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Cretaceous Stratigraphy in the Sandia Mountains, New Mexico

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CRETACEOUS STRATIGRAPHY IN THE SANDIA MOUNTAINS, NEW MEXICO

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Abstract—Cretaceous strata are exposed in two areas in the Sandia Mountains—at Placitas, near the northern end of the range, and in the Tijeras syncline along its southeastern edge. In the vicinity of Placitas, a much-faulted Cretaceous section 756 m thick can be pieced together from overlapping stratigraphic units that crop out on separate fault blocks. The following lithostratigraphic units can be recognized: Dakota Sandstone (Encinal Canyon, Oak Canyon and Cubero members), lower Mancos Formation (Graneros, Greenhorn, Carlile, Juana Lopez, D-Cross, and El Vado members), Dalton-Hosta Sandstone, Satan Member of the Mancos Formation, Point Lookout Sandstone and Menefee Formation. Limited biostratigraphic data from inoceramids and ammonites identify Turonian-age horizons in the Placitas Cretaceous section.

Cretaceous strata exposed in the Tijeras syncline are a similar succession (with the addition of the Tocito Sandstone and Gibson Coal Member of the Crevasse Canyon Formation) that is 695 m thick. Coal deposits of the "Tijeras coal field" are located at two disparate stratigraphic levels, a lower level in the Gibson Coal Member and a higher level in the lower Menefee Formation. The Cretaceous strata exposed in the Sandia Mountains record marine, shoreline and nonmarine depositional environments from the late Albian? and early Cenomanian through early Campanian (~ 80-100 Ma). These strata are generally correlative to those present in the southeastern San Juan Basin to the west-northwest, but are a thinner stratigraphic section, likely due to differential subsidence and tectonic thinning of the Cretaceous section in the Sandia Mountains.

INTRODUCTION

Cretaceous strata are exposed in and around parts of the Sandia Mountains in Bernalillo and Sandoval counties, New Mexico. These are outcrops in the vicinity of Placitas, near the northern end of the range, and in the Tijeras syncline along its southeastern edge (Fig. 1). These strata have been mapped and described in a general way (see below), but detailed lithostratigraphic and biostratigraphic data have not been published. Here, I present such data (Fig. 2) to achieve a better understanding of how the Cretaceous outcrops in the Sandia Mountains fit into a broader understanding of the Cretaceous section in central New Mexico.

METHODS

Five stratigraphic sections of the Cretaceous strata near Placitas (Fig. 3) were measured with a 1.5 m staff and pocket transit (Figs. 4-6), and 11 stratigraphic sections of the Cretaceous strata in the Tijeras syncline (Fig. 7) were similarly measured, and seven of them are illustrated here in graphic form (Figs. 8-10) Lithology was determined on outcrop or in the laboratory from hand samples collected in the field. Macrofossils were collected where encountered and are now in the collection of the New Mexico Museum of Natural History and Science (NMMNH). USGS refers to the United States Geological Survey.

PLACITAS

Geological pioneers working in central New Mexico knew of the presence of Cretaceous strata near Placitas, mostly using the nearby and now defunct town of Tejon as a reference point (e. g., Herrick and Johnson, 1900). Darton (1928, p. 101, fig. 26, pl. 24) first assigned the Cretaceous rocks that crop out near Placitas to regionally recognized lithostratigraphic units, the Dakota Sandstone, Mancos Shale and Colorado Group.

Kelley and Northrop (1975, p. 57-61, map 1) described and mapped the Cretaceous strata in the Sandia Mountains. They assigned these strata to the Dakota Sandstone, Mancos Shale and Mesaverde Formation. Molenaar (1983, fig. 2) published a cross section of the Cretaceous strata across the "east side of the Albuquerque trough-Rio Grande" (from Truth or Consequences to Los Cerrillos) in which he showed a general stratigraphic column of the Cretaceous section at Placitas (S 1/2 sec. 29, T13N, R5E). He assigned the Cretaceous strata to the (ascending) Dakota Sandstone, Whitewater Arroyo Tongue of Mancos Shale, Twowells Tongue of Dakota Sandstone, Mancos Shale, including the Greenhorn Limestone and Juana Lopez members, merged Dalton Sandstone Member of the Crevasse Canyon Formation and Hosta Tongue of the Point Lookout Sandstone, Satan Tongue of the Mancos Shale, Point Lookout Sandstone, Menefee Formation and, near the top, a possible thin interval of the Cliff House Sandstone.

Menne (1989) mapped the Placitas quadrangle as a M.S. thesis at the University of New Mexico. She identified the Cretaceous strata as (ascending) Dakota Sandstone (22 m thick), Mancos Shale (minimum thickness 344.5 m), and "Mesaverde" divided into the Hosta-Dalton Sandstone (63.5 m), Point Lookout Sandstone (74.5 m) and Menefee Formation, consisting of a lower member (111 m), Harmon sandstone (30 m) and upper member (223 m) (also see Woodward and Menne, 1995).

As part of the STATEMAP program, Connell et al. (1995) mapped the Placitas quadrangle and assigned the Cretaceous strata to the (ascending) Dakota Sandstone (22 m thick), lower Mancos Shale, including the Juana Lopez Member (total thickness 310 m), Hosta-Dalton Sandstone (65-115 m thick), upper Mancos Shale (65 m), Point Lookout Sandstone (75 m) and Menefee Formation, 250-560 m thick, stating that a "Harmon Sandstone Member" is 110 m above the base. Note, though,

that the name Harmon Sandstone refers to an informal, undefined member of the Menefee.

Lucas and Rogers (2017) presented a preliminary report on the Cretaceous stratigraphy at Placitas that is detailed here. An important point is that use of Mesaverde Formation or Group by previous workers has been incorrect (e.g., Darton, 1928; Menne, 1989). Proper use of Mesaverde is to restrict it to the Point Lookout, Menefee and Cliff House formations, and not to apply it to underlying strata that are not part of the Mesaverde Group as originally and currently defined (e.g., Molenaar, 1983; Sealey and Lucas, 2019 and references cited therein).

Lithostratigraphy

As just noted, previous workers have identified up to six mappable Cretaceous lithostratigraphic units in the Placitas area: Dakota, lower Mancos, Hosta-Dalton, upper Mancos, Point Lookout and Menefee. My stratigraphic work identifies these units and divides the Cretaceous section into 13 named

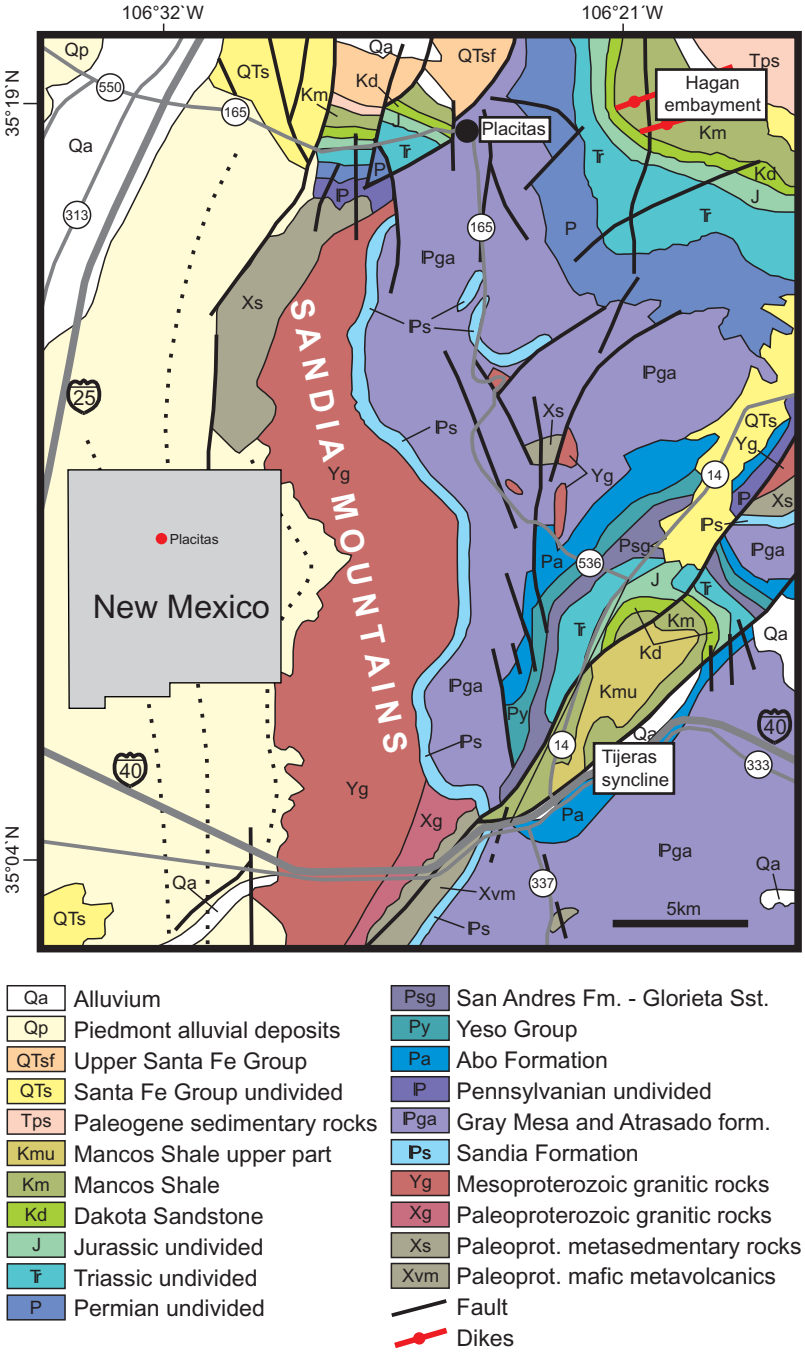


FIGURE 1. Geologic map of the Sandia Mountains and vicinity (based on New Mexico Bureau of Geology and Mineral Resources, 2003). Note the location of Placitas (the outcrops described here are those west of the village) and of part of the Hagan embayment to the northeast of Placitas, and the Tijeras syncline on the southeastern flank of the Sandia Mountains. Note that the upper Mancos is probably present in the northern Km map unit west of Placitas but likely not shown on the NM State Geologic Map because it is too small to show at the map scale

lithostratigraphic units (Table 1; Fig. 2). The total Cretaceous section around Placitas by my measurements is about 756 m thick.

Encinal Canyon Member and Dakota-Mancos Succession

At Placitas, the base of the Cretaceous section locally is the Encinal Canyon Member of the Dakota Sandstone (Aubrey, 1988), about 1-2 m of trough cross-bedded quartzose sandstone with some silica-pebble lenses (Fig. 4). The Encinal has a sharp contact on the underlying kaolinitic sandstone at the top of the Jackpile Member of the Morrison Formation (Lucas, 2018). It is a fluvial unit of possible Early Cretaceous (late Albian?) age locally present between the Jackpile and Oak Canyon members (Lucas et al., 1998). Correlation of this unit to the Burro Canyon Formation is not certain because no age data support that correlation, although it is a possible correlation.

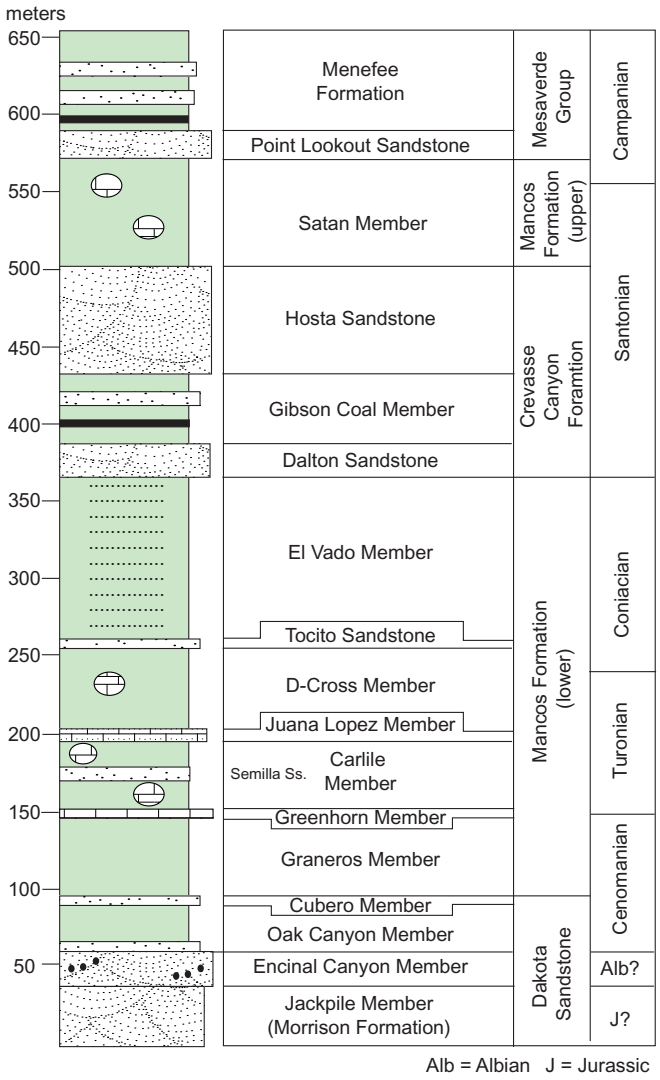


FIGURE 2. Summary of the Cretaceous stratigraphic section in the Tijeras syncline. Lithology schematic, thicknesses are maxima, and age assignments are based primarily on the ages of these units in the southeastern San Juan Basin (Sealey and Lucas, 2019) supported in part by some local biostratigraphic data summarized in the text. The Cretaceous stratigraphic section in the Placitas area is very similar, though thicknesses vary between the Tijeras syncline and the Placitas area (Table 1).

The interbedded Dakota-Mancos succession consists of sandstone-dominated sheets of the Dakota Sandstone interbedded with shale-dominated units of the Mancos Formation. At Placitas, the Dakota-Mancos succession plus the Encinal Canyon Member encompass the entire unit some previous workers referred to as the Dakota Sandstone.

Overlying the Encinal Canyon Member, the base of the Oak Canyon Member of the Dakota Sandstone consists of 0.5 m of bioturbated sandstone that overlies the Encinal Canyon Member on a sharp contact. Overlying Oak Canyon strata are 11 m of gray sandy shale and bioturbated sandstone with some small limestone concretions that contain steinkerns of marine gastropods. A bentonite bed below the middle of these strata is likely the A bentonite of Owen et al. (2005), for which they reported an $^{40}Ar/^{39}Ar$ age of 98.1 ± 2.4 Ma, which is an early Cenomanian age.

Above the Oak Canyon Member is a sandstone interval ~ 6 m thick that is mostly heavily bioturbated and a cuesta/bench former. I identify this sandstone interval as the Cubero Member of the Dakota Sandstone, by correlation to the section at Galisteo Dam, ~ 27 km to the north-northeast (Lucas, 2002). Molenaar (1983) termed the Dakota-Mancos succession at Placitas the Whitewater Arroyo Shale of the Mancos overlain by the Twowells Sandstone of the Dakota. This is a miscorrelation, as the strata at Placitas do not closely resemble the Whitewater Arroyo-Twowells lithologically, and the Twowells is of late Cenomanian age. At Placitas, the Whitewater Arroyo Shale is shale that lacks the bentonitic beds, carbonaceous beds and sandy beds of the Oak Canyon Member, and the Cubero is a fine- to medium-grained, bioturbated sandstone, unlike the coarser grained, cross-bedded Twowells Sandstone. The upper sandstone sheet of the Dakota Sandstone at Galisteo Dam is lithologically similar and in the same stratigraphic position as the upper sheet at Placitas, but at Galisteo Dam it contains fossils of the middle Cenomanian *Acanthoceras amphibolum* zone (Lucas et al., 1998; Lucas, 2002). Indeed, the Dakota strata around the Sandia uplift, at Galisteo Dam, in the Hagan embayment, at Placitas and in the Tijeras syncline, form a consistent succession of Encinal Canyon-Oak Canyon-Cubero members (Lucas et al., 1998; Lucas, 2002).

Lower Mancos Formation

At Placitas, the unit previously mapped as lower Mancos Shale consists of six named units usually treated as members of the Mancos Formation (Figs. 2 and 4). In the study area we apply the lower Mancos Shale for the shaly strata below the mappable Hosta Sandstone.

This definition contrasts with some subsurface practice (e.g., Molenaar et al., 2002) that uses the Tocito Sandstone (base of the "Niobrara" interval) unconformity near the stratigraphic interval corresponding to the top of the Gallup to separate a lower Mancos Shale from an upper Manco Shale. Extending the lower Mancos Shale up to the base of the Hosta Sandstone provides a mappable unit in the study area, as demonstrated by

previous mapping (e.g., Menne, 1989; Connell et al., 1995), so I follow that convention for the study area. Given that the Tocito has not been identified near Placitas, using it as the base of an upper Mancos interval is problematic. Furthermore, an upper Mancos so defined would include the Hosta-Dalton interval (and to the south the Gibson Coal Member), units never included in the Mancos Shale.

The lowermost unit of this lower Mancos interval is a poorly exposed interval of gray shale with some sandy beds and bentonites that is about 21 m thick. I apply the name Graneros Shale to it, as is done in the southeastern San Juan Basin (cf. Owen et al., 2007; Sealey and Lucas, 2019), even though this unit at Placitas and in the San Juan Basin represents only a small part of the Graneros Shale on the southern High Plains, where that unit was defined.

The Graneros Shale is overlain by ~ 6 m of white to gray limestone ledges intercalated with calcareous shale (marl), a very distinctive unit readily assigned to the Greenhorn Member. The shale-dominated section above the Greenhorn, the Carlile Member, is about 43 m thick and mostly brown and gray shale with some sandy beds and some large septarian nodules.

Above the Carlile Member, calcarenite beds with bioclastic debris are a characteristic lithology of the Juana Lopez Member. The Juana Lopez Member is relatively thin—a lower calcarenite bed about 1 m thick with a prolific fossil assemblage of bivalves and ammonites, an overlying 0.7 m thick shale and an upper calcarenite 0.2 m thick (Fig. 4).

The shale interval above the Juana Lopez Member is assigned to the D-Cross Member. It is mostly greenish gray shale about 54 m thick. Given that Placitas is seaward of the pinchout of the Gallup Sandstone, the upper part of the unit here called D-Cross Member may include some strata equivalent to the Mulatto Member of the Mancos, which is between the Gallup and Dalton sandstones southwest of the Gallup pinchout (cf. Hunt, 1936; Molenaar, 1983).

The pinchout of the Gallup Sandstone causes complications for field-based stratigraphy. To the west, the basal Niobrara unconformity can be observed that separates the Gallup Sandstone from the overlying Tocito Sandstone (Molenaar, 1983). However, in the absence of the Gallup Sandstone this unconformity cannot be confidently observed (i.e., it is a cryptic, shale-on-shale unconformity). This unconformity would separate what some workers consider as the lower vs upper Mancos Shales (Molenaar et al., 2002). Since I cannot identify the unconformity, I follow previous stratigraphic studies here (Black, 1979, 1982) in extending the D Cross up to the Tocito Sandstone.

The Tocito Sandstone represents offshore bars deposited following the Gallup regression (e.g., Molenaar, 1983). The Tocito is present in the Hagan embayment and in the Tijeras syncline (Molenaar, 1973; Black, 1979). However, the Tocito

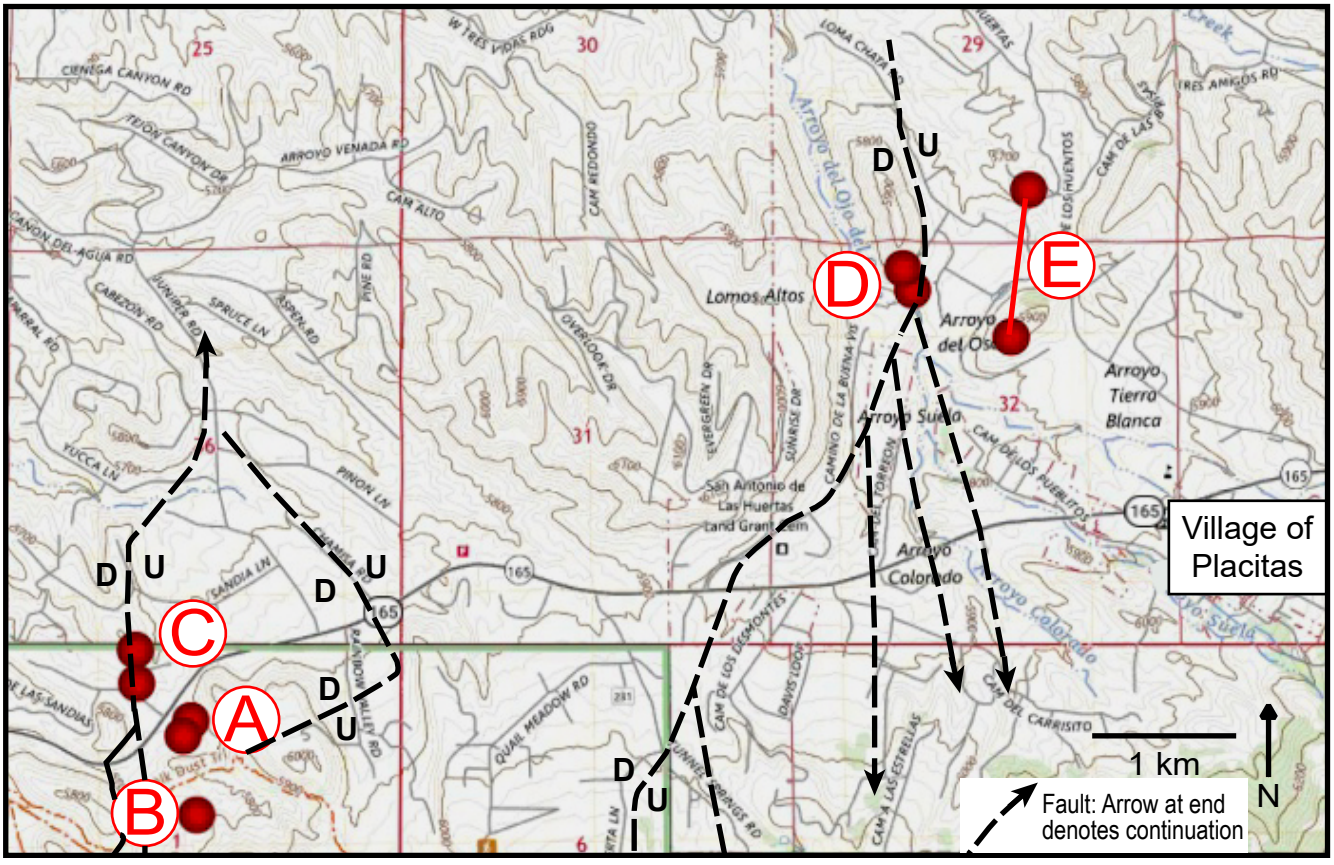


FIGURE 3. Location of measured stratigraphic sections of Cretaceous rocks near Placitas (Figs. 3-5) on a topographic map base. Sections are: A= Historical Marker A, B = Historical Marker B, C = Historical Marker C, D = Arroyo del Carbon A, and E = Arroyo del Carbon B. Partial locations of faults are shown by thick, black lines (dashed where approximate); these faults are from Connell et al. (2005). Please see that work for comprehensive fault locations.

bars are elongated NW-SE and laterally discontinuous in a dip direction (~SW-NE) (McCubbin, 1969; Valasek, 1995). Thus, the Tocito Sandstone is not present everywhere. Like Black (1979), I could not locate the Tocito Sandstone on outcrop in the Placitas area (it is likely in a covered interval or faulted away from the surface). If present, it would likely be an ~ 5

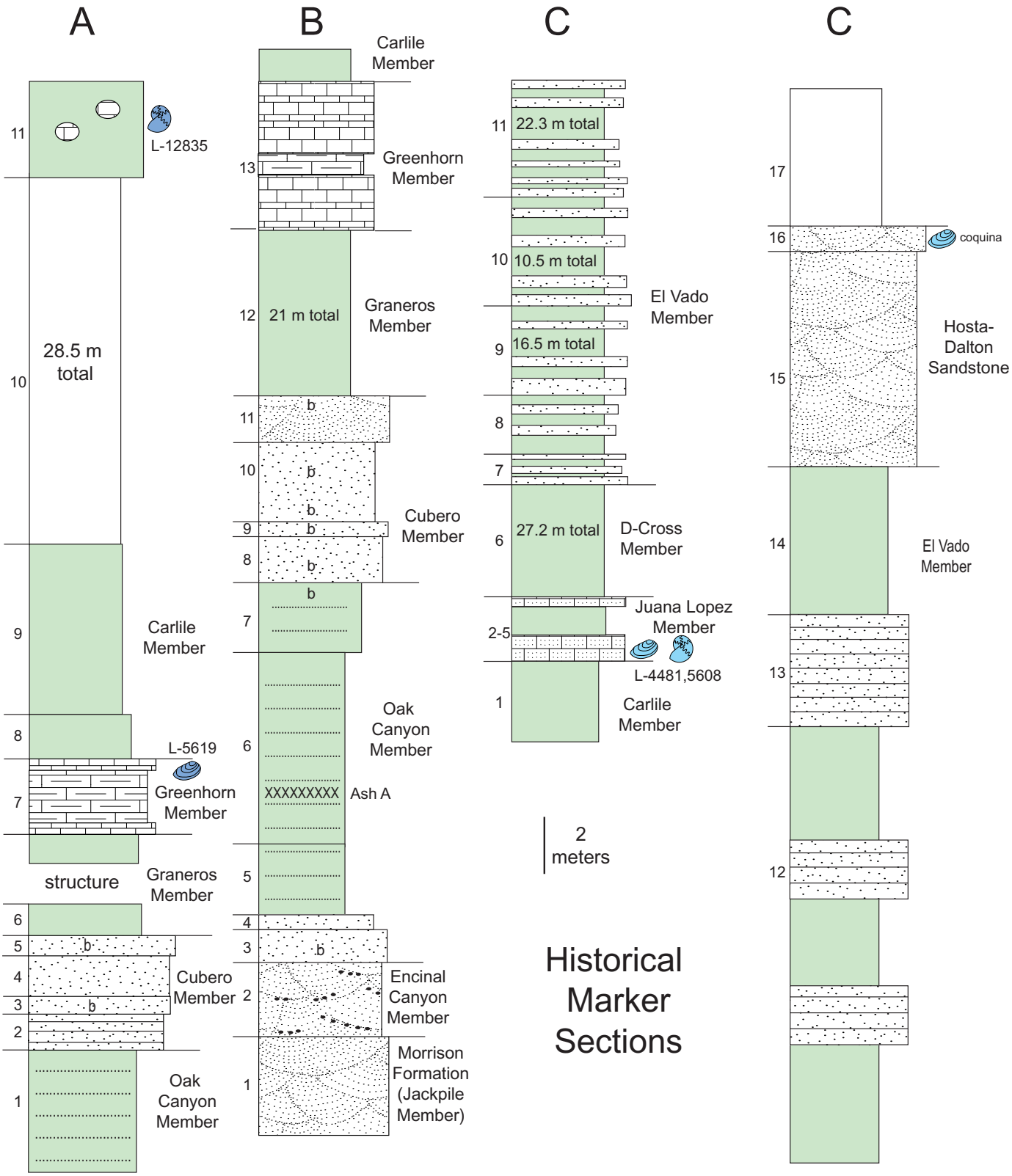


FIGURE 4. Stratigraphic sections of Cretaceous strata exposed near the Historical Marker along NM Highway 165 west of Placitas. Coordinates of the sections (UTM, datum NAD 83) are: Historical Marker A (base: 366345, 3907439, top: 366379, 3907500), Historical Marker B (base and top: base and top: 366395, 3907120), and Historical Marker C (base: 366159, 3907653, top: 366157, 3907787). For key to lithologic symbols see Figure 5.

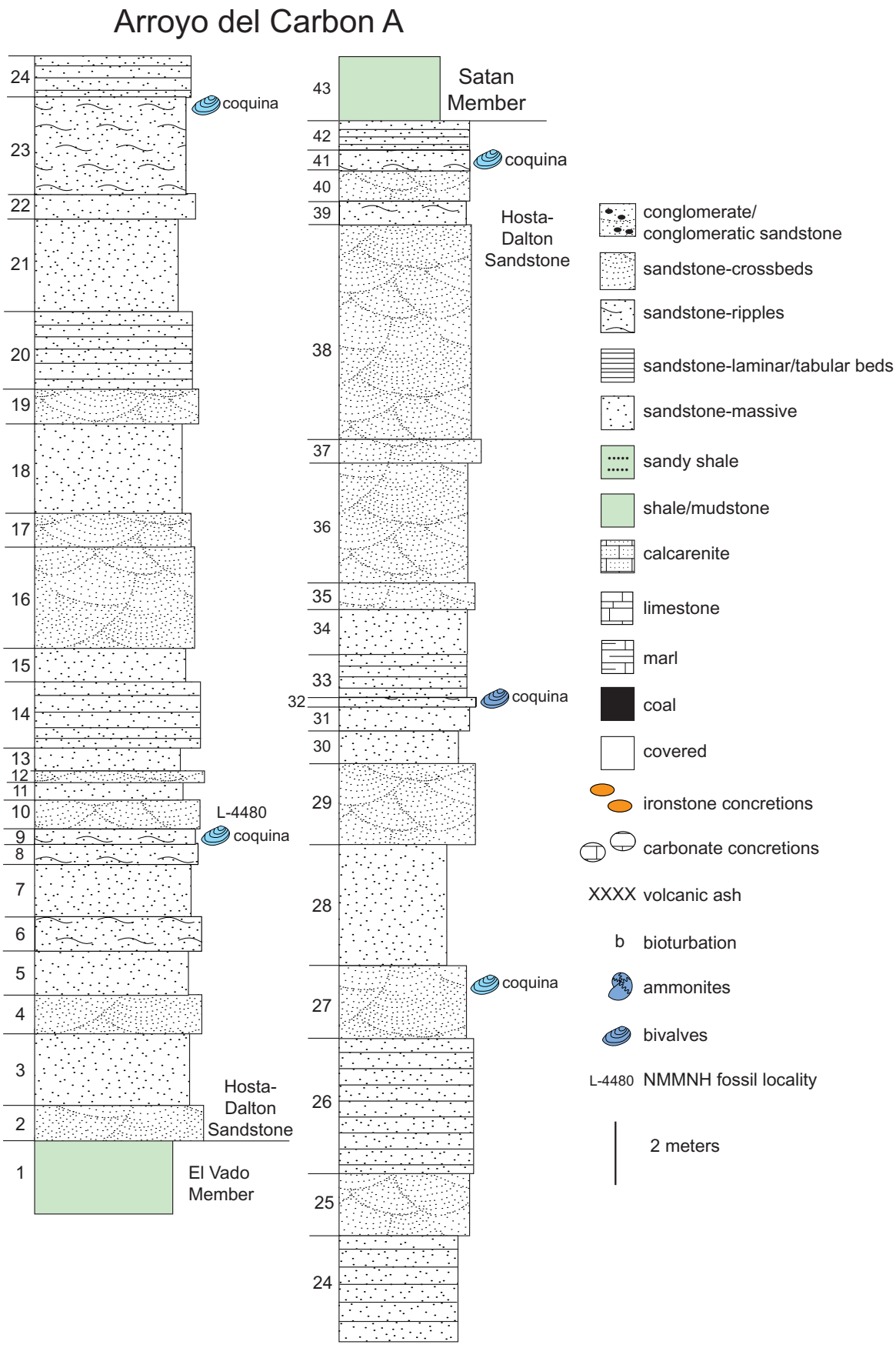


FIGURE 5. Stratigraphic section of a very well exposed outcrop of the Hosta-Dalton Sandstone at the Arroyo del Carbon A, north of Placitas. Coordinates of the section (UTM, datum NAD 83) are: base = 369317, 3909190, top = 369275, 3909273.

m thick unit of coarse-grained, cross-bedded and bioturbated sandstone at or near the El Vado base, as it is elsewhere.

The overlying El Vado Member is a very distinctive unit of thinly interbedded calcareous sandstone and sandy shale with laminar, ripple laminated, and bioturbated beds. Total thickness is 77 m. The entire thickness of the lower Mancos interval is about 203 m.

Hosta-Dalton Sandstone

Above the El Vado Member, the Hosta-Dalton Sandstone is as much as 72 m thick. A complete, well exposed section of the unit at the Arroyo del Carbon A measured section (Fig. 5) reveals it to be almost totally sandstone, which is mostly cross-bedded and tabular bedded; a few beds are ripple laminated or massive. Coquina beds (dominated by shells of the bivalve *Crasatella)* are also characteristic.

To the south, in the Tijeras syncline, the Gibson Coal Member of the Crevasse Canyon Formation is between the Dalton and Host sandstones (see below), but at Placitas and into the Hagan embayment to the north, the Gibson has pinched out, and the Hosta and Dalton are merged into one sandstone-dominated interval. The location of the pinchout is in the Hagan embayment and is the "turnaround" of the Santonian shoreline (Molenaar, 1983; Lucas et al., 2000). Stearns (1953) introduced the name Cano Sandstone for the merged Hosta-Dalton, but it has been little used, and I do not use it.

Upper Mancos

The Mancos Formation above the Hosta-Dalton was mapped by some previous workers as "upper Mancos" (Menne, 1989; Connell et al., 1995). Note that upper Mancos in this sense is defined differently elsewhere by some other workers (e.g. Molenaar et al., 2022), which would include the Tocito Sandstone through Satan Member interval (Fig. 2) as used here. The upper Mancos as used here is the Satan Member, which consists of at least 107 m of tan and yellow shale/sandy shale with a few thin sandstone interbeds and some carbonate concretions (Fig. 6).

Point Lookout Sandstone

The Point Lookout Sandstone overlies the Satan Member and is as much as 32 m thick. It consists of white to tan sandstone that is massive or tabular bedded, locally hematitic and has some calcareous sandstone lenses (Fig. 6).

Menefee Formation

The Menefee Formation (total thickness 324 m) above the Point Lookout Sandstone can be divided into three intervals, a lower, coal-bearing interval, medial sandstone interval and an upper, coal-bearing interval (Fig. 6). The lower, coal-bearing interval is 102 m thick and mostly mudstone intercalated with a few beds of cross-bedded sandstone and some coal beds. The medial sandstone interval (Fig. 6, units 68-71) is 19 m thick and is trough cross-bedded and ripple-laminated sandstone with a few sandy mudstone interbeds. The upper, coal-bearing interval is 204 m thick and mostly mudstone with ironstone concretions, some carbonate concretions and some thin sandstone beds that are cross-bedded, ripple-laminated or planar-laminated.

TABLE 1. Thickness (in meters) of Cretaceous lithostratigraphic units at Placitas compared to the southeastern San Juan Basin (thicknesses from Sealey and Lucas, 2019), Hagan embayment (thicknesses based on unpublished data) and Tijeras syncline. See text for discussion.

Lithostratigraphic unit	SE San Juan Basin	Hagan embayment	Placitas	Tijeras syncline
Menefee	458	251	324	44
Point Lookout	21	106	32	10
Satan	194	115	107	194
Hosta-Dalton	36	57	72	107*
El Vado	120	174	77	123
Mulatto	152	-	-	-
Tocito	5	5	-	5
D-Cross**	100	93	54	
Juana Lopez	40	4	2	3
Carlile	115	30+	43	43+
Greenhorn	21	5	6	4
Graneros	107	63	21	63
Cubero	12	10	6	9
Oak Canyon	17	43	11	29
Encinal	6	30	1	
total	1404	986	756	695

* Includes 47 m thick Gibson Coal Member between Dalton and Hosta
**Called Montezuma Valley Member in SE San Juan Basin

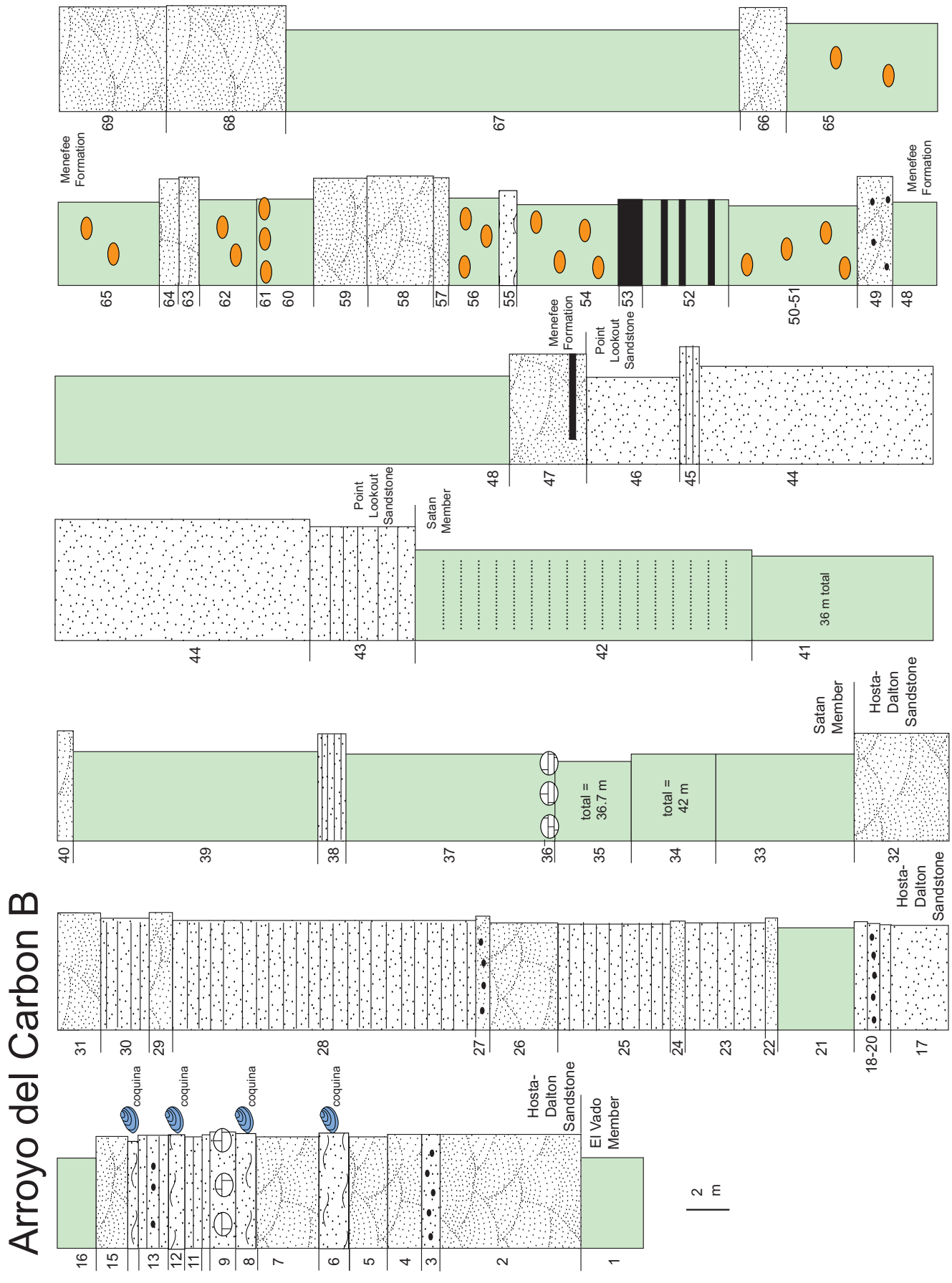


FIGURE 6. Stratigraphic section of the Hosta-Dalton Sandstone, Satan Member of the Mancos Formation, Point Lookout Sandstone and Menefee Formation at the Arroyo del Carbon B section, north of Placitas. Coordinates of the section (UTM, datum NAD 83) are: base = 369699, 3908985, top = 369792, 3909588. For key to lithologic symbols see Figure 5.

In my opinion, the three intervals deserve member rank. However, given lithofacies differences it is doubtful that the San Juan Basin member names Cleary, Allison and upper coal members can be applied, so new stratigraphic nomenclature will be needed. The top of the Menefee Formation has been removed by erosion, so the younger Cretaceous units (Cliff House, Lewis, Pictured Cliffs and Fruitland-Kirtland formations) that crop out in the southeastern San Juan Basin are not present, if they were even deposited, in the Placitas area.

Molenaar (1983) suggested that part of the Cliff House Sandstone may be present above the Menefee Formation at Placitas. In my stratigraphic section, the only possible candidate for a part of the Cliff House Sandstone is the cross-bedded sandstone at the top of the Arroyo del Carbon B section (Fig. 6, unit 130). However, because of its contained pebbles and coaly debris, lack of marine bioturbation and sharp, erosive basal contact, this appears to be a fluvial sandstone of the Menefee, not a shoreline sandstone of the Cliff House. Therefore, I do not identify any strata of the Cliff House Sandstone at Placitas.

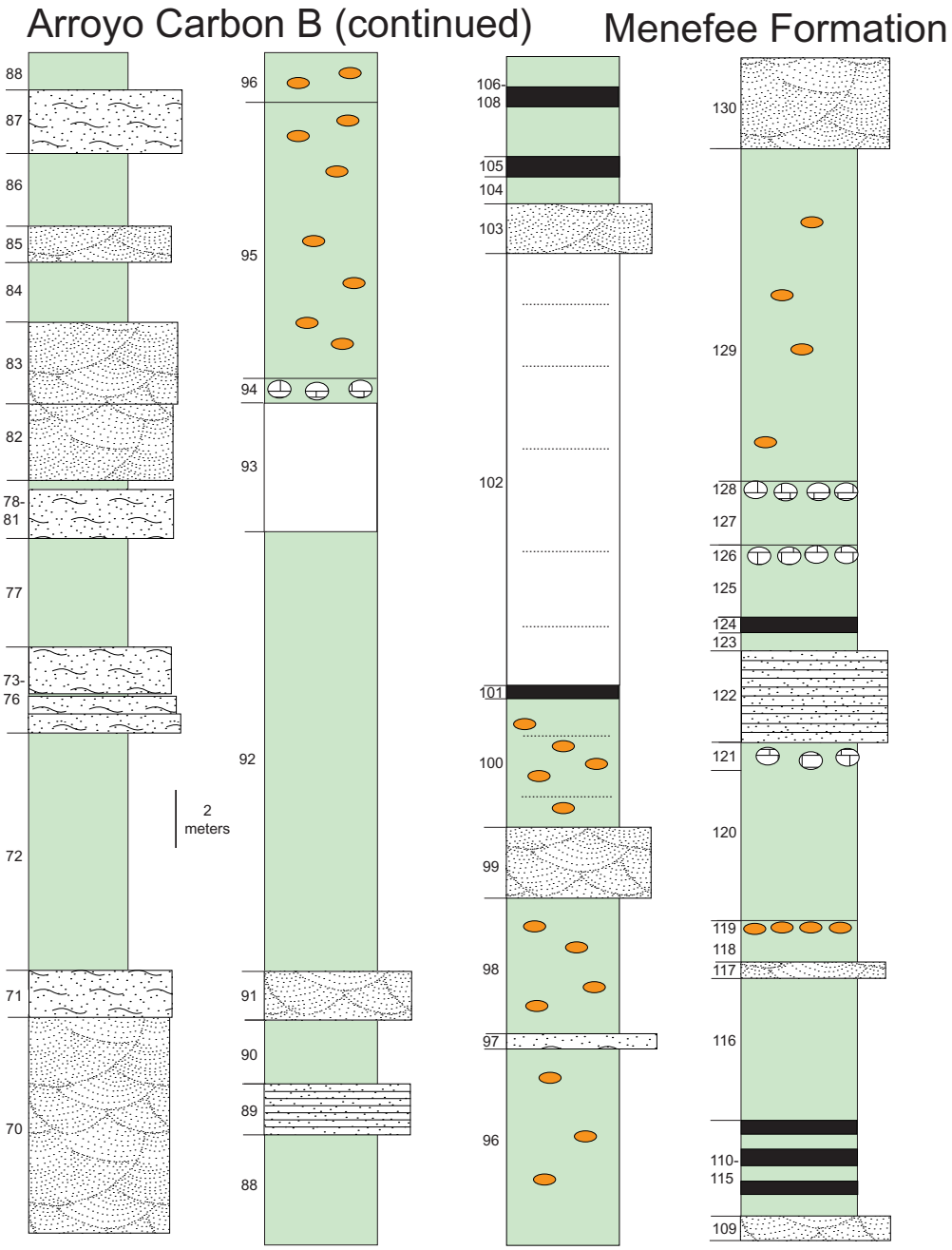


FIGURE 6. (continued) Stratigraphic section of the Hosta-Dalton Sandstone, Satan Member of the Mancos Formation, Point Lookout Sandstone and Menefee Formation at the Arroyo del Carbon B section, north of Placitas. Coordinates of the section (UTM, datum NAD 83) are: base = 369699, 3908985, top = 369792, 3909588. For key to lithologic symbols see Figure 5.

Biostratigraphy

No fossils have previously been reported from the Cretaceous outcrops at Placitas, but I did recover a few fossils, most of biostratigraphic value, from those rocks:

1. The Bridge Creek Member of the Greenhorn Limestone contains numerous bivalves, including the lower Turonian index *Mytiloides mytiloides*, at NMMNH locality 5619 (Fig. 4).
2. In the upper part of the Carlile Member at NMMNH locality 12835, large concretions contain the index ammonite *Prionocyclus hyatti*, indicative of the middle Turonian zone of that name (Fig. 4).
3. The basal calcarenite of the Juana Lopez Member at NMMNH localities 4481 and 5608 contains the bivalve *Inoceramus dimidius* and the ammonites *Scaphites* sp. and *Prionocyclus wyomingensis*, indicative of the *Prionocyclus wyomingensis* Zone of late Turonian age (Fig. 4).
4. The Hosta-Dalton Sandstone contains coquina beds dominated by shells of the bivalve *Crasatella* at NMMNH locality 4480 (Fig. 5) and in other beds and at other locations, but these are not indicative of a precise age.

These fossils are consistent with the paleontology and biostratigraphy of the same stratigraphic units in the southeastern San Juan Basin (Sealey and Lucas, 2019) and in the Hagan embayment (unpublished data).

TIJERAS SYNCLINE

In the early twentieth century geologists working in central New Mexico identified Cretaceous strata on the southeastern flank of the Sandia Mountains (e.g., Herrick and Johnson, 1900) (Figs. 1, 7). Lee (1912, 1917) described these Cretaceous strata as located in the "Tijeras coal field." He noted that "the coal-bearing rocks occupy the center of a syncline of irregular outline about 5 miles [8 km] long and 2 miles [3.2 km] wide" (Lee, 1912, p. 574). Lee (1912) described a stratigraphic section of the Cretaceous strata measured in the coal field as 873 m

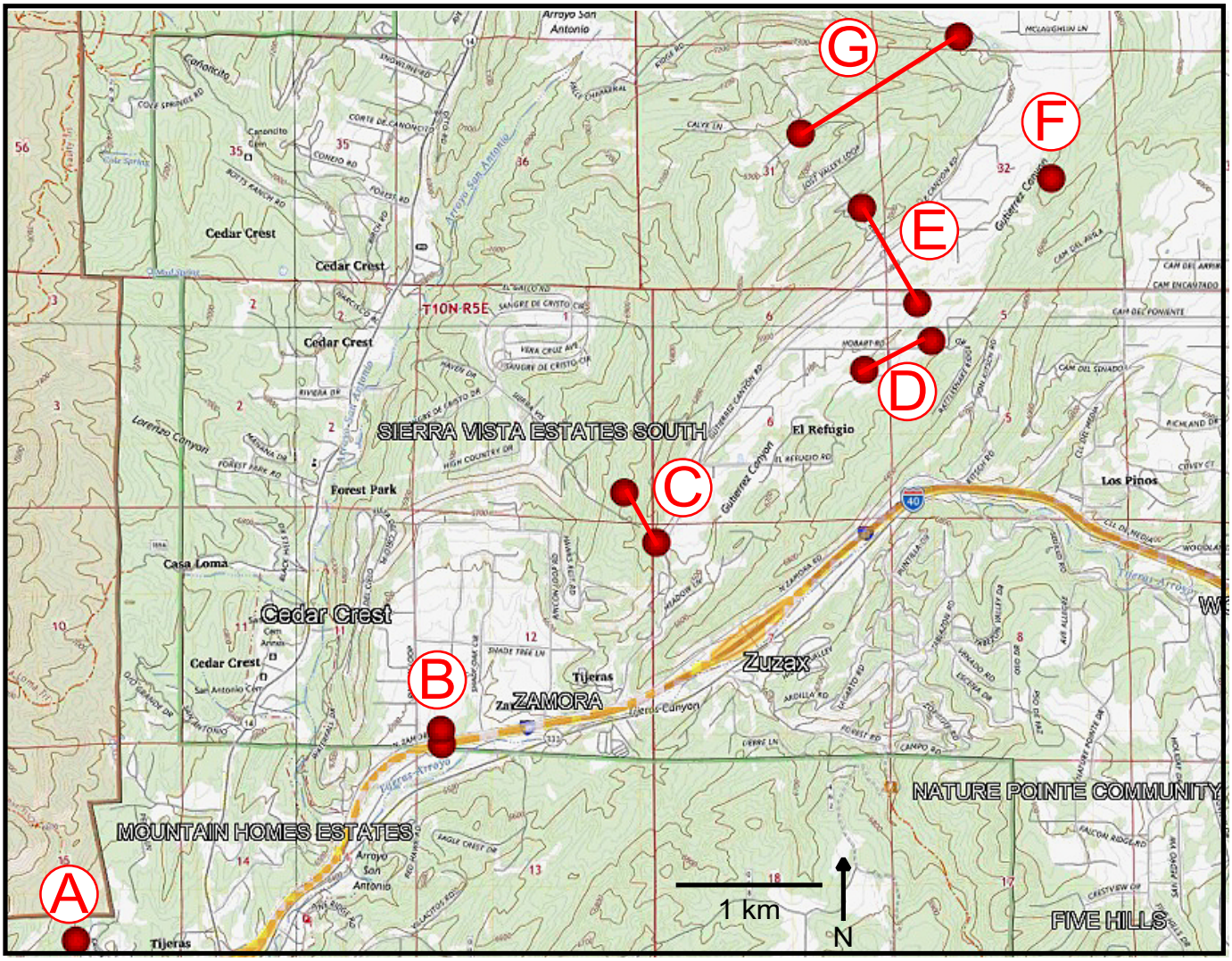


FIGURE 7. Location of measured stratigraphic sections of Cretaceous rocks in the Tijeras syncline (Figs. 8-10) on a topographic map base. Sections are: A= Canyon Estates, B = Zamora, C = Holmes Mine, D = Gutierrez B, E = Gutierrez G, F = Gutierrez H, and G = Gutierrez East.

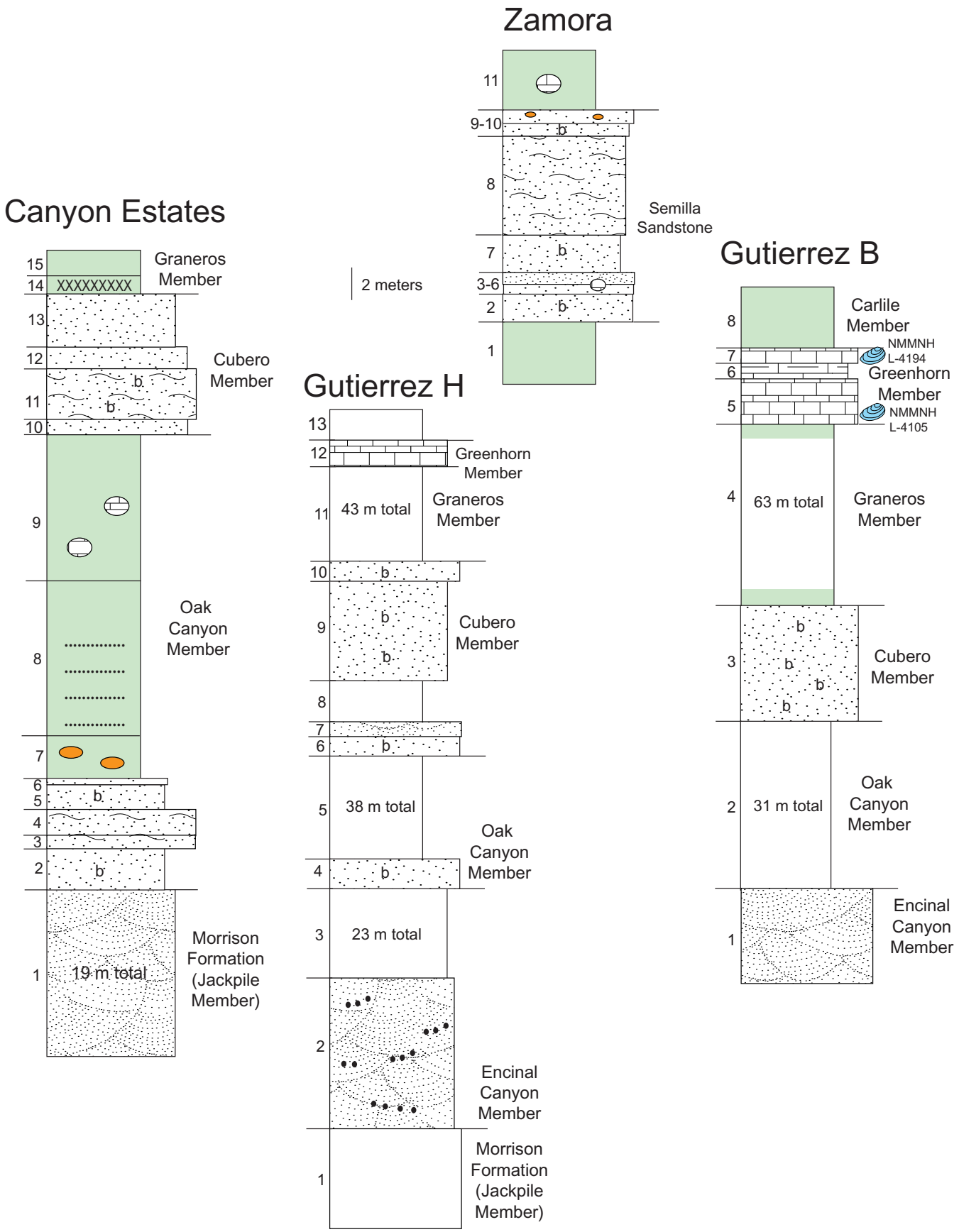


FIGURE 8. Stratigraphic sections of some Cretaceous strata in the Tijeras syncline. UTM coordinates (zone 13, datum NAD 83) of the stratigraphic sections are: Canyon Estates (base and top: 373184, 3883669), Gutierrez H (base and top = 379839, 3888700), Zamora (base = 375667, 3884944, top = 375662, 3885042), Gutierrez B (base = 379239, 3889673, top = 378152, 3889025). See Figure 9 for legend to lithologic symbols.

thick and divided it into (ascending) Dakota Sandstone (20 m), Mancos Shale (410 m) and Mesaverde Group (568 m). Significantly, Lee (1912, pl. 59) identified two-coal bearing intervals in the "Mesaverde Group," one stratigraphically low and the other 122-137 m above the base. Lee (1912, pl. 59) identified two named coal mines in the Tijeras syncline, the Holmes Mine in the lower coal-bearing interval and, to the north, the Tocco Mine in the upper coal-bearing interval. The coal beds in the coal field are less than (mostly much less than) 1 m thick, and Lee (1912, p. 576) noted that "many attempts have been made to find coal in the Tijeras field in beds thick enough to be worked with profit, but most of these attempts have proved futile." Indeed, there was never any economic coal production from the "Tijeras coal field" (Read et al., 1950; Elston, 1967).

Darton's (1928, p. 98, fig., 25, pl. 24) mapping and description of the Cretaceous strata in the "Tijeras coal field" differed little from that of Lee (1912, 1917). Many years later, Kelley and Northrop (1975, p. 58-61, map 1) described and mapped the Cretaceous strata in the Tijeras syncline as Dakota, Mancos and Mesaverde, much as had Lee and Darton.

Molenaar (1983, fig. 2; 1987, fig. 8) published a cross section of the Cretaceous strata across the "east side of the Albuquerque trough-Rio Grande" (from Truth or Consequences to Los Cerrillos) in which he showed a general stratigraphic column of the Cretaceous section in the Tijeras syncline (sec. 6, T10N, R5E). He assigned the Cretaceous strata to the (ascending) Dakota Sandstone, Whitewater Arroyo Tongue of the Mancos Shale, Twowells Tongue of the Dakota Sandstone, Mancos Shale, including the Greenhorn Limestone and Juana Lopez members, Dalton Sandstone Member of the Crevasse Canyon Formation, Crevasse Canyon Formation, Hosta Tongue of the Point Lookout Sandstone, Satan Tongue of the Mancos Shale, Point Lookout Sandstone and Menefee Formation.

In the 1990s, geologists funded by STATEMAP mapped the geology of the two quadrangles that encompass the Tijeras syncline, Sedillo and Sandia Park (Ferguson et al., 1996; Read et al., 1998). These geologists essentially mapped the same units as had Lee, Darton and Kelley and Northrop—Dakota, Mancos and Mesaverde--with a few formal and informal subdivisions identified. It is thus fair to say that other than Molenaar (1983), understanding of the Cretaceous stratigraphy in the Tijeras syncline has progressed little since the work of Lee (1912, 1917).

Lithostratigraphy

As described above, previous workers have identified only three mappable Cretaceous lithostratigraphic units in the Tijeras syncline: Dakota, Mancos, and Mesaverde. My stratigraphic work identifies these units and recognizes 17 named lithostratigraphic units within them (Figs. 2, 8-10; Table 1).

However, as already stated, earlier use of the term Mesaverde was incorrect. The Mesaverde Group is three formations—Point Lookout, Menefee and Cliff House—of Santonian-Campanian age (cf. Sealey and Lucas, 2019 and references cited therein). However, earlier workers, including Lee (1912, 1917), referred any coal-bearing strata in the middle part of the New Mexico Cretaceous section to the Mesaverde. Thus, in addition to the Menefee Formation, the Crevasse Canyon Formation of Coniacian-Santonian age was included by these earlier workers in the Mesaverde Formation or Group. Here, I use Mesaverde in its restricted and correct sense (Fig. 2).

Dakota-Mancos Succession

The interbedded Dakota-Mancos succession consists of interbedded sandstone-dominated sheets of the Dakota Sandstone and shale-dominated units of the Mancos Formation. It encompasses most of the unit some previous workers referred to as the Dakota Sandstone. The sandstone sheets are shallow marine deposits of shoals and bars, whereas the shale units are offshore marine deposits. Locally, at its base is the Encinal Canyon Member. Where present, the Encinal Canyon Member rests disconformably on Morrison Formation strata and is disconformably overlain by bioturbated sandstone at the base of the Oak Canyon Member of the Dakota Sandstone. At the Gutierrez H section the Encinal Canyon Member is about 32 m thick and consists primarily of trough crossbedded conglomeratic sandstone and sandstone (Fig. 8). However, at the Canyon Estates section, the Encinal Canyon Member is not present, and the Oak Canyon Member rests directly on the Morrison Formation (Fig. 8). At the Gutierrez B section part of the Encinal Canyon, but not its base, is exposed (Fig. 8).

Three of the measured sections, Canyon Estates, Guitierrez H and Gutierrez Canyon B, expose the Dakota-Mancos succession (Fig. 8). At Canyon Estates, the lowermost part of the Dakota above the Jackpile Member of the Morrison Formation is ~ 7 m of bioturbated, ripple laminated sandstone, which is the basal sandstone of the Oak Canyon Member of the Dakota Sandstone. Overlying Oak Canyon strata are 2.8 m of bentonitic mudrock with ironstone concretions overlain by 19 m of shale with some sandy lenses and limestone concretions. The A bentonite, an ash bed in the middle of the Oak Canyon Member (Owen et al., 2005), was not identified.

The overlying Cubero Member of the Dakota Sandstone is ~ 9 m of very bioturbated (numerous *Thalassinoides*) and ripple laminar sandstone (Fig. 8). I identify this sandstone interval as the Cubero Member of the Dakota Sandstone, by correlation to the sections at Placitas and Galisteo Dam to the north (see earlier discussion and Lucas et al., 1999). At the Gutierrez B section (Fig. 8), the interval between the Encinal Canyon and Cubero is covered and estimated to be ~ 31 m thick and may include part of the Encinal Canyon Member and the entire Oak Canyon Member.

Lower Mancos Formation

In the Tijeras syncline, the lower part of the Mancos Formation consists of the (ascending) Graneros, Greenhorn, Carlile, Juana Lopez, D-Cross, Tocito and El Vado members of the Mancos Formation (Figs. 2, 8-9). These strata are diverse offshore marine deposits, ranging from shallow marine sandy units (Juana Lopez, Tocito) to offshore marine shaley units (Graneros, Carlile, D-Cross and El Vado) to offshore marine carbonates (Greenhorn). Above the Cubero Member of the

Dakota at the Gutierrez B section, a poorly exposed interval of gray shale with some sandy beds and bentonites is as much as 63 m thick (Fig. 8), and I apply the name Graneros Shale to these offshore marine deposits, as I do at Placitas (cf. Owen et al., 2007; Sealey and Lucas, 2019).

The Graneros is overlain by as much as ~ 4 m of white to gray limestone ledges intercalated with calcareous shale (marl), a very distinctive unit readily assigned to the Greenhorn Member (Fig. 8). The shale-dominated section above the Greenhorn, the Carlile Member, is relatively thick (at least 43 m thick) and mostly covered. At the Gutierrez G section (Fig. 9) the upper part of the Carlile Member is exposed as ~ 26 m of gray shale with some thin calcarenite interbeds and large septarian nodules. At the Zamora section (Fig. 8), the Semilla Sandstone of the medial part of the Carlile Shale is 10 m of bioturbated, massive and ripple-laminated sandstone. This appears to be the only outcrop of the Semilla Sandstone in the Tijeras syncline.

Above the Carlile Member, calcarenite beds with bioclastic debris are a characteristic lithology of the Juana Lopez Member. The Juana Lopez is well exposed at the Gutierrez G section where it is ~ 3 m thick (Fig. 9). The shale interval above the Juana Lopez Member is assigned to the D-Cross Member. It is mostly gray and brown calcareous shale with a few thin beds of bioturbated sandstone, small limestone nodules and septaria about 61 m thick.

The Tocito Sandstone is present at the Gutierrez G section where it is coarse-grained quartz sandstone that has a sharp, scour base and is crossbedded, ripple laminated, tabular bedded or bioturbated (Fig. 9). Its base is seen as a regional unconformity at the onset of the "Niobrara cycle" of deposition (e. g., Molenaar, 1983). Total thickness is ~ 6 m. The base of the Tocito is an unconformity, referred to as the "sub-Niobrara unconformity" in the San Juan Basin in the older literature (e. g., Dane, 1960).

The overlying El Vado Member is a very distinctive unit of thinly interbedded calcareous sandstone, siltstone and sandy shale with laminar, ripple laminar or bioturbated bedforms. Total thickness is as much as ~ 123 m.

Dalton Sandstone Member, Crevasse Canyon Formation

Above the El Vado Member, the Dalton Sandstone is a shoreline sandstone as much as 23 m thick. It is almost totally sandstone, which is mostly crossbedded and tabular bedded, and some beds are ripple laminar or massive. The Dalton is a resistant unit that forms cuestas and ridges.

Gibson Coal Member, Crevasse Canyon Formation

Coal-bearing strata above the Dalton are assigned to the coastal plain deposits of the Gibson Coal Member of the Crevasse Canyon Formation (Figs. 9-10). They are much covered but consist primarily of shale, carbonaceous shale, coal, ironstone concretions and thin sandstone beds that are crossbedded or laminar. Maximum thickness is 47 m. The Holmes Mine was a coal mine stratigraphically high in the Gibson Member (Fig. 10).

Hosta Sandstone

Like the Dalton Sandstone, the Hosta Sandstone is a shoreline sandstone and is well exposed in the Tijeras syncline, defending ridges and benches. It is as much as 39 m thick (Fig. 10) and almost all sandstone that is laminar, trough crossbedded or tabular (horizontally) bedded; it also contains some sandy shale beds. Coquina beds (dominated by shells of the bivalve *Crasatella*) are also characteristic.

Upper Mancos Formation

The Mancos Formation above the Hosta Sandstone is the Satan Member, offshore marine deposits that are about 72 m of tan and yellow shale/sandy shale with a few thin sandstone interbeds, thin limestone beds and carbonate concretionary zones (Fig. 10). It is generally poorly exposed.

Point Lookout Sandstone

The Point Lookout Sandstone is a shoreline sandstone that overlies the Satan Member and is ~ 17 m thick at the Gutierrez East section (Fig. 10). In the southeastern San Juan Basin, the Point Lookout Sandstone is generally 20-25 m thick but is locally as much as 79 m thick (Sealey and Lucas, 2019). Lee (1912, p. 575) indicated a thickness of 15 m for the Point Lookout in the Tijeras syncline but later (Lee, 1917, p. 199) revised that thickness up to 35 m. Molenaar (1983, fig. 2) showed a Point Lookout Sandstone that is 20 m thick in the Tijeras syncline. It consists of white to tan sandstone that is mostly crossbedded, locally hematitic and has some sandy shale interbeds.

Menefee Formation

In the Hagan embayment and in the Placitas area, the Menefee Formation is coastal plain deposits above the Point Lookout Sandstone that can be divided into three intervals, a lower, coal-bearing interval, medial sandstone interval and an upper, coal-bearing interval. However, in the Tijeras syncline only the lower coal-bearing interval is preserved, the rest of the formation having been removed by erosion. These are about 86 m of poorly exposed mudrock with thin coal beds, some ironstone concretions and some sandstone beds that are crossbedded or horizontally laminated (Fig. 10). The Tocco Mine was stratigraphically low in this interval of the Menefee Formation.

Biostratigraphy

Fossil plants, invertebrates and a few shark teeth are present in the Cretaceous strata in the Tijeras syncline. The plants are from the Gibson Coal Member of the Crevasse Canyon Formation and are mostly angiosperm leaves of no particular biostratigraphic significance other than indicating a likely Late

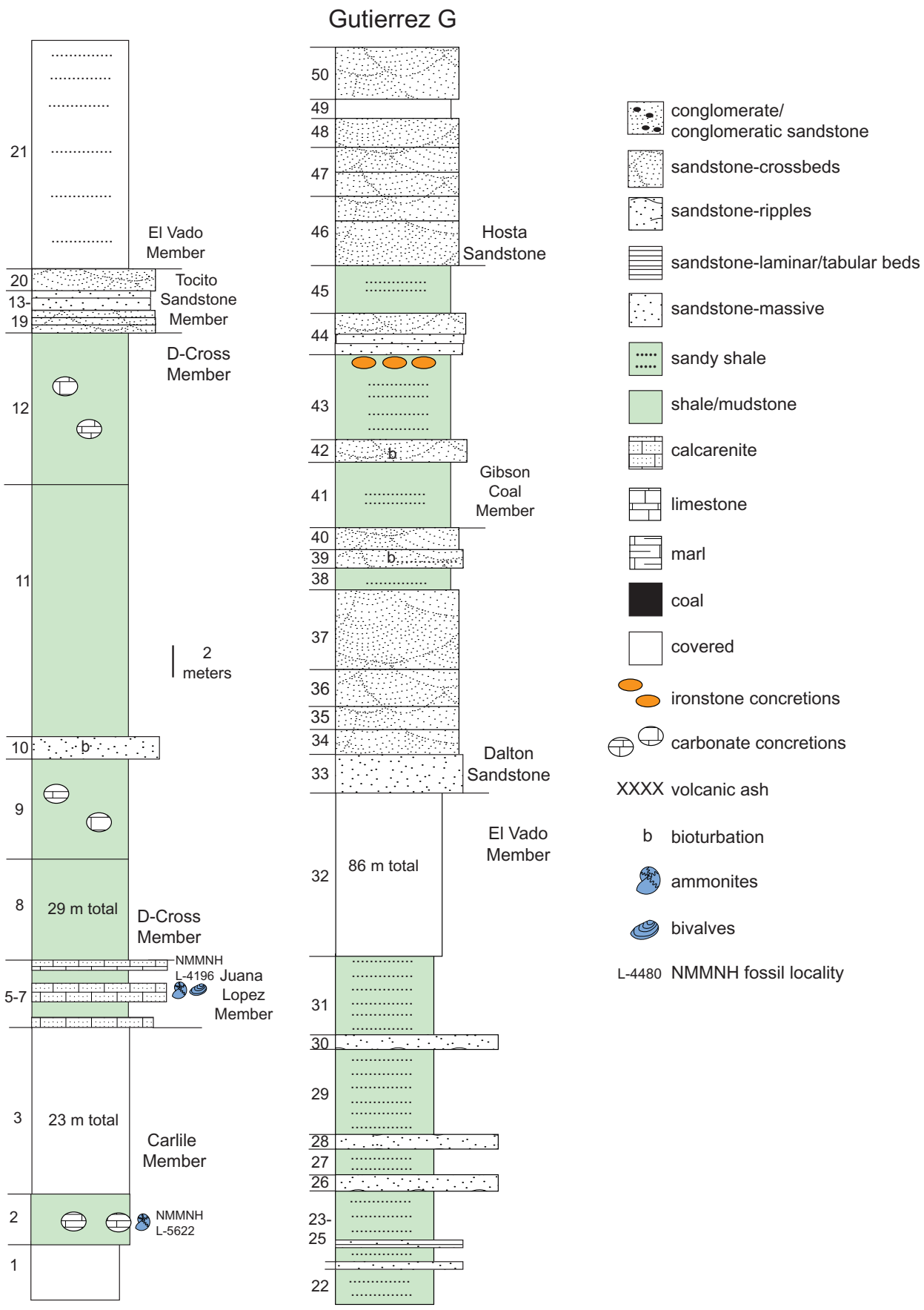


FIGURE 9. The Gutierrez G section of some Cretaceous strata in the Tijeras syncline. UTM coordinates (zone 13, datum NAD 83) of the stratigraphic section are: base = 379021, 3887620, top = 378568, 3887434.

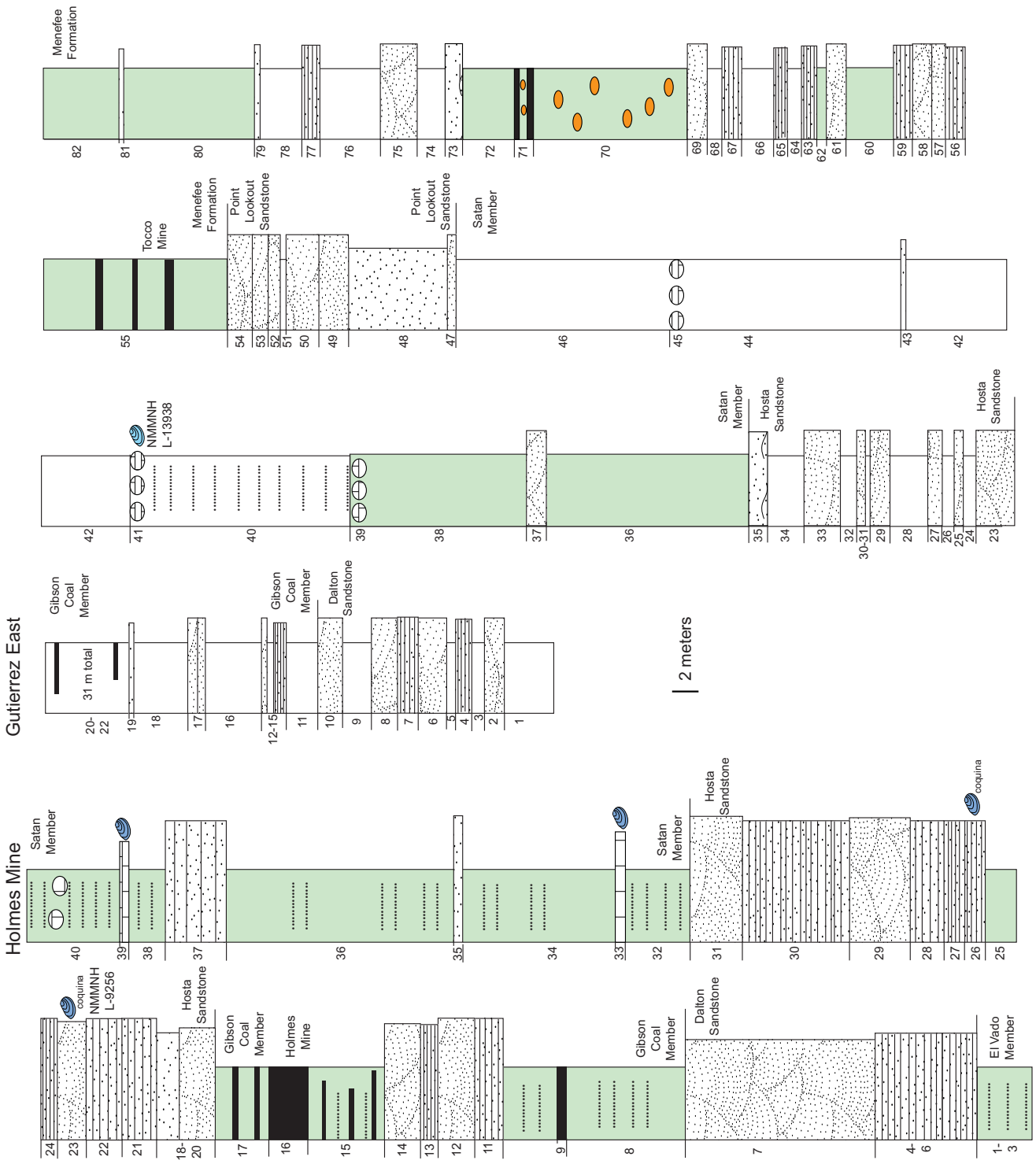


FIGURE 10. Stratigraphic sections of some Cretaceous strata in the Tijeras syncline. UTM coordinates (zone 13, datum NAD 83) of the stratigraphic sections are: Holmes Mine (base = 377141, 3886288, top = 376928, 3886628), Gutierrez East (base = 378934, 3887878, top = 378549, 3888511). See Figure 9 for legend to lithologic symbols.

Cretaceous age. Similarly, the few shark's teeth are typical Late Cretaceous lamniform taxa but of no precise biostratigraphic value. The invertebrate fossils, however, include some bivalves and ammonites that allow age assignments to be made to parts of the Cretaceous marine strata. Lee (1917, p. 199) reported the following fossils (using my stratigraphic assignments of his section):

1. Dalton Sandstone: marine bivalves and gastropods of no precise biostratigraphic value from USGS locality 7186.
2. Gibson Coal Member: similar marine bivalves at USGS locality 7183.
3. Gibson Coal Member: fossil leaves at USGS locality 6031.
4. Gibson Coal Member: at USGS locality 7184, bivalves, gastropods, shark teeth and the ammonite "*Placenticeras sancarlosense* (Hyatt)," a synonym of *P. syrtale* (Morton), a Santonian-Coniacian taxon that is likely Santonian at this site (Sealey and Lucas, 2026).
5. Hosta Sandstone: bivalves, the ammonites "*Placenticeras planum*" and "*P. sancarlosense*" (both synonyms of *P. syrtale*: Sealey and Lucas, 2019) at USGS localities 7182 and 7185.
6. Satan Member: marine bivalves, including "*Inoceramus barabini"* (a Campanian taxon, so likely not correctly identified: Sealey and Lucas, 2026) and gastropods at USGS locality 7187.
7. Menefee Formation: plant fossils at USGS locality 6033.

My collections of invertebrate fossils are:

1. Greenhorn Member: the late Cenomanian index bivalve *Pycnodonte newberryi* at NMMNH locality 4105 and the early Turonian index bivalve *Mytiloides mytiloides* at NMMNH locality 4194, so the Cenomanian-Turonian boundary is within the Greenhorn Member in the Tijeras syncline (Fig. 8).
2. Lower Carlile Member: the middle Turonian index ammonite *Prionocylcus hyatti* at NMMNH locality 5622 (Fig. 9).
3. Lower Carlile Member: the middle Turonian index ammonite *Prionocyclus hyatti* from NMMNH locality 13941.
4. Juana Lopez Member: The upper Turonian index ammonite *Prionocyclus wyomingensis* and *Scaphites* sp. from NMMNH locality 4196 (Fig. 9).
5. Satan Member: indeterminate bivalves at NMMNH localities 13938 and 13941.
6. Gibson Member, angiosperm leaves at NMMNH locality 13936.
7. Top of Hosta Sandstone, the bivalve *Crasatella* at NMMNH localities 13937 and 13939.

Thus, the biostratigraphically useful fossils in the Cretaceous strata of the Tijeras syncline are of Cenomanian, Turonian and Santonian ages (Fig. 2). These fossils are consistent with the paleontology and biostratigraphy of the same stratigraphic units in the southeastern San Juan Basin (Sealey and Lucas, 2019).

REGIONAL CRETACEOUS STRATIGRAPHY

Cretaceous stratigraphy and biostratigraphy have been studied extensively in the southeastern San Juan Basin, about 100-150 km to the west-northwest of Placitas and about 80 km northwest of the Tijeras syncline (e.g., Molenaar, 1983; Sealey and Lucas, 2019, and references cited by them). Most of the stratigraphic units present in the southeastern San Juan Basin are also present at Placitas and in the Tijeras syncline (cf. Black, 1979, 1982; Molenaar, 1983) (Table 1; Fig. 2). The exceptions are:

1. At Placitas and in the Tijeras syncline, only the lower two members of the intertongued Dakota-Mancos succession (Oak Canyon and Cubero) are present. In the southeastern San Juan Basin, stratigraphically higher Dakota-Mancos units are present. Nevertheless, the Dakota Sandstone beds (Oak Canyon basal sandstone, Cubero, Paguate, Twowells) are known to be discontinuous deposits, primarily of offshore bars and shoals (e.g., Molenaar, 1983; Head and Owen, 2005). This explains their local absence in the San Juan Basin and likely explains the absence of the Paguate and Twowells at Placitas and in the Tijeras syncline.
2. In the San Juan Basin, the Carlile Member is three units--lower and upper shale-dominated units separated by a medial Semilla Sandstone. However, the Semilla is a lenticular, offshore bar deposit that is only mapped in the southeastern San Juan Basin, and even there is not present locally (LaFon, 1981; Fleming, 1989). Its absence at Placitas may reflect that or simply be for lack of outcrop of the Semilla interval; there is only one good Carlile outcrop near Placitas, at the Historical Marker A section (Fig. 4, units 8 and 9). The Semilla is present in the Hagan embayment and in the Tijeras syncline, north and south of Placitas (Fleming, 1989).
3. It is not certain that the Tocito Sandstone Member of the Mancos Formation is present in the Placitas area, but it is present in the Tijeras syncline. As noted above, it likely is present in the Placitas area but is not exposed.
4. The Hosta-Dalton Sandstone at Placitas is the merged regressive Dalton Sandstone Member of the Crevasse Canyon Formation and the transgressive Hosta Tongue of the Point Lookout Sandstone. This merged sandstone unit is present east to northeast of the pinchout of the intervening Gibson Coal Member of the Crevasse Canyon Formation and southward/southwestward of the pinchout of the Hosta-Dalton into Mancos Formation. This relationship is present in the southeastern San Juan Basin, where the merged Hosta-Dalton crops out in the Guadalupe-Cabezon area (Hunt, 1936; Sealey and Lucas, 2019).
5. In the southeastern San Juan Basin, the Menefee Formation is as much as 458 m thick and consists of a lower, coal-bearing member (Cleary Coal), middle member with insignificant coal (Allison Member) and an upper, informally named coal-bearing member. At Placitas, a three-part Menefee Formation is also present but incomplete because of post-Menefee erosion. However, the

lithofacies and thicknesses of the Menefee members in the San Juan Basin differ significantly from the three parts of the Menefee Formation at Placitas. Based on the lithologic differences, applying the San Juan Basin member names at Placitas is not warranted. New lithostratigraphic nomenclature is needed.

The Cretaceous sections at Placitas (total thickness 756 m) and in the Tijeras syncline (total thickness 695 m) are much thinner than the correlative section in the San Juan Basin (total thickness 1404 m). Most of the difference can be seen in shale-dominated units (Table 1). At least some of the thickness differences may reflect tectonic thinning (normal faulting out) of parts of the Cretaceous section in the Tijeras syncline, particularly of the shale-dominated units. However, some of this may also reflects differential subsidence during deposition, a subject that merits further investigation.

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