostracods, echinoderms, mollusc shell debris, foraminiferans) and a few quartz grains. Sample F8. **D**–**F**—Floatstone–rudstone with bivalve fragments, agglutinated foraminiferans, echinoderms, and corals embedded in micritic matrix. **D**–**E** = sample F10, **F** = sample F14. Width of photographs is 6.3 mm.

and generally altered. Accessory grains are micas (muscovite), tourmaline, zircon, apatite, and opaque grains. The sandstone is cemented by authigenic quartz overgrowths, and locally also by microcrystalline quartz and opaque cement (Fe-hydroxides). Unit 10 (Fig. 11) includes a lens of strongly recrystallized stromatolite composed of irregularly laminated algal mats.

Unit 23 (Fig. 11) is a crossbedded, fine-grained, bioturbated bioclastic wackestone, locally a packstone, containing a few larger bioclasts (Fig. 23E). Most abundant are dasycladacean algae and mollusc shell fragments (bivalves, gastropods). Less common are foraminiferans, echinoderms, echinoid spines, ostracods, and other fragments. The matrix is micrite to pelmicrite.

The uppermost Mojado Formation (Fig. 11, units 25–26) is composed of laminated siltstone to fine-grained sandstone. Grain size is mostly < 0.1 mm; however, a few quartz grains as much as 0.5 mm are present. The most abundant grain type is quartz; carbonate grains are subordinate, and opaques and glauconite are rare. The siltstone to fine-grained sandstone contains some ostracods,

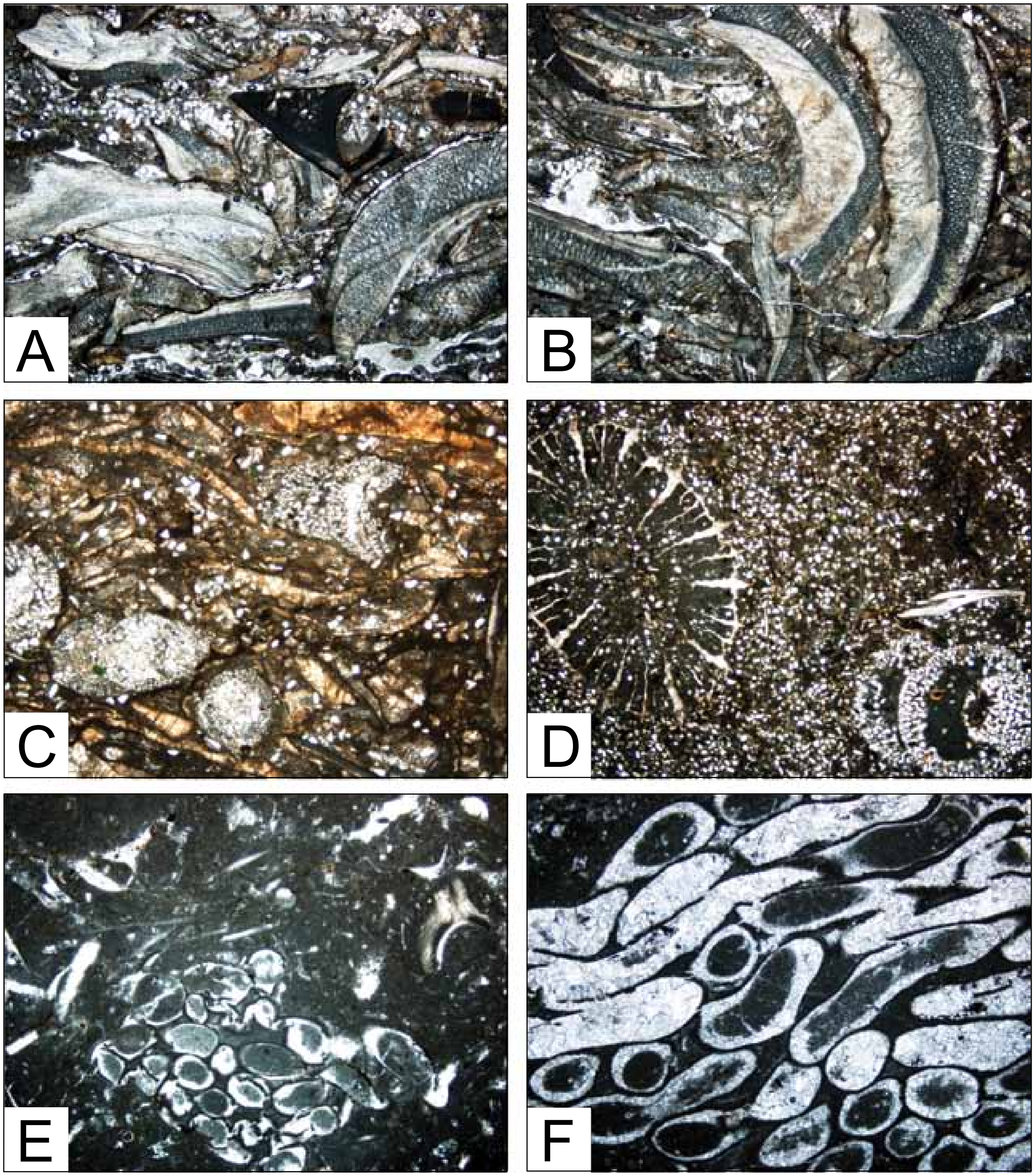

FIGURE 22—Thin section photographs of microfacies of the Mesilla Valley Formation at Cerro de Cristo Rey (Fig. 10). Sample numbers correspond to unit numbers in Figure 10. **A**–**B**—Bioclastic packstone–rudstone containing densely packed bivalve fragments, subordinate echinoderms and other bioclasts, a few detrital quartz grains, and rare glauconite. Sample G1. **C**—Bioclastic packstone–rudstone composed of abundant recrystallized shell fragments and agglutinated foraminiferans in silty matrix containing small angular quartz grains. Sample G3. **D**—Bioclastic siltstone composed of small and larger fossils such as corals, bivalves, and agglutinated foraminiferans floating in silty matrix. Sample G4. **E**—Bioclastic wackestone containing bivalve shell fragments, echinoderms, ostracods, and worm tubes embedded in micritic to pelmicritic matrix. Sample G10. **F**—Worm tubes in a bioclastic wackestone. Sample G10. Width of photographs is 6.3 mm, except for F, which is 3.2 mm.

shell fragments, rare foraminiferans, and echinoderms. Shell fragments are oriented parallel to the bedding in unit 26.

Depositional environments

The lower part of the Mojado Formation (Fig. 11) represents an upward-coarsening and shallowing succession, starting with hummocky crossbedded sandstone of the lower shoreface followed by upper shoreface deposits represented by alternating, horizontally laminated, ripple-laminated, and trough crossbedded sandstone. A shallow-marine environment is also indicated by a thin stromatolite lens within unit 10 (Fig. 11).

The overlying trough crossbedded intervals (Fig. 11, units 13 and 15) probably represent fluvial channel-fill deposits of a delta plain, which are again overlain by shallow-marine siliciclastic sediments (units 16–22). The thin, intercalated sandstone beds (ripple laminated, horizontally laminated, trough crossbedded) indicate high-energy conditions and may

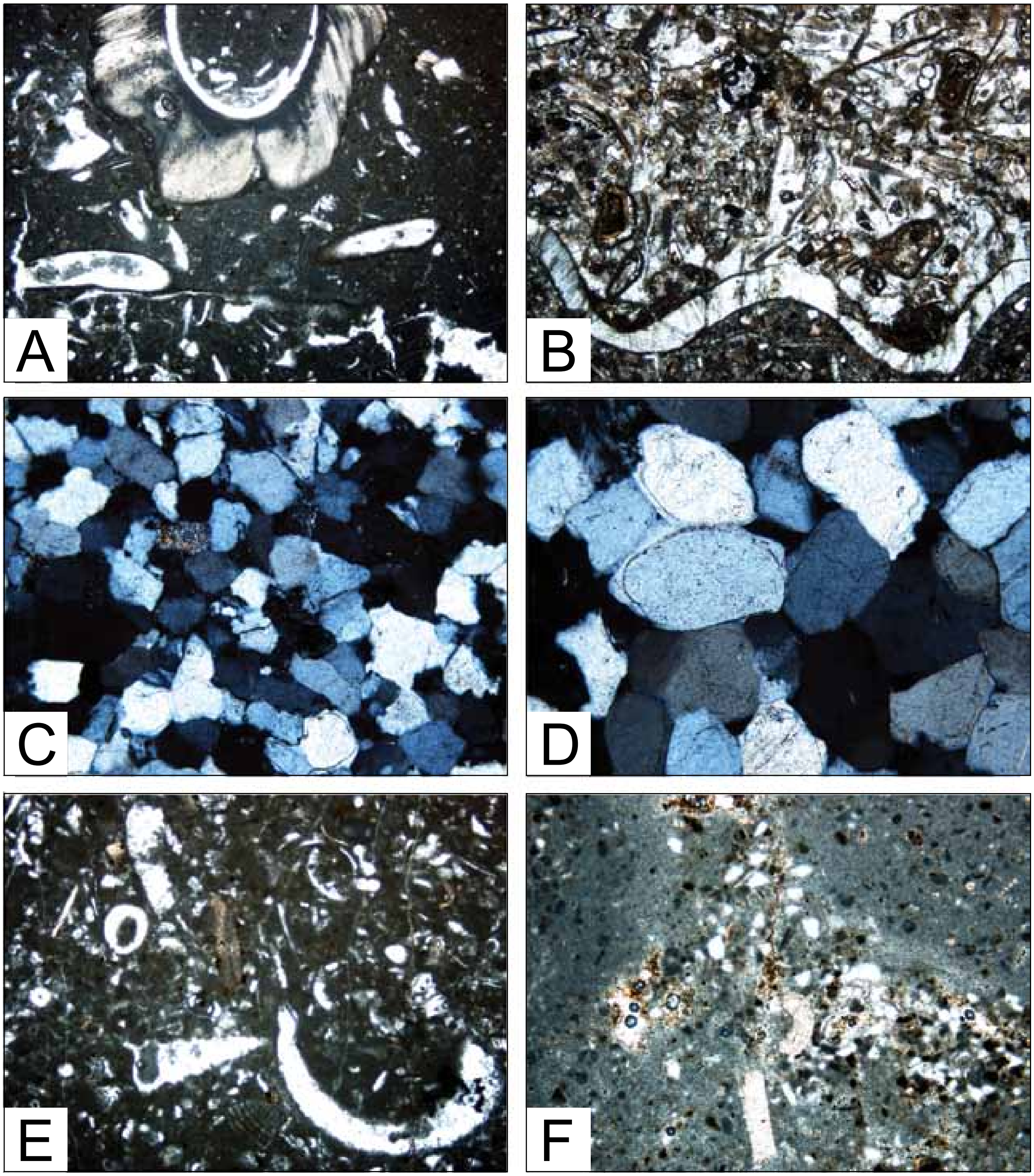

FIGURE 23—Thin section photographs of microfacies of the Mancos Formation (A–B) and Mojado Formation (C–F) at Cerro de Cristo Rey (Figs. 11, 15). Sample numbers correspond to unit numbers in Figures 11 and 15. **A**—Bioclastic wackestone with bivalve shell fragments, calcareous algae, and echinoderms floating in micrite. Sample I1. **B**—Bioclastic wackestone–packstone with mostly bivalve fragments, echinoderms, and subordinate other bioclasts, micritic matrix, and some calcite cement. Sample I3. **C**—Fine-grained quartz arenite composed mostly of monocrystalline quartz, rare polycrystalline quartz, cemented by quartz as authigenic overgrowths. Sample H3. **D**—Quartz arenite showing abundant monocrystalline quartz grains with well-displayed authigenic quartz overgrowths. Sample H3. **E**—Bioclastic wackestone containing abundant fragments of dasycladacean algae and bivalves, subordinate foraminiferans, and echinoderms floating in micritic to pelmicritic matrix. Sample H23. **F**—Bioturbated peloidal mudstone containing some quartz grains and a few bioclasts. Sample H27. Width of photographs is 6.3 mm, except for D, which is is 3.2 mm.

represent storm deposits. A shallow-marine environment is also indicated by a thin lens of fossiliferous limestone (bioclastic wackestone; Fig. 11, unit 23) that contains abundant dasycladacean algae.

The trough crossbedded sandstone of the succeeding 7 m may represent fluvial or upper shoreface deposits. The overlying, horizontally laminated sandstone (Fig. 11, unit 26) is of shallow-marine origin, indicated by the marine fossils.

Del Rio Formation

Lithostratigraphy

The Del Rio Formation at our measured section is approximately 33 m thick (Fig. 13). Lovejoy (1976) reported its thickness as 24–27 m. In our measured section (Fig. 13), the lower 9.7 m (most of unit 2) is a nodular limestone interval composed of abundant limestone nodules in a yellow clay slope (Fig. 12D). This interval contains many fossils of *Gyrostrea (=Exogyra) whitneyi* and gastropods. Above follows a shale slope with some nodular limestone and three thin limestone beds, each 0.2–0.3 m

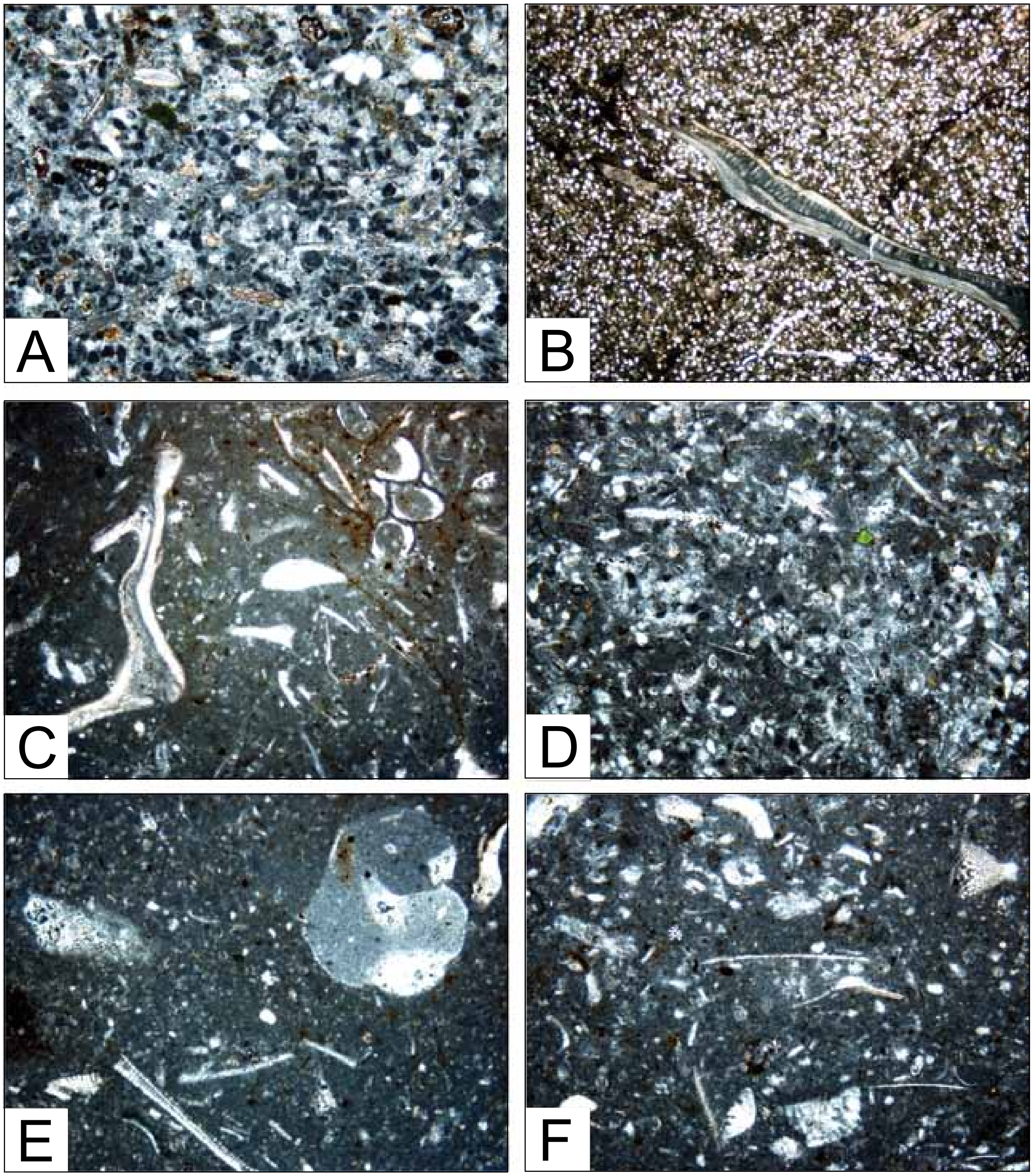

FIGURE 24—Thin section photographs of microfacies of the Del Rio Formation (A–C) and Buda Formation (D–F) at Cerro de Cristo Rey (Figs. 13–14). Sample numbers correspond to unit numbers in Figures 13–14. **A**—Peloidal wackestone with some angular quartz grains and bioclasts such as ostracods, smaller foraminiferans, and echinoid spines. Sample C3. **B**—A few bioclasts (bivalve shell fragments, echinoderms, ostracods, foraminiferans) floating in siltstone composed of angular quartz and carbonate grains, rare glauconite. Sample C7. **C**—Bioclastic mudstone–wackestone containing many small and a few larger fossil fragments (bivalves, echinoderms) floating in micritic matrix. Sample C9. **D**—Peloidal bioclastic mudstone containing a few angular quartz grains, some bioclasts (ostracods, shell fragments, foraminiferans, echinoderms), and rare glauconite. Sample D5. **E**—Bioclastic mudstone composed of gray micrite with small and a few larger fossil fragments. Sample D7. **F**—Fine-grained bioclastic wackestone containing mostly bivalve fragments, subordinately echinoderms, ostracods, and foraminiferans floating in gray micrite. Sample D5. Width of photographs A and D is 3.2 mm, and of photographs B, C, E, F is 6.3 mm.

thick and forming ledges (units 3–7). Above the uppermost limestone ledge, yellowish shale with some nodular limestone is exposed with a thickness of 12.8 m (unit 8). *Gyrostrea whitneyi* is also common in the upper part. Turnšek et al. (2003, p. 154) stated that *Ilymatogyra arietina* is the "dominant fossil" in the Del Rio, but our field observations suggest it is *Gyrostrea whitneyi*. The top of the Del Rio Formation is composed of nodular limestone with thin yellow shale interbeds (unit 9, 4.5 m thick), overlain by white limestone of the Buda Formation (Fig. 13).

Paleontology

The Del Rio Formation at Cerro de Cristo Rey yields bivalves (especially *Gyrostrea whitneyi* and *Ilymatogyra arietina*), gastropods, spatangoids, and ammonoids. In thin section we observed foraminiferans, ostracods, echinoderms, and annelid worm tubes. From the Del Rio Formation at Cerro de Cristo Rey, Mauldin (1985) and Mauldin and Cornell (1986) determined 52 species of foraminiferans. The foraminiferal assemblage is dominated by rotaliine foraminiferans (38 species), which

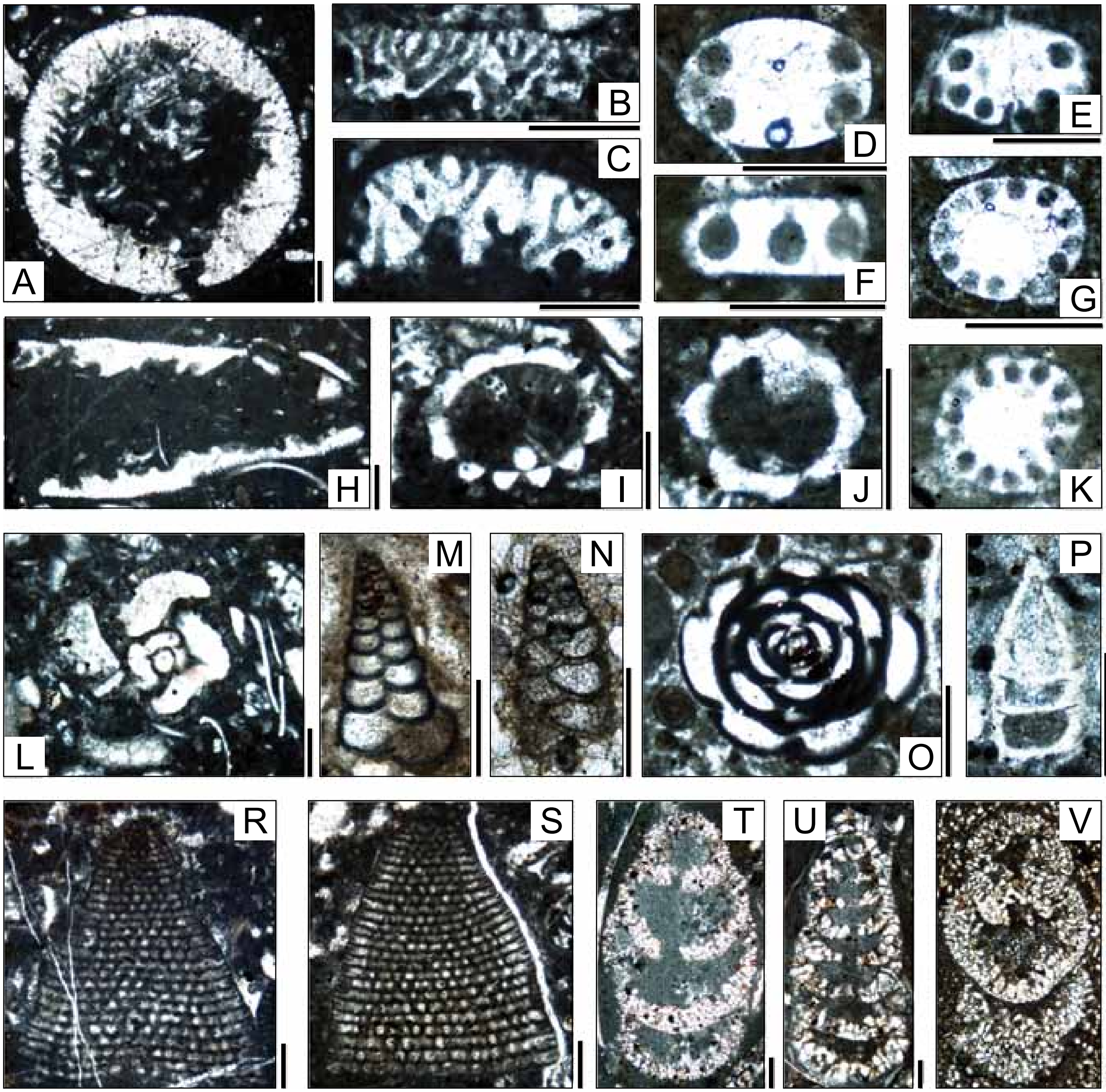

FIGURE 25—Some Cretaceous microfossils of the Cerro de Cristo Rey sections. **A**, **H**—*Permocalculus* sp. (Finlay Formation, A unit 14, H unit 27, Fig. 6). **B**, **C**—*Boulina* sp. (Finlay Formation, B unit 12, C unit 20, Fig. 6). **D**, **E**, **G**, **K**—*Acicularia* or *Terquemella* sp. (Finlay Formation, D unit 14, E unit 27, K unit 26, Fig. 6; Del Norte Formation, G unit 9, Fig. 7). **F**—*Neomeris* sp. (Finlay Formation, unit 20, Fig. 6). **I**, **J**—*Salpingoporella* sp. (Finlay Formation, unit 24, Fig. 6). **L**—*Pseudocyclammina* sp. (Finlay Formation, unit 27, Fig. 6). **M**, **N**—Textulariid foraminiferans (M—Del Norte Formation, unit 14, Fig. 7; N—Smeltertown Formation, unit 7). **O**—*Pseudonummuloculina heimi* (Finlay Formation, unit 10, Fig. 6). **P**—*Lenticulina* sp. (Del Rio Formation, unit 3, Fig. 13). **R**, **S**—Orbitolinoid foraminiferans (*Dictyoconus*) (Finlay Formation, unit 8, Fig. 6). **T**, **U**, **V**—Agglutinated foraminiferans (*Ammobaculites*? and/or *Cribratina*) (T, U—Smeltertown Formation, unit 9, Fig. 8; V—Buda Formation, unit 7, Fig. 14). Scale bar is 0.3 mm, except for K, which is 0.1 mm.

constitute 82% of the individuals. Agglutinated foraminiferans (suborder Textulariina) comprise 12 species and 17% of all individuals. Two species belong to milioline foraminiferans, constituting 1% of the individuals. These foraminiferans support correlation of the Del Rio outcrops with the Grayson Formation elsewhere in Texas.

Sedimentary petrography (Figs. 13, 24A–C)

At the top of our section of the Mojado Formation, the basal interval of the overlying Del Rio Formation (Fig. 11, unit 27) is composed of interbedded nodular limestone and shale. The limestone beds are bioturbated peloidal mudstone containing many peloids, a few quartz grains, rare glauconite, and a few small bioclasts such as ostracods, echinoderms, and rare foraminiferans (Fig. 23F). Similarly, in our section of the Del Rio Formation (Fig. 13), the lowermost interval (unit 2) is nodular limestone and shale capped by a thin limestone bed (unit 3) that consists of peloidal wackestone (Fig. 24A), grading up into fine-grained sandstone containing abundant quartz. The peloidal wackestone (unit 3) is indistinctly laminated and contains as much as about 20% quartz (with a grain size as much as approximately 0.2 mm) and rare glauconite. Most abundant are small peloids and many small bioclasts such as ostracods, foraminiferans, echinoid spines, and some other small fossils, floating in microspar (cement?). The amount of quartz grains increases upward to about 30%, and the peloidal wackestone is overlain by fine-grained sandstone that contains about 50–60% angular quartz grains, rare glauconite, and a few bioclasts (including ostracods, echinoid spines, echinoderms, shell fragments, and rare foraminiferans) in brownish micritic matrix.

The limestone bed of unit 5 of the Del Rio Formation (Fig. 13) is a peloidal wackestone–grainstone with abundant small peloids and foraminiferans. Subordinate are ostracods, echinoderms, echinoid spines, small quartz grains (5–10%), a few micritic intraclasts, and rare glauconite. The rock is indistinctly laminated and calcite cemented.

Unit 7 (Fig. 13) is a bioclastic limestone with some small and larger bioclasts floating in silty matrix (Fig. 24B). The silty matrix is composed of predominantly small angular quartz and carbonate grains, subordinate glauconite, and some opaque grains. Bioclasts include echinoderms, ostracods, shell fragments (bivalves), and rare agglutinated and other foraminiferans. The rock is locally bioturbated and calcite cemented.

The nodular limestone of the Del Rio Formation is a gray, nonlaminated, bioturbated bioclastic mudstone. The micritic to pelmicritic matrix contains many small and a few larger bioclasts. A few small quartz grains and rare glauconite grains are present. Bioclasts include ostracods, bivalve shells, echinoderms, a few foraminiferans, rare gastropods, and annelid worm tubes. The uppermost limestone bed of the Del Rio Formation (unit 9) is composed of bioturbated bioclastic mudstone (Fig. 24C). Small bioclasts of ostracods, echinoderms, foraminiferans, gastropods, bivalves, rare quartz grains, and very rare glauconite float in a micritic matrix.

Depositional environments

Del Rio Formation facies (Fig. 13) are similar to those of the lower part of the Del Norte Formation (Fig. 7) and indicate shallow-marine deposition. Mauldin and Cornell (1986) concluded that the foraminiferans of the Del Rio Formation indicate a deepening of marine waters (transgression) that culminated in the middle part of the Del Rio, followed by a regression during deposition of the upper Del Rio.

Mauldin and Cornell (1986) indicate that the lower half of the Del Rio succession is dominated by rotaliine foraminiferans; the upper half is enriched in agglutinated foraminiferans. The ratio of planktonic to benthic foraminiferans is 0.1–0.6 in the lower half, indicating water depths from 60 to 100 m. The value drops in the upper half, indicating water depths of 20 m or less (Mauldin and Cornell 1986). The foraminiferal assemblages indicate that the basal part of the Del Rio Formation marks a transgression, and that a deeper shelf environment (60–100 m) persisted until deposition of the middle Del Rio Formation, followed by a drop in sea level to water depths of approximately 20 m in the upper half (Mauldin and Cornell 1986).

However, shale with limestone nodules and nodular to wavy limestone indicate deposition under quiet-water conditions in a deeper, outer-shelf environment. This is also indicated by the presence of glauconite, which in modern oceans occurs at depths between 50 and 500 m (Flügel 2004). Even the wavy to nodular limestone in the uppermost part of the Del Rio Formation formed in a low-energy environment. Lithologic evidence of a drop in sea level to water depths of approximately 20 m in the upper half suggested by Mauldin and Cornell (1986) is not observed. Even the uppermost wavy to nodular limestone (bioclastic mudstone) with intercalated shale was deposited in a low-energy environment below wave base. High-energy deposits such as grainstone or packstone are absent.

Buda Formation

Lithostratigraphy

At Cerro de Cristo Rey, the best exposed and most complete section of the Buda Formation is in Bowen Gulch where it is a prominent, resistant interval of white limestone that forms ridges and cuestas (Figs. 12E, 14). Here, the Buda Formation is 15.5 m thick (Lovejoy 1976 reported its thickness as approximately 12 m) and composed of alternating limestone and shale with limestone nodules. The lowermost limestone of the Buda Formation is 0.8 m thick (unit 5) and nodular, overlain by a thin nodular limestone with shale and a prominent limestone cliff 2.7 m thick (units 6–7). Above the limestone cliff follows a succession of alternating limestone and shale (units 8–21). Limestone beds are 0.3–0.6 m thick and full of gastropods. Shale intervals measure 0.3–2.5 m and contain limestone nodules, which are locally fossiliferous.

The lithology of the Buda Formation section exposed at Cerro de Cristo Rey most resembles that of the middle member (Red Light Member) of the Buda in Trans-Pecos Texas (Reaser and Robinson 2003) in being a mixture of thin-bedded lime mudstone and nodular, marly limestone. In contrast, the lower member (Lecheguilla Member) and the upper member (Love Station Member) of the Buda Formation in Trans-Pecos Texas are ridge-forming beds of lithographic, muddy limestone (Reaser and Robinson 2003). Correlation of the Buda Formation section at Cerro de Cristo Rey to only the Red Light Member to the southeast thus has a lithostratigraphic basis, but cannot be confirmed biostratigraphically because the entire Buda Formation falls within one ammonoid zone, which is the biostratigraphic means by which Buda sections are correlated (Young 1979).

As Hook (2008; also see Cooper et al. 2008) noted, the top of the Buda Formation usually displays evidence of erosion in the form of microkarst features at the Buda–Mancos contact. However, at Cerro de Cristo Rey the Buda–Mancos contact is poorly exposed and tectonized (Fig. 12F), so evidence of microkarst features is not clear. The best evidence of the Buda–Mancos unconformity at Cerro de Cristo Rey is provided by ammonoid biostratigraphy (Cobban et al. 2008). The base of the Mancos Formation is in the upper middle Cenomanian *Acanthoceras amphibolum* Zone, whereas the upper Buda is in the lower Cenomanian *Neophlycticeras* (=*Budaiceras*) *hyatti* Zone—thus, two lower Cenomanian and four middle Cenomanian ammonoid zones are missing at the Buda–Mancos contact, an unconformity of more than one million years duration (Cobban et al. 2008, fig. 2).

Paleontology

The Buda Formation yields many gastropods (mostly turritellids) and bivalves, as well as some ammonoids, dinoflagellates, serpulids, spatangoid echinoderms, crustaceans, corals, and fish teeth (Böse 1910; Young 1979; Cornell 1997; Turnšek et al. 2003). Ammonoids we have collected (and will document elsewhere) place it in the early Cenomanian zone of *Neophlycticeras* (=*Budaiceras*) *hyatti* (Young 1979).

Sedimentary petrography (Figs. 14, 24D–F)

The basal limestone of the Buda Formation (Fig. 14, unit 5) is composed of fine-grained, bioturbated bioclastic wackestone containing a few larger skeletons (Fig. 24F). Most abundant are mollusc shell fragments. Less abundant are echinoderms, ostracods, echinoid spines, foraminiferans, and other recrystallized, indeterminate skeletons. The skeletons float in a micritic to pelmicritic matrix. This type grades into bioclastic mudstone containing small and a few larger bioclasts that float in gray micrite (Fig. 24E).

The thick limestone cliff of the Buda Formation (Fig. 14, unit 7) consists of fine-grained, bioturbated, bioclastic wackestone with a few larger skeletons. Most abundant are mollusc shell fragments (bivalves and gastropods) and dasycladacean algae; ostracods, echinoderms, echinoid spines, smaller foraminiferans, and rare bryozoans(?) are subordinate. Many skeletons, particularly molluscs and algae, are recrystallized. A few micritic intraclasts are present. The skeletons are embedded in a micritic to pelmicritic matrix.

The lowermost, gastropod-rich limestone bed (Fig. 14, unit 9) is a bioturbated bioclastic mudstone containing small and rare larger bioclasts floating in a pelmicritic matrix (Fig. 24D). Most skeletons are derived from bivalves and gastropods, and also from dasycladacean algae. Rare ostracods, echinoderms, echinoid spines, and smaller foraminiferans are present. The rock also contains a few small, detrital quartz grains. Another thin section indicates a bioturbated bioclastic mudstone composed of micritic matrix and small bioclasts such as ostracods, bivalve shell fragments, echinoid spines, echinoderms, and smaller foraminiferans floating in the matrix. Small quartz grains and rare glauconite are present.

The uppermost limestone bed of the Buda Formation (Fig. 14, unit 21) is composed of bioturbated bioclastic wackestone containing a few larger bivalve and shell fragments floating in a fine-grained bioclastic matrix. Small recrystallized shell fragments and algal debris, ostracods, subordinate small gastropods, echinoderms, and smaller foraminiferans are abundant. The fossils are embedded in micritic matrix. Similarly, at our Mancos Formation section, the topmost Buda Formation (Fig. 15, unit 1) is bioturbated bioclastic wackestone that is poorly sorted, contains mollusc shell debris (bivalves, gastropods), calcareous algae, echinoderms, echinoid spines, ostracods, worm tubes, and foraminiferans. A few peloids and rare glauconite grains are present. The matrix is micrite.

Depositional environments

Regional deposition of the Buda Formation took place in shallow-marine waters on a broad, shallow carbonate ramp that extended across much of Texas and parts of northern Mexico (Reaser and Robinson 2003). Our analysis of Buda microfacies (most limestones are bioclastic wackestone and mudstone) at Cerro de Cristo Rey indicates they correspond well to the shallow-water wackestone–mudstone facies of Reaser and Robinson (2003).

According to Reaser and Robinson (2003), the lower member of the Buda Formation was deposited on a broad open shelf with normal marine water near the basin margin during the last marine incursion by the Comanchean sea. The middle member is interpreted as deposits of a shallow, slightly hypersaline shelf during a drop in sea level. Sediments of the upper member accumulated in a similar environment (on the distal part of an open shelf) as those of the lower member and represent the final highstand event.

At Cerro de Cristo Rey (Fig. 14) muddy textures, common bioturbation, diverse fossil assemblage, and the presence of dasycladacean algae indicate to us that the limestone of the lower part of the Buda Formation was deposited in an open, normal marine, low-energy shelf environment below the wave base. Carbonate sedimentation periodically was interrupted by deposition of thin shale intercalations.

Intercalated limestone beds of the upper part of the Buda are of the same composition as those of the lower part, indicating a similar depositional environment. Shale is more abundant in the upper part, indicating high rates of fine siliciclastic influx that was periodically interrupted, causing the deposition of limestone beds. A greater amount of shale may be the result of a slight drop in sea level, although deposition still occurred below wave base.

Mancos Formation ("Boquillas Formation")

Lithostratigraphy

At Cerro de Cristo Rey, the exposed thickness of the Mancos Formation is 18.6 m (Fig. 15). The total estimated thickness is approximately 110 m (Böse 1910; Lovejoy 1976), but we cannot confirm this estimate with outcrop data. White, gastropod-rich, nodular limestone of the Buda Formation is sharply and unconformably overlain by approximately 5 m of shale intercalated with thin sandy limestone and limestone beds. The uppermost limestone bed of this interval is 0.2 m thick and forms a ledge. Above is a 3.9-m-thick covered interval that conceals a cross fault or fold. Overlying strata are a 10-m-thick succession of shale with a few thin sandstone beds.

Böse (1910) and some subsequent workers (Fig. 3) referred to these strata as the Eagle Ford Formation (Shale). Strain (1976) first brought the term Boquillas Formation into Cerro de Cristo Rey, although he suggested that the names Chispa Summit or Ojinaga might better be applied. We prefer to use the name Mancos Formation (Shale), widely used across New Mexico, for this shaley interval at the base of the Greenhorn cycle of deposition (e.g., Seager 1981; Molenaar 1983; Lucas and Estep 1998a; Lucas et al. 2000). Indeed, Mancos Formation is applied to the same lithosome at nearby outcrops in the southern San Andres Mountains, approximately 75 km north of Cerro de Cristo Rey, and in the southern Cooke's Range, approximately 120 km northwest of Cerro de Cristo Rey.

Paleontology

Kennedy et al. (1988) described a middle Cenomanian molluscan fauna of bivalves (*Ostrea beloiti* Logan and *Inoceramus arvanus* Stephenson) and diverse ammonoids (including *Acanthoceras amphibolum*) from a thin bed of calcarenitic and coquinoidal limestone near the base of the Mancos Formation (Fig. 15, bed 3). Turnšek et al. (2003) also state that shark teeth (notably *Ptychodus*) are present in the Mancos Formation at Cerro de Cristo Rey. Cornell (1997) reported dinoflagellate cysts. We observed dasycladacean algae, foraminiferans, ostracods, echinoderms, and bryozoans(?) in thin section.

Sedimentary petrography (Figs. 15, 23A–B)

The lowermost thin limestone bed of the Mancos Formation (Fig. 15, unit 3) is a bioclastic wackestone–packstone–rudstone that is poorly sorted and indistinctly laminated (Fig. 23A–B). The rock contains a micritic matrix, and locally some calcite cement is present. It is strongly recrystallized, and it contains a few centimeter-sized bivalve shell fragments, abundant small bioclasts, mostly shell debris and foraminiferans (globigerinids?), subordinate echinoderms, and other bioclasts. A few angular quartz grains, ooids, and intraclasts are present.

Depositional environments

Deposition of the Mancos Formation took place in normal marine waters. Muddy sea bottoms supported characteristic benthic organisms such as inoceramid bivalves, and nektonic organisms such as ammonoids lived in the water column.

Depositional cycles and sequence boundaries

Introduction

Deposition of the Cretaceous strata exposed at Cerro de Cristo Rey took place just off of the northern margin of the Chihuahua trough, one of the actively subsiding basins bordering the late Aptian–early Cenomanian Comanche Shelf, which extended from eastern Arizona across part of southern New Mexico and northern Mexico through Texas and farther east (Fig. 26). The Cretaceous section at Cerro de Cristo Rey encompasses the uppermost Fredricksburg Group (upper part of Finlay Formation), the entire Washita Group (Del Norte, Smeltertown, Muleros, Mesilla Valley, Mojado, Del Rio, and Buda Formations), and the basal unit (lower Mancos Formation) of the overlying Greenhorn cycle. It represents a hierarchy of at least three clearly definable depositional cycles (Scott et al. 2003). Here, we identify sequence boundaries (unconformities) and transgressive-regressive (deepening-shallowing) cycles in the Cretaceous section at Cerro de Cristo Rey (Fig. 27).

First order cycles and sequence boundaries

Scott et al. (2000, 2003) consider the entire Comanchean Series of Texas and adjacent areas to represent a single, first-order cycle of deposition. This cycle includes the Trinity, Frederickburg, and Washita Groups of late Aptian to early Cenomanian age. The lower part of this cycle (Trinity Group and most of the Fredericksburg Group) is not exposed at Cerro de Cristo Rey. However, the upper part of the cycle, and its upper bounding unconformity (between the Buda and Mancos Formations, see above), is well exposed at Cerro de Cristo Rey.

In northern Texas, the entire Comanchean section is approximately 250 m thick, whereas at Cerro de Cristo Rey that part of the Comanchean section exposed is thicker, approximately 350 m thick. This probably reflects greater clastic influx into (and greater subsidence of) the Cerro de Cristo Rey Comanchean section because of its more landward position relative to the more offshore sections in northern and central Texas (Fig. 26).

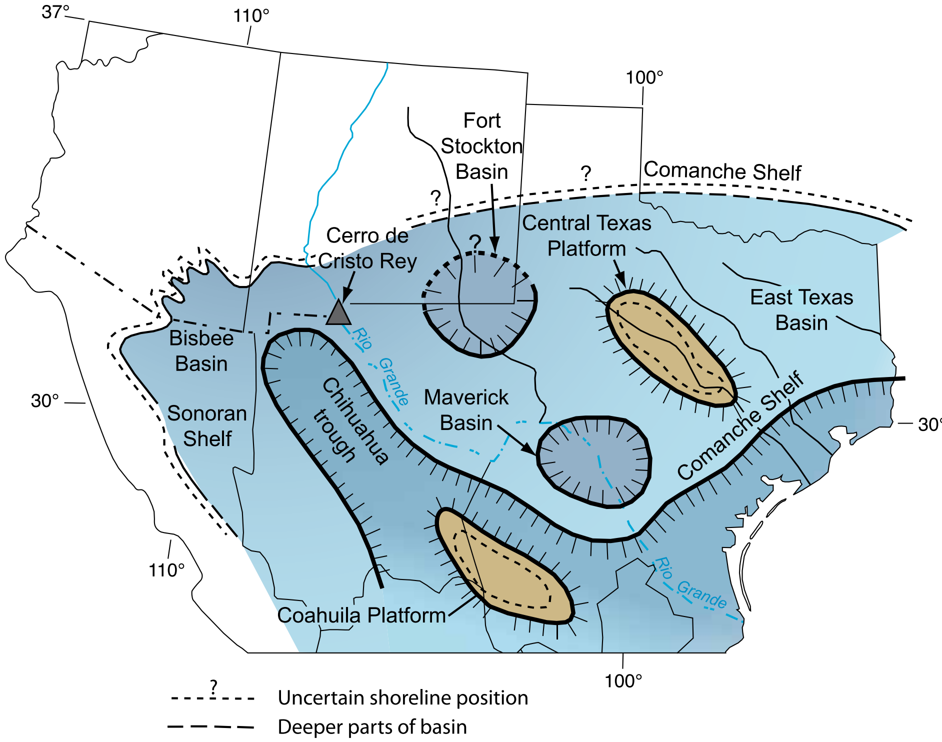

FIGURE 26—Early Cretaceous depositional basins of the Comanchean Series (uppermost Lower and lowermost Upper Cretaceous) in Texas, northern Mexico, and adjacent areas (after Scott et al. 2003).

Second order cycles and sequence boundaries

In Texas the Fredericksburg and Washita Groups have long been regarded as second-order cycles of deposition (e.g., Lozo and Stricklin 1956; Hendricks 1967; Scott et al. 2003). Across much of Texas, the top of the Fredricksburg Group is a regional hardground with subaerial exposure (unconformity) overlain by the Kiamichi Formation (base of the Washita Group; Amsbury 2003; Scott et al. 2003). Thus, the Fredericksburg and Washita Groups are unconformity-bounded units with a basal clastic facies that generally grades up into intercalated shallow-marine carbonates and clastics. At Cerro de Cristo Rey, the entire Washita Group second-order cycle is exposed (Fig. 27). It is bounded by distinct unconformities at the base of the Del Norte and Mancos Formations. Only the uppermost part of the Fredericksburg cycle (upper Finlay Formation) and the lowermost part of the Greenhorn cycle (lower Mancos Formation) are exposed at Cerro de Cristo Rey (Fig. 27).

Third order cycles and sequence boundaries

Based on the interpretation of Scott et al. (2001, 2003), the Cretaceous section exposed at Cerro de Cristo Rey represents eight smaller-scale (third order?) depositional cycles, six of which comprise the Washita Group section (Fig. 27). In the Washita Group section, Scott et al. (2001, 2003) identify these six cycles (WA1 through WA6) as shale-sandstone or mudstone-limestone cycles. Our data strongly support this interpretation, although we differ from Scott et al. (2001, 2003) in our placement of the sequence boundaries (and thus stratigraphic extent) of the lower three cycles. We thus identify six upward-shallowing shale-sandstone or shale-limestone cycles bounded by unconformities in the Washita Group section at Cerro de Cristo Rey (Fig. 27).

The Finlay Formation is the final highstand of the Fredericksburg second-order cycle. Steinhoff (2003) identified high-frequency cycles in the Finlay Formation that begin with nodular, marly layers and grade up into massive limestones and are 1–4.5 m thick. The upper part of the Finlay Formation exposed at Cerro de Cristo Rey encompasses 12 such cycles (Fig. 6). These cycles may correlate to 12 of the 18 high-frequency cycles that Steinhoff (2003) recognized as part of an upper, high-frequency sequence 2 of the Finlay Formation formed during a time of relative sea-level highstand. By this interpretation, the upper Finlay at Cerro de Cristo Rey represents shoaling up followed by sea level fall at the end of the last cycle of deposition of the Fredericksburg Group (Amsbury 2003; Scott et al. 2003).

As noted above, Scott et al. (2000, 2003) identified six third-order cycles of deposition in the Washita Group of northern Texas (and at Cerro de Cristo Rey) that they labeled WA1 through WA6. Thus, WA1 begins at the base of the Del Norte Formation (= base of Washita Group), where a ferruginous sandstone rests directly on lime mudstone at the top of the Finlay Formation (Fig. 27). The contact reflects an abrupt increase in water depth and siliciclastic influx, thus representing a transgressive surface. The transgressional-progradational succession of cycle WA1 is visible in the lower member of the Del Norte Formation at Cerro de Cristo Rey, whereas the upper member indicates shallowing.

A strong candidate for the next unconformity (sequence boundary) is the base of the Smeltertown Formation (Fig. 7, unit 24). The sharp contact of shale on limestone at the base of the Smeltertown Formation indicates deepening and marks the next transgressive surface. The absence of ammonites indicative of the *Craginites serratescens* and *Eopachydiscus marcianus* Zones at Cerro de Cristo Rey may be indicative of a hiatus at the base of the Smeltertown Formation where strata of the *Mortoniceras equidistans* Zone rest directly on strata of the *Adkinsites bravoensis* Zone, or it may be that facies restrictions precluded ammonite presence/preservation in part of the Del Norte–Smeltertown interval. The shoaling trend from deeper to shallower shelf of cycle WA2, corresponding to the Smeltertown Formation, is also observed at Cerro de Cristo Rey.

Cycle WA3 in north Texas was deposited during a period of general shoreline retreat along the northern basin margin (Scott et al. 2003). An upward-deepening trend is also observed within most of the Muleros Formation with a regressive trend in the uppermost part. Cycle WA3 (Fig. 27) thus encompasses the entire Muleros Formation, and begins with an upward-deepening trend into offshore shale (Fig. 9, unit 2) and then shallowing into the bioturbated limestones and *Texigryphaea* packstones of the middle to upper Muleros Formation (Fig. 9, units 3–14). WA3 is an important regional cycle in New Mexico as it is represented by the Tucumcari and Glencairn Formations, which are the first extensive Albian seaway in the northeastern part of the state (e.g., Kues and Lucas 1987; Scott et al. 2001).

An abrupt deepening of marine waters at the base of the Mesilla Valley Formation marks the beginning of the next cycle (WA4, Fig. 27). This cycle begins relatively deep in offshore marine muds of member A (Fig. 10, unit 2) and then shallows through sandstone and *Texigryphaea* packstones of member B. In north Texas, cycle WA4, which corresponds to most of the Mesilla Valley Formation at Cerro de Cristo Rey (Fig. 27), is a succession from shallow shelf within the storm wave base to a nearshore high-energy setting. A shallowing trend is also recorded within the Mesilla Valley Formation from member A to member B. The sharp contact between limestone (Muleros) and shale (Mesilla Valley) is the likely sequence boundary at the base of the WA4 cycle.

Relatively offshore black shale of member C of the Mesilla Valley Formation (Fig. 10, unit 12) appears to represent an abrupt deepening and thus can be interpreted as the base of the next cycle, WA5. The succession shallows upward into interbedded sandstone and shale of the basal Mojado Formation. We thus place the base of WA5 at the base of member C of the Mesilla Valley Formation (Fig. 27). A deepening trend above the first thick, crossbedded fluvial sandstone of the Mojado Formation (Fig. 10, unit 14; Fig. 11,

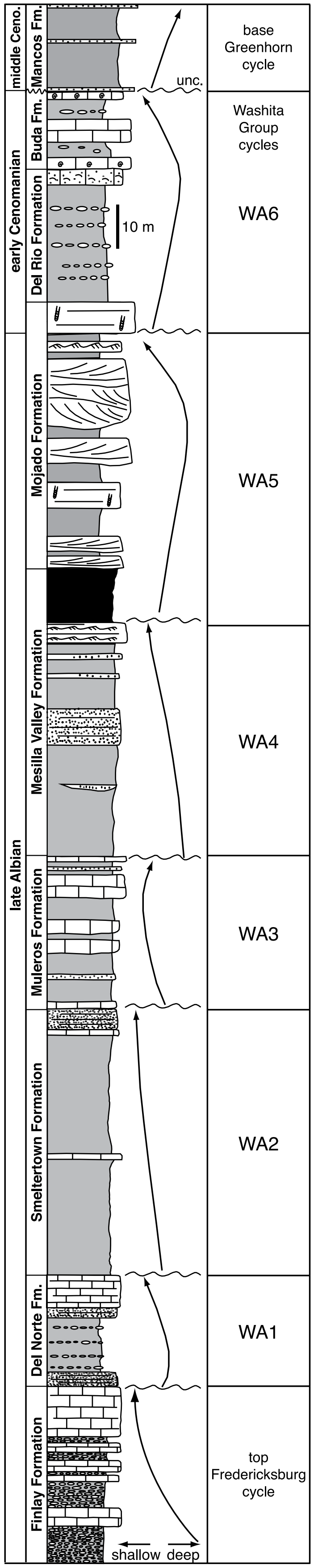

FIGURE 27—Summary of Cretaceous section at Cerro de Cristo Rey showing sequence boundaries and depositional cycles.

unit 4) is indicated by bioturbated sandstones and interbedded siltstones (Fig. 11, units 7–14) and is followed by shallowing, indicated by prograding fluvial sandstones (Fig. 11, units 15–25).

In north Texas, WA5 represents a regressive trend from deep to shallow shelf conditions (Scott et al. 2003). This trend is indicated by the facies of the Pawpaw Formation, which northward becomes very sandy with thin-bedded and trough crossbedded sandstone of deltaic origin. The overlying Main Street Formation also indicates a northward change from a carbonate shelf to shoreface environment with significant input of quartz. A similar shoaling trend is clearly visible within the Mojado Formation, which approximately corresponds to cycle WA5: lower shoreface to upper shoreface and finally to fluviodeltaic sandstone.

Cycle WA6 in north Texas is represented by the Grayson and Buda Formations, which correlate to the uppermost Mojado, Del Rio, and Buda Formations at Cerro de Cristo Rey (Scott et al. 2001, 2003). The Grayson is characterized by a progressive change from carbonate to clay. The lower part is composed of shale with intercalated ripple-laminated beds of carbonate silt and sand interpreted as storm layers overlain by clay mainly deposited below the storm wave base. The middle part is represented by nodular wackestone and shale, and the uppermost part by shale, interbedded marl, and bioturbated limestone. Similar lithologies are recognized within the Del Rio Formation, although storm layers are absent, and deposition took place in a low-energy outer-shelf environment below the storm wave base.

The uppermost Mojado Formation preserves a transgressive surface that we identify as the basal unconformity of the WA6 cycle (Fig. 11, base of unit 26; Fig. 27). This cycle deepens upward through the lower Del Rio, then shallows into the platform carbonates of the Buda Formation. The Buda Formation represents the last marine transgression of the Comanchean Seaway, and Reaser and Robinson (2003) interpreted Buda deposition (in Trans-Pecos Texas) as representing a transgression across a broad, low-relief carbonate ramp (lower Buda = Lecheguilla Member), followed by a break in transgression and a regression during which terrigenous clays were deposited (middle Buda = Red Light Member), culminated by a final transgression and highstand (upper Buda = Love Station Member). The Buda outcrop at Cerro de Cristo Rey is the westernmost outcrop of the formation, and is a relatively thin (< 20 m thick) and shaly section of the formation. Given that the Del Rio shows an upward-shallowing trend, we think it most likely that the Buda was deposited during regression or during a prograding highstand. Limestone of the Buda Formation at Cristo Rey suggests deposition in an open-marine, low-energy shelf environment below wave base. Increased deposition of shale in the upper part may indicate a drop in sea level.

The unconformity at the base of the Mancos Formation (Fig. 27) begins the next cycle of deposition (Greenhorn cycle). It represents a major tectonic reorganization of the Cretaceous marine basins of the American Southwest (e.g., Mack 1987). At Cerro de Cristo Rey, this was the change from deposition along an extensive carbonate platform (Comanchean Platform) that bordered a rift basin (Chihuahua trough) to deposition in the retroarc foreland basin of the Late Cretaceous Western Interior Seaway. The persistence of cycles from the tectonically passive, open-marine margin of the Gulf of Mexico into the tectonically active Chihuahua trough suggests that regional, if not global eustasy, not local tectonism, drove late Early to early Late Cretaceous sedimentation at Cerro de Cristo Rey.

Acknowledgments

We are grateful to George Cudahy for access to land, and assistance in the field from Josh Smith. We thank Daniel Vachard, who helped us to identify foraminiferans and algae in thin sections. Comments by Robert W. Scott on an earlier version of this manuscript greatly improved its content and organization. W. R. Dickinson, T. Lawton, and R. W. Scott provided helpful reviews of the submitted manuscript.

References

Adkins, W. C., 1932, The Mesozoic system in Texas; *in* Sellards, E. H., Adkins, W. C., and Plummer, F. B. (eds.), The geology of Texas: University of Texas, Publication 3252, pp. 329–518.

Amsbury, D. L., 2003, Stratigraphy of Fredericksburg Group (middle–upper Albian Cretaceous) north-central Texas; *in* Scott, R. W. (ed.), Cretaceous stratigraphy and paleoecology, Texas and Mexico: Perkins Memorial volume, GCSSEPM Foundation, Special Publications in Geology, v. 1, pp. 227–276.

Böse, E., 1910, Monografia geológica y paleontological del Cerro de Muleros cerca de Ciudad Juárez, Estado de Chihuahua, y descripción de la fauna cretácea de La Encanatada, Placer de Guadalupe, Estado de Chihuahua: Instituto Geologico de Mexico, Bulletin 25, 193 pp.

Bullock, J. S., 1985, Biostratigraphic study of foraminifera from the Smeltertown Formation (Lower Cretaceous, Albian) of southeastern New Mexico: Unpublished M.S. thesis, University of Texas at El Paso, 155 pp.

Bullock, J. S., and Cornell, W. C., 1986, Biostratigraphy and paleoecology of the Smeltertown Formation, Cerro de Cristo Rey, Doña Ana County, New Mexico; *in* Hoffer, J. M. (ed.), Geology of south-central New Mexico: El Paso Geological Society, Guidebook, pp. 73–76.

Cobban, W. A., 1987, Ammonite faunas of the Sarten Sandstone (Cretaceous), Luna County, New Mexico: U.S. Geological Survey, Bulletin 1641–B, pp. B1–B17.

Cobban, W. A., Hook, S. C., and McKinney, K. C., 2008, Upper Cretaceous molluscan record along a transect from Virden, New Mexico, to Del Rio, Texas: New Mexico Geology, v. 30, pp. 75–92.

Cooper, R. W., Cooper, D. A., Stevens, J. B., and Stevens, M. S., 2008, Geology of the Hot Springs Trail area, Ernst and San Vicente Members of the Boquillas Formation; *in* Cooper, D. A. (ed.), The southern extension of the Western Interior Seaway: Geology of the Big Bend National Park and Trans-Pecos, Texas, 2008 Joint Annual Meeting of the Geological Society of America and the Houston Geological Society, pp. 24–33.

Córdoba, D. A., 1968, Juárez Mountains: West Texas Geological Society, Guidebook, Publication 68-55, pp. 85–86.

Córdoba, D. A., 1969a, Mesozoic stratigraphy of northeastern Chihuahua, México; *in* Córdoba, D. A., Wengerd, S. A., and Shomaker, J. (eds.), Guidebook of the border region: New Mexico Geological Society, Guidebook 20, pp. 91–96.

Córdoba, D. A., 1969b, Geologia del area de Cerro de Muleros o Cristo Rey [inset on the] Carta geológica de México, scale 1:100,000, hoja Ciudad Juárez 13R-a(3); *in* Córdoba, D. A., Wengerd, S. A., and Shomaker, J. (eds.), Guidebook of the border region: New Mexico Geological Society, Guidebook 20, rear pocket.

Cornell, W. C., 1982, Dinoflagellate cysts from the Mesilla Valley Shale (late Albian), El Paso, Texas (abs.): American Association of Stratigraphic Palynologists, 14th Annual Meeting, October, 1981, Program and Abstracts, p. 17.

Cornell, W. C., 1997, Dinoflagellate cysts from the Buda Limestone (Cenomanian) Cerro de Cristo Rey, Doña Ana County, New Mexico: Review of Paleobotany and Palynology, v. 98, pp. 153–157.

Cornell, W. C., and LeMone, D. V., 1987, The Anapra Sandstone of Cerro de Cristo Rey, Doña Ana County, New Mexico (abs.): New Mexico Journal of Science, v. 27, p. 123.

Cornell, W.C., LeMone, D.V., and Norland, W. D., 1991, Albian ophiuroids from Cerro de Cristo Rey, Doña Ana County, New Mexico: Journal of Paleontology, v. 65, pp. 1009–1013.

Emory, W. H., 1857, Report of the United States and Mexican boundary survey: U.S. 34th Congress, 1st session, Senate ex. Doc. 108, v. 1, pt. 2, 174 pp.

Flügel, E., 2004, Microfacies of carbonate rocks: analysis, interpretation and application: Springer, Berlin, 976 pp.

Hendricks, L., 1967, Comanchean stratigraphy of the Cretaceous of north Texas; *in* Hendricks, L. (ed.), Comanchean (Lower Cretaceous) stratigraphy and paleontology of Texas: Society of Economic Paleontologists and Mineralogists (SEPM), Permian Basin Section, Publication 67-8, pp. 51–63.

Hobday, D. K., and Morton, R. A., 1984, Lower Cretaceous shelf storm deposits, northeast Texas; *in* Tillman, R. W., and Siemers, C. T. (eds.), Siliciclastic shelf sediments: Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication 34, pp. 205–213.

Hook, S. C., 2008, Gallery of geology—Sierra de Cristo Rey: New Mexico Geology, v. 30, pp. 93–94.

Imlay, R. W., 1944, Cretaceous formations of Central America and Mexico: American Association of Petroleum Geologists, Bulletin 28, pp. 878–1028.

Kappus, E. J., 2007, Middle Cretaceous dinosaur tracks at Cerro de Cristo Rey, Sunland Park, New Mexico, and a comparison with other paleocoastal tracksites of the southwestern US: Unpublished M.S. thesis, University of Texas at El Paso, 152 pp.

Kappus, E. J., Lucas, S. G., Heckert, A. B., Hunt, A. P., and Lockley, M. G., 2003, Dinosaur footprints from the Lower Cretaceous Sarten Member of the Mojado Formation at Cerro de Cristo Rey, Doña Ana County, New Mexico: Ichnos, v. 10, pp. 263–267.

Kennedy, W. J., Cobban, W. A., and Hook, S. C., 1988, Middle Cenomanian (Late Cretaceous) molluscan fauna from the base of the Boquillas Formation, Cerro de Muleros, Doña Ana County, New Mexico; *in* Contributions to Late Cretaceous paleontology and stratigraphy of New Mexico, Part II: New Mexico Bureau of Mines and Mineral Resources, Bulletin 114, pp. 35–44.

Kollmann, H. A., Decker, K., and LeMone, D. V., 2003, Facies control of Lower Cretaceous gastropod assemblages, southwestern United States; *in* Scott, R. W. (ed.), Cretaceous stratigraphy and paleoecology, Texas and Mexico: Perkins Memorial volume, GCSSEPM Foundation, Special Publications in Geology, v. 1, pp. 101–146.

Kues, B. S., 1989, Taxonomy and variability of three *Texigryphaea* (Bivalvia) species from their Lower Cretaceous (Albian) type localities in New Mexico and Oklahoma: Journal of Paleontology, v. 63, pp. 454–483.

Kues, B. S., 1997, New bivalve taxa from the Tucumcari Formation (Cretaceous, Albian), New Mexico, and the biostratigraphic significance of the basal Tucumcari fauna: Journal of Paleontology, v. 71, pp. 820–839.

Kues, B. S., and Lucas, S. G., 1987, Cretaceous stratigraphy and paleontology in the Dry Cimarron Valley, New Mexico, Colorado, and Oklahoma; *in* Lucas, S. G., and Hunt, A. P. (eds.), Northeastern New Mexico: New Mexico Geological Society, Guidebook 38, pp. 167–198.

LeMone, D. V., and Simpson, R. D., 1983, Cretaceous biostratigraphy of the Franklin Mountains, El Paso County, Texas; *in* Allen, R. (ed.), Delaware Basin: West Texas Geological Society, Publication 82–76, pp. 85–87.

Lovejoy, E. M. P., 1976, Geology of Cerro de Cristo Rey uplift, Chihuahua and New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 31, 84 pp.

Lozo, F. E., and Stricklin, F. L., Jr., 1956, Stratigraphic notes on the outcrop basal Cretaceous, central Texas: Gulf Coast Association of Geological Societies, Transactions, v. 6, pp. 67–78.

Lucas, S. G., and Estep, J. W., 1998a, Cretaceous stratigraphy and biostratigraphy in the southern San Andres Mountains, Doña Ana County, New Mexico; *in* Mack, G. H., Austin, G. S., and Barker, J. M. (eds.), Las Cruces country II: New Mexico Geological Society, Guidebook 49, pp. 187–196.

Lucas, S. G., and Estep, J. W., 1998b, Lithostratigraphy and biostratigraphy of the Lower-Middle Cretaceous Bisbee Group, southwestern New Mexico, USA; *in* Lucas, S. G., Kirkland, J. I., and Estep, J. W. (eds.), Lower and middle Cretaceous terrestrial ecosystems: New Mexico Museum of Natural History and Science, Bulletin 14, pp. 39–55.

Lucas, S. G., and Estep, J. W., 2000, Lower Cretaceous stratigraphy, correlation and paleogeography of New Mexico; *in* Lucas, S. G. (ed.), New Mexico's fossil record 2: New Mexico Museum of Natural History and Science, Bulletin 16, pp. 45–61.

Lucas, S. G., Estep, J. W., Boucher, L. D., and Anderson, B. G., 2000, Cretaceous stratigraphy, biostratigraphy and depositional environments near Virden, Hidalgo County, New Mexico; *in* Lucas, S. G. (ed.), New Mexico's fossil record 2: New Mexico Museum of Natural History and Science, Bulletin 16, pp. 107–119.

Lucas, S. G., Kues, B. S., Hayden, S. N., Allen, B. D., Kietzke, K. K., Williamson, T. E., Sealey, P., and Pence, R., 1988, Cretaceous stratigraphy and biostratigraphy, Cooke's Range, Luna County, New Mexico; *in* Mack, G. H., Lawton, T. F., and Lucas, S. G. (eds.), Cretaceous and Laramide tectonic evolution of southwestern New Mexico: New Mexico Geological Society, Guidebook 39, pp. 143–167.

Mack, G. H., 1987, Mid-Cretaceous (late Albian) change from rift to retroarc foreland basin in southwestern New Mexico: Geological Society of America, Bulletin, v. 98, pp. 507–514.

Mauldin, R. A., 1985, Foraminiferal biostratigraphy, paleoecology, and correlation of the Del Rio Clay (Cenomanian), from Big Bend National Park, Brewster County, Texas, to the Cerro de Muleros area, Doña Ana County, New Mexico: Unpublished M.S. thesis, University of Texas at El Paso, 89 pp.

Mauldin, R. A., and Cornell, W. C., 1986, Paleoecology and biostratigraphic correlation of the Del Rio Clay, Cerro de Cristo Rey, Doña Ana County, New Mexico; *in* Hoffer, J. M. (ed.), Geology of south-central New Mexico: El Paso Geological Society, Guidebook, pp. 77–84.

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 west-central United States: Society of Economic Peleontologists and Mineralogists (SEPM), Rocky Mountain Section, Rocky Mountain Paleogeography Symposium 2, pp. 201–224.

Nye, O. B., Jr., and LeMone, D. V., 1978, Multilaminar growth in *Reptomulticava texana*, a new species of cyclostome bryozoa: Journal of Paleontology, v. 52, pp. 830–885.

Reaser, D. F., and Malott, V. E., 1985, Finlay Limestone: A key to geological interpretation in western Trans-Pecos Texas and northeastern Texas and northeastern Chihuahua, Mexico; *in* Dickerson, P. W., and Muehlberger, W. R. (eds.), Structure and tectonics of Trans-Pecos Texas: West Texas Geological Society, Publication 85–81, pp. 213–219.

Reaser, D. F., and Robinson, W. C., 2003, Cretaceous Buda Limestone in west Texas and northern Mexico; *in* Scott, R. W. (ed.), Cretaceous stratigraphy and paleoecology, Texas and Mexico: Perkins Memorial volume, GCSSEPM Foundation, Special Publications in Geology, v. 1, pp. 337–373.

Richardson, G. B., 1909, Description of the El Paso quadrangle Texas; *in* Geologic atlas of the United States, El Paso folio no. 166: U.S. Geological Survey, 11 pp.

Scott, R. W., 1970, Stratigraphy and sedimentary environments of Lower Cretaceous rocks, southern Western Interior: American Association of Petroleum Geologists, Bulletin, v. 54, pp. 1225–1244.

Scott, R. W., and Kidson, E. J., 1977, Lower Cretaceous depositional systems, west Texas; *in* Bebout, D. G., and Loucks, R. G. (eds.), Cretaceous carbonates of Texas and Mexico: Texas Bureau of Economic Geology, Report of Investigations 89, pp. 169–181.

Scott, R. W., Holbrook, J. M., Evetts, M. J., and Oboh-Ikuenobe, F. E., 2001, Albian–Cenomanian depositional cycles transgressed from Chihuahua trough to Western Interior; *in* Lucas, S. G., and Ulmer-Scholle, D. S. (eds.), Geology of the Llano Estacado: New Mexico Geological Society, Guidebook 52, pp. 221–228.

Scott, R. W., Hooman, L., and Fee, D. W., 1975, Density-current strata in Lower Cretaceous Washita Group, north-central Texas: Journal of Sedimentary Petrology, v. 45, pp. 562–575.

Scott, R. W., Schlager, W., Fouke, B., and Nederbragt, S. A., 2000, Are mid-Cretaceous eustatic events recorded in Middle East carbonate platforms? *in* Alsharhan, A. S., and Scott, R. W. (eds.), Middle East models of Jurassic/Cretaceous carbonate systems: SEPM (Society for Sedimentary Geology), Special Publication 69, pp. 73–84.

Scott, R. W., Benson, D. G., Morin, R. W., Shaffer, B. L., and Oboh-Ikuenobe, F. E., 2003, Integrated Albian–lower Cenomanian chronostratigraphy standard, Trinity River section, Texas; *in* Scott, R. W. (ed.), Cretaceous stratigraphy and paleoecology, Texas and Mexico: Perkins Memorial volume, GCSSEPM Foundation, Special Publications in Geology, v. 1, pp. 277–334.

Seager, W. R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 36, 97 pp.

Stanton, T. W., and Vaughan, T. W., 1896, Sections of the Cretaceous at El Paso, Texas: American Journal of Science, 4th series, v. 1, pp. 21–26.

Steinhoff, D., 2003, Albian Finlay Formation stratotype, Rimrock escarpment, west Texas; *in* Scott, R. W. (ed.), Cretaceous stratigraphy and paleoecology, Texas and Mexico: Perkins Memorial volume, GCSSEPM Foundation, Special Publications in Geology, v. 1, pp. 69–99.

Strain, W. S., 1968, Cerro de Muleros (Cerro de Cristo Rey): West Texas Geological Society, Delaware Basin Exploration Guide, Publication 68–55, p. 82.

Strain, W. S., 1976, New formation names in the Cretaceous at Cerro de Cristo Rey, Doña Ana County, New Mexico; *in* Lovejoy, E. M. P., Geology of Cerro de Cristo Rey uplift, Chihuahua and New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 31, pp. 77–82.

Turnšek, D., LeMone, D. V., and Scott, R. W., 2003, Tethyan Albian corals, Cerro de Cristo Rey uplift, Chihuahua and New Mexico; *in* Scott, R. W. (ed.), Cretaceous stratigraphy and paleoecology, Texas and Mexico: Perkins Memorial volume, GCSSEPM Foundation, Special Publications in Geology, v. 1, pp. 147–185.

Young, K., 1966, Texas Mojsisovicinae (Ammonoidea) and the zonation of the Fredericksburg: Geological Society of America, Memoir 100, 225 pp.

Young, K., 1979, Lower Cenomanian and late Albian (Cretaceous) ammonites, especially Lyelliceridae, of Texas and Mexico: Texas Memorial Museum, Bulletin 26, 99 pp.

Zeller, R. A., Jr., 1965, Stratigraphy of the Big Hatchet Mountains area, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 16, 128 pp.

Appendix

Location of measured sections

Finlay Formation (Fig. 6)—base at UTM Zone 13, 355011E 3518134N (NAD 27), top at 355064E 3518629N.

Del Norte Formation (Fig. 7)—base at top of section A, top at UTM Zone 13, 355084E 3517962N (NAD 27).

Smeltertown Formation (Fig. 8)—base at UTM Zone 13, 355178E 3517669N, top at 355040E 3517595N.

Muleros Formation (Fig. 9)—base at UTM Zone 13, 354953E 3517640N, top at 354922E 3517683N.

Mesilla Valley Formation (Fig. 10)—base at UTM Zone 13, 354508E 3518122N, top at 354535E 3518200N.

Mojado Formation (Fig. 11)—base at UTM Zone 13, 354003E 3518452N, top at 353967E 3518553N.

Del Rio Formation (Fig. 13)—base at UTM Zone 13, 353899E 3118636N, top at 353871E 3518678N.

Buda Formation (Fig. 14)—base at UTM Zone 13, 353881E 3518823N, top at 353859E 3518828N.

Mancos Formation (Fig. 15)—base at UTM Zone 13, 353534E 3518775N, top at 353524E 3518792N.