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THE LOWER PERMIAN YESO GROUP IN THE FRA CRISTOBAL AND CABALLO MOUNTAINS, SIERRA COUNTY, NEW MEXICO

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Abstract—Strata of the Lower Permian Yeso Group exposed in the Fra Cristobal and Caballo Mountains of Sierra County can be assigned to the Arroyo de Alamillo and overlying Los Vallos formations. The Arroyo de Alamillo Formation is 42-87 m thick and consists primarily of red-bed sandstone, which is very fine grained, silty, often gypsiferous and mostly thinly laminated or ripple laminated. Siltstone (mostly massive) is much less common, and there are a few beds of dolomite and gypsum in the Arroyo de Alamillo Formation. At Massacre Gap in the Fra Cristobal Mountains, the overlying Los Vallos Formation is ~ 234 m thick and can be divided into the Torres Member (~ 134 m of interbedded dolomite, gypsiferous siltstone, gypsum and siltsone to fine-grained sandstone), Cañas Member (~ 58 m of gypsum with lesser beds of gypsiferous siltstone and dolomite) and the Joyita Member (~ 42 m of red-bed siltstone and fine-grained sandstone) overlain by the Lower Permian Glorieta Sandstone. A generally similar but much covered section of the Los Vallos Formation is exposed in the McLeod Hills of the southern Caballo Mountains and directly overlain by the San Andres Formation (the Glorieta Sandstone is not present in the Caballo Mountains). However, at nearby Hidden Tank, the Los Vallos Formation is represented by only a 75-m thick section of the Torres Member. Six, dolomite-dominated intervals of the Torres Member can be readily correlated from the Yeso Group type section in Socorro County to the Fra Cristobal Mountains. Correlation farther south, into the Caballo Mountains is more difficult, due to facies and thickness changes within the Los Vallos Formation and stratigraphic relief of the unconformity at the base of the overlying San Andres Formation. Deposition of the Arroyo de Alamillo Formation took place by eolian and fluvial processes on an arid coastal plain during a time of regional low sea level. Deposition of the Torres and Cañas members of the Los Vallos Formation was in cyclically shallow marine and sabkha environments. Joyita Member deposition again records eolian and fluvial processes during a time of regionally low sea level.

INTRODUCTION

In Sierra County in southern New Mexico, the Lower Permian Yeso Group is well exposed in the Fra Cristobal and Caballo Mountains (Fig. 1). Thus, a complete Yeso Group section is exposed at Massacre Gap in the southern Fra Cristobal Mountains. In the Caballo Mountains, Yeso Group strata crop out on the eastern dipslope of the range. In the northern part of the Caballos, in the vicinity of Palomas Gap, Yeso strata can be traced some distance from the northwest to southeast but are relatively poorly exposed because of low topography. More complete Yeso outcrops in the Caballo Mountains are present to the south in the McLeod Hills and in the Apache Valley, where particularly good sections of at least part of the Yeso Group can be studied at Broken House Tank, Hidden Tank, and in the McLeod Hills. These are the locations of Yeso Group sections we studied in the Fra Cristobal and Caballo Mountains (Fig. 1). They are the basis of a revised Yeso Group lithostratigraphy, an analysis of Yeso deposition and correlation of the Yeso Group between Socorro and Sierra Counties.

PREVIOUS STUDIES

Stratigraphic study of the Abo-Yeso lithosome began with Lee (1909), who divided the earlier defined Manzano Group of Herrick (1900) into the Abo, Yeso and San Andreas (sic) formations (Fig. 2). Lee's (1909, p. 12) Yeso Formation derived its name from Mesa del Yeso near Soccoro, New Mexico, and he described it there as "1,000 to 2,000 feet [~ 310-620 m] of sandstone, shale, earthy limestone, and gypsum." He also included a sandstone-dominated interval in the top of the Abo Formation that was later included in the overlying Yeso Formation (see below) (Fig. 2). Furthermore, Lee's Yeso Formation also included strata later recognized as a separate formation by Keyes (1915), the Glorieta Sandstone.

Lee (1909, fig. 5) presented a stratigraphic section of the Yeso Formation at Saddle Peak in the southern Fra Cristobal Mountains, depicting the Yeso as ~ 200 m of gypsum, limestone, gypsiferous shale and sandstone (Fig. 3). In the northern Caballo Mountains, Lee (1909, fig. 6) depicted a poorly-exposed Yeso section about 210 m thick consisting of shale, gypsum and limestone (Fig. 3).

Darton (1928) was unable to separate the Yeso and San Andres formations regionally, so he combined them in his "Chupadera Formation," a stratigraphic concept abandoned in the 1940s (Lucas, 2009). Darton (1928, figs. 149, 152) presented sections of the "Chupadera Formation" in the Fra Cristobal and Caballo Mountains similar to Lee's (1909) sections of the Yeso and "San Andreas" formations. Significantly, Darton (1928) reported invertebrate fossils (primarily bivalves and brachiopods) identified by George Girty from the upper limestone interval of the "Chupadera Formation" in the Fra Cristobal and Caballo Mountains, which is the San Andres Formation of our usage (Fig. 2). Harley (1934) also referred to Yeso strata in Sierra County as Chupadera Formation but added no significant observations to those of Lee (1909) and Darton (1928).

Needham and Bates (1943) described type sections of the Abo and Yeso formations of Lee, and thereby modified somewhat his concepts of those units and proposed and named some formal subdivisions of the Yeso Formation. Thus, Needham and

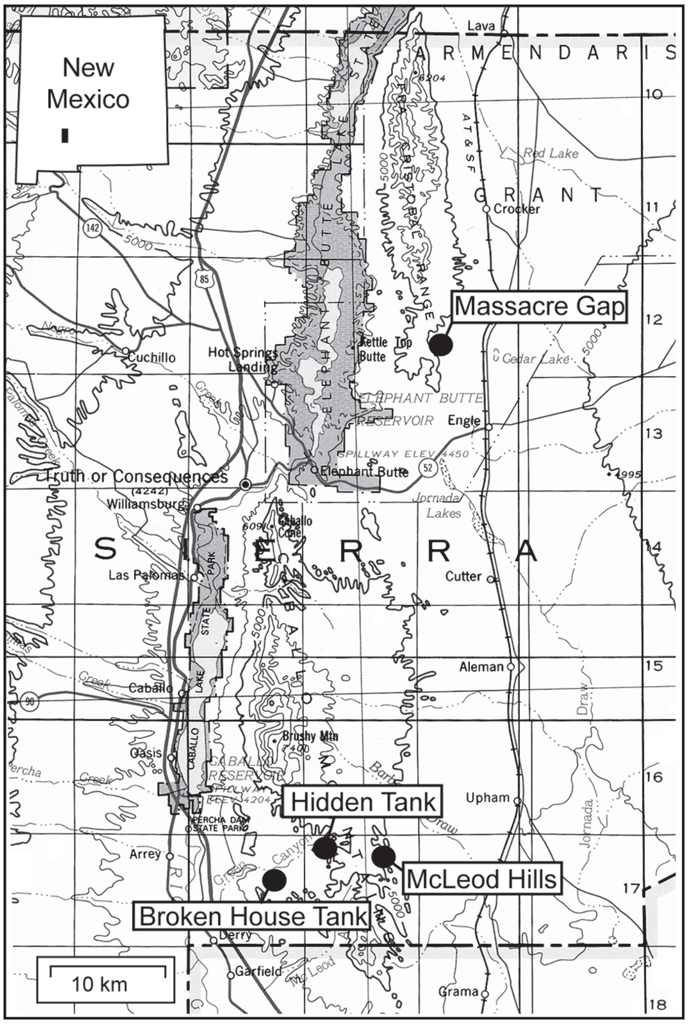

FIGURE 1. Map of the Fra Cristobal and Caballo Mountains in Sierra County, New Mexico, showing locations of measured sections of the Yeso Group discussed in the text.

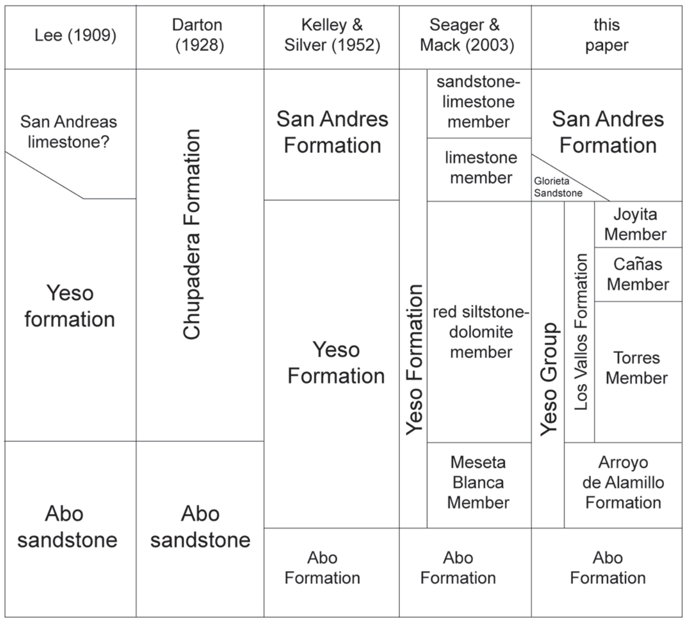

FIGURE 2. Development of lithostratigraphic nomenclature of the Yeso interval in Sierra County, New Mexico.

Bates (1943) excluded the Glorieta Sandstone from the Yeso, and named two members of the upper part of the Yeso Formation, the Cañas [gypsum] member and the Joyita [sandstone] member.

Until 2005, the concept of the Yeso Formation used in New Mexico came from four maps published between 1946 and 1951 by the United States Geological Survey (USGS) as part of mapping carried out during World War II. These were maps of the Jemez Pueblo and Sierra Nacimiento in Sandoval County (Wood and Northrop, 1946), the Lucero uplift of Valencia County (Kelley and Wood, 1946), the Joyita Hills, the Los Piños Mountains and northern Chupadera Mesa of Socorro County (Wilpolt, et al., 1946) and the Cerrillos del Coyote, northern Jornada del Muerto and southern Chupadera Mesa of Socorro County (Wilpolt and Wanek, 1951). Most significantly, these workers removed the upper sandstone interval from the Abo Formation, and called it the Meseta Blanca sandstone member of the Yeso Formation (name proposed by Wood and Northrop, 1946). They also proposed three member names for all or most of the remaining Yeso Formation: San Ysidro, Los Vallos and Torres members.

Kelley and Silver (1952) described the Yeso Formation in the Caballo Mountains as poorly exposed sandstone and gypsum with lesser amounts of siltstone, limestone and claystone, ranging in thickness from 183-230 m to as little as 55-76 m. They attributed the thickness differences to local depositional thinning and the unconformity at the Yeso-San Andres contact, although Kelley and Silver failed to address the absence of the intervening Glorieta Sandstone. Aware of the various member names applied to Yeso strata to the north, Kelley and Silver (1952, p. 103) noted that "the lower third of the Yeso section is dominated by brown, tan-brown, buff, and white sandstone….[that] occupies the same stratigraphic position as the Meseta Blanca member…[but] the differences are enough to make correlation doubtful." Thus, they did not apply the then available member-level stratigraphic nomenclature to Yeso strata that crop out in the Caballo Mountains.

Geologic mapping in the Fra Cristobal Mountains by masters thesis students from the University of New Mexico briefly characterized the Yeso Formation outcrops exposed in the southern portion of that range (Thompson, 1955; McCleary, 1960). Cserna (1956), in an unpublished doctoral thesis done at Columbia University, also briefly described the Yeso Formation in the Fra Cristobal Mountains. These students gave a maximum Yeso thickness of about 181 m in the Fra Cristobal Mountains and described it as a mixture of sandstone and gypsum with lesser amounts of siltstone, limestone and claystone. Nelson (1986) most recently described the Yeso Formation in the Fra Cristobal Mountains as ~ 396 m thick and assigned it to the (in ascending order) Meseta Blanca, Los Vallos (= Torres Member of our usage), Cañas and Joyita members. He provided brief but generally accurate descriptions of the lithologies of these units.

Baars' (1962) important synthesis of Lower Permian stratigraphy on the Colorado Plateau used Abo Formation in the same sense as the USGS maps of 1946 cited earlier. However, he con-

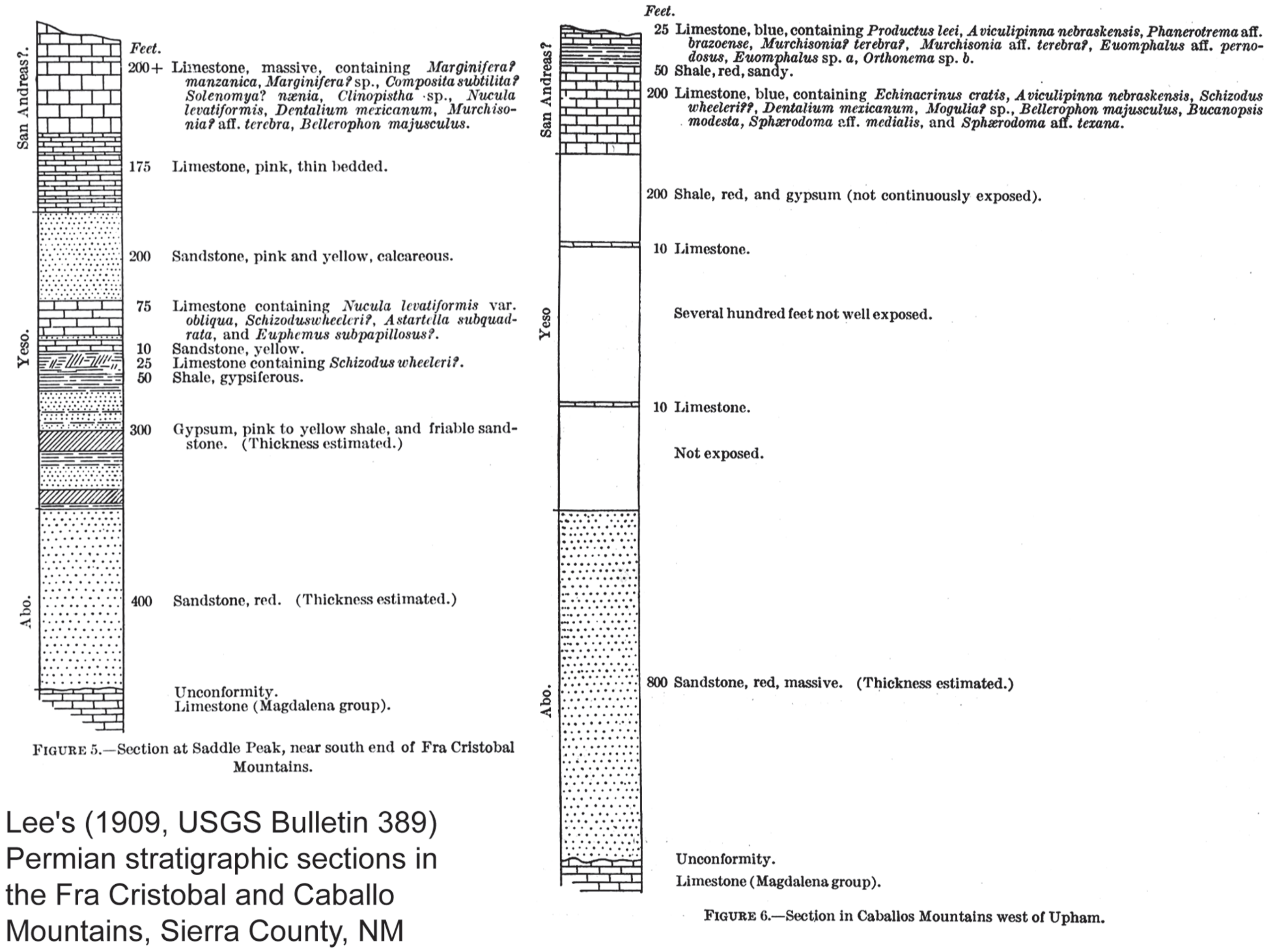

FIGURE 3. Lee's (1909) Permian stratigraphic sections in the Fra Cristobal and Caballo Mountains.

cluded that the type section of the Meseta Blanca Member of the Yeso Formation near Jemez Pueblo is simply the same unit that Gregory (1917) had named the De Chelly Sandstone near Chinle, Arizona. Therefore, Baars (1962) abandoned the name Meseta Blanca and replaced it with De Chelly Sandstone, which he removed from the Yeso Formation. He also advocated abandoning member names such as San Ysidro and Los Vallos because they were synonyms of his redefined Yeso Formation, though Baars (1962) did concede that in the area of the type Yeso section it could be divided into multiple members.

Baars (1962) recommendations, however, were not heeded by subsequent workers in New Mexico, who have continued to use the Yeso stratigraphic nomenclature of the 1946 published maps (e.g., Hatchell et al., 1982; Mack and Suguio, 1991; Dinterman, 2001; Mack and Dinterman, 2002; Seager and Mack, 2003; Kues and Giles, 2004). Nevertheless, our own work (Lucas et al., 1999; Lucas and Krainer, 2004; Lucas and Zeigler, 2004; Lucas et al., 2005) convinced us that some modifications were justified to produce a lithostratigraphic nomenclature that better reflects current understanding of the lithostratigraphy of the Yeso Group interval in central New Mexico. Therefore, Lucas et al. (2005) elevated Yeso to group status consisting of three formation-rank units and several members. That work focused on data from Socorro, Valencia, Bernalillo and Sandoval Counties, New Mexico. Here, we expand our detailed examination of the Yeso Group southward into Sierra County.

Seager and Mack (2003) divided the Yeso section in the Caballo Mountains into four members (in ascending order): Meseta Blanca, red siltstone-dolomite, limestone and the sandstone-limestone members (Fig. 2). They noted that Kelley and Silver (1952) had assigned strata of the limestone and the sandstone-limestone members to the San Andres Formation in the northern Caballo Mountains. But, according to Seager and Mack (2003, p. 30) to do so would either "require dramatic thickness and lithologic variations in the Yeso between the San Andres and Caballo Mountains…or a significant unconformity between the Yeso and San Andres formations." We follow Kelley and Silver (1952) in assigning the limestone and the sandstone-limestone members of the Yeso of Mack and Seager (2003) to the San Andres Formation (Fig. 2). As we conclude below, there are indeed major variations in Yeso thickness in Sierra County and some of this is due to the unconformity at the base of the San Andres Formation.

LITHOSTRATIGRAPHY

Yeso Group

The Yeso Formation of traditional usage consists of various members, some of which are relatively thick (250-300 m) and lithologically distinctive units that have been routinely mapped by various workers at reasonable scales (including 1:24,000). Because of this, we concluded that the Yeso members merit formation rank, so we raised the Yeso to group rank (Lucas et al., 2005). The stratigraphic code (NACSN, 2005, p. 1569 [article 28]) states that a group rank unit is designed to "express the natural relationship of associated formations," and the Yeso Group meets this requirement. In other words, it unites an array of mappable formations that consist of siliciclastic, carbonate and evaporite sedimentary rocks that share a genesis in eolian, wadi, sabkha and arid coastal plain settings that lends them a lithostratigraphic integrity that long justified their inclusion in a single formation. However, the thickness, lithologic distinctiveness and great areal extent of the Yeso subdivisions (traditional members), and the fact that some of them can be further subdivided, warrant raising Yeso to group rank. Broadly correlative or homotaxial units of similar thickness and extent are also group-rank units, such as the Clear Fork Group of Texas, the Supai Group of Arizona and the Cutler Group of the Four Corners.

A further change that was long overdue was to adopt Baars' (1962) recognition that the Meseta Blanca Member of the Yeso Formation of Wood and Northrop (1946) at its type section at Jemez Pueblo is the same unit as the De Chelly Sandstone of Gregory (1917) (also see Huffman and Condon, 1993). The name Meseta Blanca thus needed to be abandoned, and we included the De Chelly Sandstone in New Mexico as a formation-rank unit in the Yeso Group (Lucas et al., 2005). In Arizona, the De Chelly Sandstone is a formation in the Cutler Group (e.g., Peirce, 1989), a change in group inclusion regionally that is consistent with usage endorsed by the NACSN (2005).

In the Fra Cristobal and Caballo Mountains, the Yeso Group is similar to the outcrops farther north in Socorro County and consists of a lower, dominantly clastic unit and an upper unit that is a mixture of gypsum, carbonate (mostly dolomite) and clastic rocks. Thus, the same lithostratigraphic nomenclature used in Socorro County at the Yeso type section can be applied to Yeso strata in the Fra Cristobal and Caballo Mountains (Fig. 2).

Arroyo de Alamillo Formation

Strata previously called Meseta Blanca Member of the Yeso Formation in Sierra County (Mack and Suguio, 1991; Dinterman, 2001; Mack and Dinterman, 2002; Seager and Mack, 2003) differ substantially from the Meseta Blanca type section. Thus, these strata are not the sandstone beds with large scale crossbed sets that characterize the De Chelly, but instead are mostly siltstone, ripple-laminated sandstone and some dolomitic limestones. Therefore, these strata belong in a separate lithostratigraphic unit. We named this unit, which is homotaxial with the De Chelly Sandstone, the Arroyo de Alamillo Formation (Lucas et al., 2005).

The Arroyo de Alamillo Formation is the basal unit of the Yeso Group in the Fra Cristobal and Caballo Mountains. We measured three complete sections of the Arroyo de Alamillo Formation in Sierra County---at Massacre Gap in the Fra Cristobal Mountains, at Broken House Tank and in the McLeod Hills of the Caballo Mountains (Figs. 4-6, 8A, C-E). At these sections, the Arroyo de Alamillo Formation ranges in thickness from approximately 42 to 87 m. To the north, at Massacre Gap in the Fra Cristobal Mountains, the Arroyo de Alamillo Formation is mostly thinly laminated or ripple-laminated sandstone (63% of the measured section). However, to the south, in the Caballo Mountains, siltstone is the dominant lithology---at least 42% of the measured stratigraphic section in the McLeod Hills (most of the covered intervals in this section are likely siltstone) and 52% of the measured stratigraphic section at Broken House Tank.

At the Massacre Gap section (Figs. 4, 8A), the uppermost 4 m of the Abo Formation are blocky red mudstone, fissile mudstone and mudstone with carbonate nodules (Fig. 4, segment A, units 1-8). Intercalated in the mudstone are fine-grained sandstone with climbing ripples (0.6 m thick), overlain by a mixed siliciclastic-carbonate siltstone bed (0.2 m thick). This siltstone bed is reddish and composed of carbonate and siliciclastic grains. Among the siliciclastic grains most abundant are angular-subangular, monocrystalline quartz grains, and subordinate are detrital feldspars, a few opaque grains and very rare muscovite. Carbonate grains are recrystallized, partly forming dolomite rhombs. The siltstone bed is laminated; the lamination is partly destroyed, probably by bioturbation. Also present are a pedogenic limestone bed (0.2 m thick) and a bed of trough crossbedded sandstone (with lateral accretion sets), 0.3 m thick, overlain by ripple laminated and horizontally laminated, fine-grained sandstone.

The overlying Arroyo de Alamillo Formation section at Massacre Gap (Fig. 4, segment A, units 9-95, segment B, units 1-5) is 81 m thick and almost completely exposed, with only a few covered intervals. The section consists of the following lithofacies:

1. Mudstone-siltstone, in which various types are distinguished: laminated red mudstone, partly calcareous, rarely containing small carbonate nodules (pedogenic); green mudstone; green laminated dolomitic mudstone (?stromatolitic), rarely containing halite pseudomorphs; greenish gypsiferous mudstone; and greenish mudstone to fine-grained siltstone composed of quartz and recrystallized carbonate (dolomite) in 1-3 cm thick ripple laminated beds.

2. Intercalated in the mudstone-siltstone are: coarse-grained siltstone to fine-grained sandstone beds, mostly red, rarely greenish, displaying the following sedimentary structures: ripple lamination, climbing ripples (Sr facies), trough crossbedding (St facies), partly with small ripples on top, crossbedding with small ripples on the foresets, horizontal lamination (Sh facies), and rare synsedimentary deformation structures. Individual coarse-grained siltstone to fine-grained sandstone intervals are up to 3 m thick. Siltstone to fine-grained sandstone is moderately to well sorted and composed of abundant monocrystalline quartz grains, subordinate detrital feldspars, a few micas (muscovite) and opaque grains and very rare polycrystalline quartz and detrital chlorite. Feldspars are dominantly potassium feldspars, including

microcline and perthitic types. Rare polysynthetic twinned feldspar grains are present. Most grains are slightly altered. Accessory minerals are zircon and tourmaline. The rock is cemented by dolomite, randomly replacing quartz and feldspar. Subordinately, some quartz cement is present, which occurs as authigenic overgrowths on detrital quartz grains.

3. Greenish gypsiferous siltstone to fine-grained sandstone (beds are 0.6 and 1.5 m thick).

4. In the lower part of the Arroyo de Alamillo Formation, several carbonate beds 1-20 cm thick are present. Under the microscope the carbonate beds appear as mixed carbonate-siliciclastic siltstone with a maximum grain size of 0.03 mm. Carbonate grains predominate, and quartz grains are subordinate. The carbonate beds are recrystallized and dolomitized, and indistinctly laminated to massive.

In the Caballo Mountains, at Broken House Tank, a 96-m-thick succession of the lower part of the Yeso Group includes a complete section of the Arroyo de Alamillo Formation (Figs. 5, units 2-86, 8D). The Arroyo de Alamillo Formation here (Fig. 5, units 2-86) is 74 m thick and overlain by 21.5 m of the lower part of the Torres Member of the Los Vallos Formation (Fig. 5, units 87-99). The basal unit 1 of red and green silty mudstone (0.6 m) is the top bed of the Abo Formation. The following lithofacies can be recognized within the Arroyo de Alamillo Formation: (1) red and greenish mudstone to fine-grained siltstone, commonly thinly laminated, also massive; individual beds are 0.2-1.1 m thick; (2) horizontally and ripple-laminated red siltstone to fine-grained sandstone, beds up to 1.9 m thick; (3) crossbedded fine-grained sandstone with erosional contacts at the bases, beds up to 1.1 m thick; (4) massive to indistinctly horizontally laminated sandstone, up to 1.8 m thick; (5) crossbedded, fine-grained sandstone, beds up to 1.1 m thick; (6) rare bioturbated siltstone to fine-grained sandstone, beds up to 0.3 m thick; (7) gypsiferous siltstone to fine-grained sandstone, partly horizontally laminated, beds 0.2-0.7 m thick; and (8) red gypsiferous siltstone to fine-grained sandstone containing clay rip-ups (resediment clasts), beds up to 0.3 m thick.

The Yeso Group in the McLeod Hills section (Figs. 6, 8C) is 372 m thick (about 50 m thicker than at Massacre Gap), but less well exposed and can be divided into Arroyo de Alamillo Formation (~ 42 m), and the Los Vallos Formation (~ 330 m), which is further divided into the Torres Member (~240 m) and Cañas Member (~55 m). The Joyita Member, if present, is completely covered. The overlying succession of bedded dolomite and fossiliferous limestone (Fig. 6, units 96-115) is assigned to the San Andres Formation (see below). The Arroyo de Alamillo Formation in the McLeod Hills is composed of alternating lithofacies of the following types: greenish mudstone/shale (near the base), massive to indistinctly laminated siltstone to fine-grained sandstone, laminated siltstone to fine-grained sandstone, dolomitic siltstone to silty dolomite and gypsiferous siltstone to fine-grained sandstone. The lower 10 m of the formation are mostly greenish, subordinately red, and above that red colors predominate. Crossbedded and ripple-laminated siltstone to fine-grained sandstone was not observed.

In general, sandstones of the Arroyo de Alamillo Formation are very fine grained, silty, often gypsiferous and mostly thinly laminated and ripple laminated. Only a few sandstone beds are cross bedded. Siltstones are also often gypsiferous and sometimes display thin laminations or ripple laminations. However, most siltstone beds are massive and blocky. A very characteristic lithology of the Arroyo de Alamillo Formation is halite pseudomorphs that are most commonly present in beds of dolomitic siltstone stratigraphically low in the formation (Fig. 8E). However, such pseudomorphs sometimes do occur stratigraphically high in the unit, as at the section we measured at Broken House Tank. A few beds of dolomite and gypsum are also present in the Arroyo de Alamillo Formation.

The base of the Arroyo de Alamillo Formation is the stratigraphically lowest dolomitic siltstone or gypsiferous siltstone bed above Abo mudstone. The Abo-Yeso contact to the north has long been described as gradational or interbedded by various authors (cf. Lucas et al., 2005). This contact is similar in Sierra County, as is best seen at our Massacre Gap measured stratigraphic section (Fig. 4). Here, thinly-laminated dolomitic siltstone beds are interbedded with red mudstone beds of Abo lithology over a stratigraphic thickness of about 8 m (Fig. 4), which suggests a transitional Abo-Yeso contact.

Los Vallos Formation

The upper part of the Yeso Group in the Fra Cristobal and Caballo Mountains is assigned by us to the Los Vallos Formation and divided (in ascending order) into the Torres, Cañas and Joyita members, as is done in Socorro County to the north (Lucas et al., 2005). The "red siltstone-dolomite member" of the Yeso of Seager and Mack (2003) refers to the Torres, Cañas and Joyita members (Fig. 2). In the McLeod Hills section (Fig. 6), the Los Vallos Formation is ~ 240 m thick, where it is exposed between the Arroyo de Alamillo Formation and the overlying San Andres Formation. However, at Hidden Tank in the Caballo Mountains (Fig. 7), the Torres Member is only ~ 70 m thick where it is the only part of the Los Vallos Formation between the Arroyo de Alamillo and the San Andres formations.

The upper part of the Yeso Group at the Massacre Gap section (Figs. 4, 8B) can be divided into the Torres Member of the Los Vallos Formation (~ 134 m; Fig. 4, segment B, units 6-72), Cañas Member of the Los Vallos Formation (~ 58 m; Fig. 4, segment B, units 73-97) and Joyita Member of the Los Vallos Formation (~ 42 m; Fig. 4, segment B, units 98-119). The principle lithologies of the Torres Member are dolomite, gypsiferous siltstone, gypsum and siltstone to fine-grained sandstone. The dolomite is gray to dark gray, and the following types can be distinguished: indistinctly bedded dolomite, indistinctly bedded vuggy dolomite, thin-bedded (5-20 cm) dolomite with local halite casts, thin-bedded (5-20 cm) dolomite alternating with thin gypsum beds (10 cm), thicker-bedded (20-40 cm) dolomite, rarely containing fossil fragments (brachiopods, crinoids) and intercalated rare, thin (5-10 cm) coquina layers containing abundant gastropods and brachiopods.

Within the succession six dolomite intervals occur (Fig. 4). Each dolomite interval is intercalated with gypsiferous siltstone

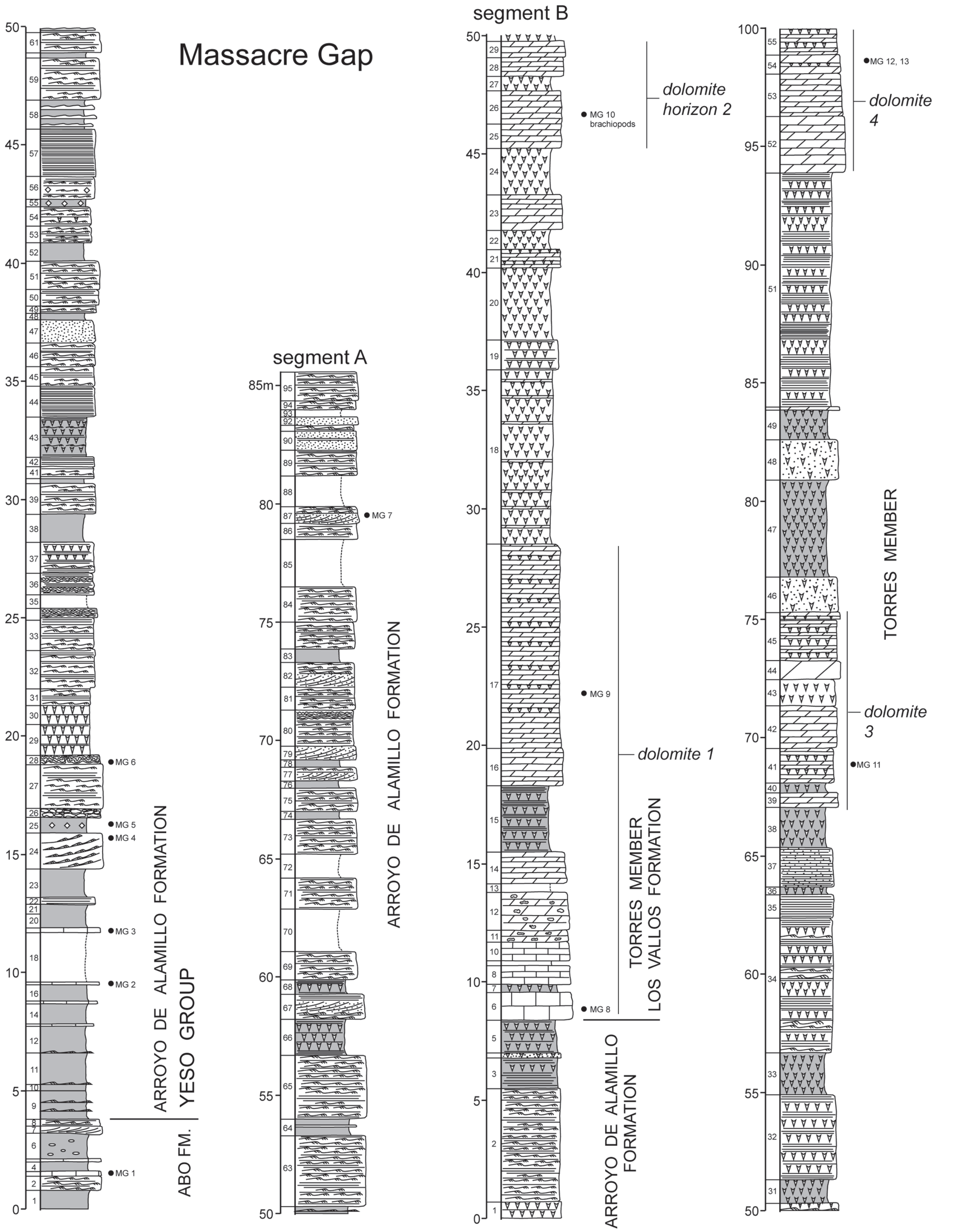

FIGURE 4. Measured stratigraphic section of the Yeso Group at Massacre Gap in the southern Fra Cristobal Mountains. Note that the section is measured in two segments, A and B, and that the top of A correlates approximately to the base of B. See Appendix for map coordinates of location.

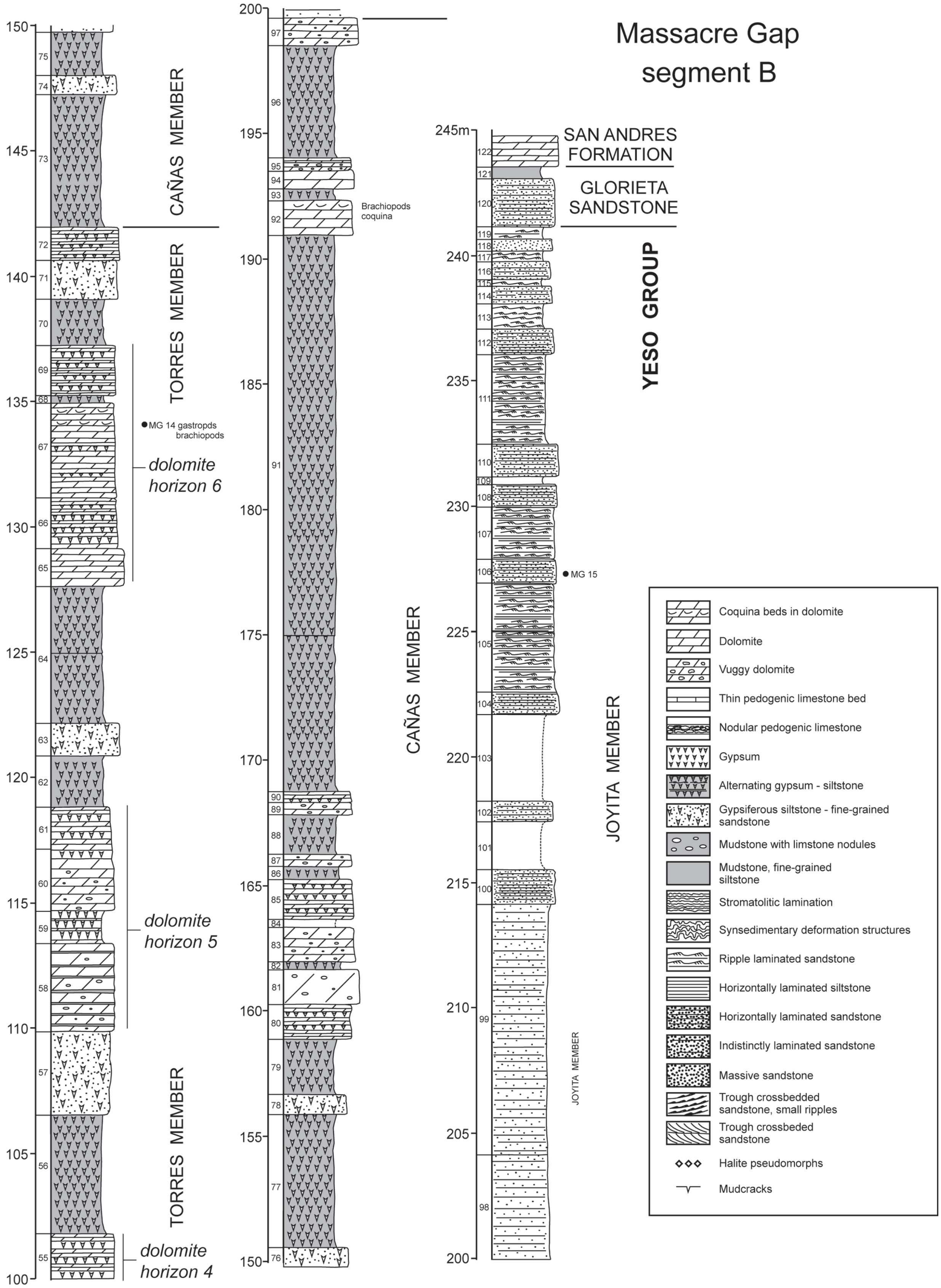

FIGURE 4. Cont.

and gypsum layers up to 2.8 m thick. In thin section, the dolomite is mostly recrystallized, indistinctly laminated to massive and locally contains a few quartz grains. Within dolomite interval 2, an oncoidal floatstone to rudstone is present, composed of oncoids up to 6 mm in diameter, coated grains and fossil fragments. The matrix is recrystallized dolomicrite containing small quartz grains. Oncoids and coated grains contain a nucleus (recrystallized bivalve shell fragments, algal fragments) encrusted by cyanobacteria. Within oncoids many authigenic quartz crystals occur. The fossil assemblage includes abundant recrystallized shell fragments (bivalves, brachiopods), small gastropods, calcareous algae, foraminiferans, a few ostracods and rare echinoderm fragments.

Thin dolomite beds intercalated with gypsum in dolomite interval 3 (sample MG 11) are laminated and composed of alternating layers of originally peloidal grainstone to packstone and grainstone composed of abundant small shells (bivalves, brachiopods), peloids, rare ostracods and intraclasts. Individual layers are 2-4 mm thick. The rock is dolomitized and recrystallized.

Within dolomite interval 4 dolomitized wackestone is composed of peloidal matrix in which fossil fragments are floating, such as shell fragments, gastropods, ostracods, calcareous algae, some echinoderms and foraminiferans. A few micritic intraclasts and detrital quartz grains occur. The intercalated coquina layer is a rudstone containing abundant brachiopod and bivalve shells, subordinately small gastropods and ostracods, and rare echinoderm fragments. Individual shells are up to 15 mm long. The rudstone is partly well washed and cemented, and partly contains micritic matrix. Pore space is locally filled with chalcedony. Coquina layers in dolomite intervals 5 and 6 are dolomitized floatstone composed of dolomicritic to siltitic matrix with small quartz grains. In the matrix shell fragments up to 15 mm long derived from bivalves, gastropods and brachiopods are floating.

Gypsiferous siltstone beds in the Torres Member at Massacre Gap are 0.8 to 3.3 m thick and are present throughout the section, intercalated with gypsum. This lithofacies may grade into gypsum, which is partly laminated and partly silty. Gypsum is a very common lithofacies, and individual gypsum beds are 0.3-22.1 m thick. Rarely, chicken wire gypsum is present. Commonly thin gypsum layers alternate with thin dolomite beds. Locally gypsum is partly laminated and partly silty. Siltstone to fine-grained sandstone is rare, and occurs in the middle of the Torres Member as up to 1.7 m thick beds of red, horizontally- or ripple-laminated siltstone to fine-grained sandstone, alternating with gypsum.

At Massacre Gap, the Cañas Member of the Los Vallos Formation (Fig. 4) is mainly composed of gypsum with gypsiferous siltstone beds intercalated in the lower part (each 0.8 m thick). In the middle of the member, a 10-m thick dolomite interval is developed. This interval is composed of massive and bedded dolomite and intercalated thin gypsum beds. Three thin-bedded, vuggy dolomite horizons (1.2-1.4 m thick), separated by gypsum, form the top of the Cañas Member. A coquina layer is developed on top of the lowermost dolomite interval.

At Massacre Gap, the uppermost unit of the Los Vallos Formation is red-bed siliciclastics of the Joyita Member (Fig. 4). The lower 20 m of the Joyita Member is massive to indistinctly laminated siltstone to fine-grained sandstone. The upper part consists of horizontally laminated and ripple laminated red siltstone and some massive red siltstone to fine-grained sandstone. Sandstone

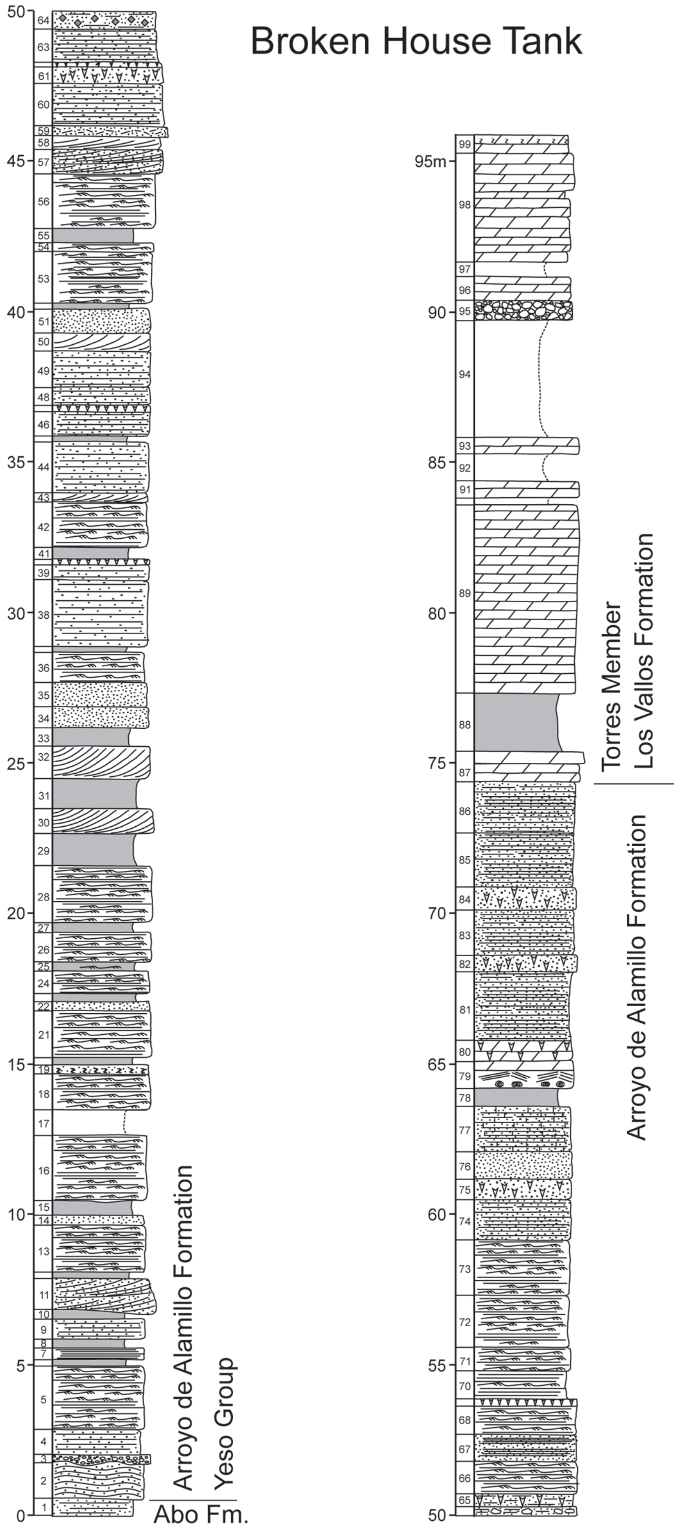

FIGURE 5. Measured stratigraphic section of the lower part of the Yeso Group at Broken House Tank in the southern Caballo Mountains. See Appendix for map coordinates of location, and Figure 4 for lithology symbols legend.

from the middle of the member (sample MG 15) is fine grained (grain size is mostly 0.1-0.2 mm with a maximum of 0.4 mm) and moderately to well sorted. The grains are dominantly subrounded to rounded and cemented by carbonate. The most common grain type is monocrystalline quartz, and polycrystalline quartz grains are rare. Detrital feldspars are a common constituent, dominantly represented by untwinned potassium feldspars. A few microcline grains, perthitic feldspars, polysynthetic twinned plagioclase feldspars and small chert grains are present, too. Zircon is a common accessory mineral, and apatite and tourmaline are rare. Mica grains are extremely rare. Carbonate cement (dolomite) replaces quartz and feldspar.

At Massacre Gap, the Glorieta Sandstone overlies the Yeso Group (Fig. 4) and is thin (1.8 m) and fine grained with an average grain size of 0.1 and maximum grain size of 0.3 mm. The sandstone is well sorted, and the grains are mostly subangular to subrounded. Compared to the underlying Joyita Member, detrital feldspars are less common and heavy minerals are more abundant, particularly rounded zircon, and also tourmaline, apatite and rutile. The amount of carbonate cement is high (~ 30%), and feldspar grains in particular are replaced by carbonate.

At Broken House Tank (Fig. 5), only the lower 20 m of the Torres Member of the Los Vallos Formation crop out above the Arroyo de Alamillo Formation. These strata are mostly dolomite beds similar to the lower part of the Los Vallos Formation at the Massacre Gap and Hidden Tank sections.

In the McLeod Hills (Fig. 6), the facies of the Torres Member are similar to those at Massacre Gap, but less well exposed. The following lithofacies are distinguished: greenish siltstone; red siltstone to fine-grained sandstone, horizontally and ripple laminated (upper part), gypsiferous siltstone, massive to indistinctly laminated; and gypsum and dolomite, indistinctly bedded to well bedded (mostly 20-30 cm), gray, micritic, rarely containing fossils (brachiopods) and with gypsum-filled vugs. Three thicker (12.6-15 m) and four thin (0.3-0.6 m) dolomite intervals are exposed, separated by gypsiferous siltstone and gypsum, and rare siltstone to fine-grained sandstone. Two samples from the dolomite horizon in the middle of the member are mudstone to wackestone composed of recrystallized and dolomitized peloidal micrite with a low-diversity fossil assemblage of locally abundant ostracods, echinoderm fragments and a few smaller foraminiferans. A few small, silt-sized detrital quartz grains are present, too. Due to lack of complete exposure a correlation of the dolomite intervals with those of the Massacre Gap section is difficult. The lowermost exposed dolomite interval of the McLeod Hills section may correlate with interval 2 at Massacre Gap, and the uppermost exposed dolomite interval may correlate with interval 6 at Massacre Gap (Fig. 10).

In the McLeod Hills section, the upper contact of the Torres Member with the overlying Cañas Member is not exposed (Fig. 6). The exposed thickness of the Cañas Member is approximately 32 m and it is composed of gypsum (~16 m), thin-bedded (5-20 cm) dolomite (4.2 m) and alternating gypsum and gypsiferous siltstone (~12 m). The boundary with the overlying Joyita Member, and the Joyita Member, itself, if present, are covered.

At Hidden Tank (Figs. 7, 8F), only the uppermost beds of the Arroyo de Alamillo Formation were measured at the base of the section. These are reddish-brown, ripple-laminated siltstone and gypsiferous sandstone. The overlying Yeso section is ~ 75 m thick and is overlain by slightly cherty, fossiliferous limestone at the base of the San Andres Formation. We assign the relatively thin upper part of the Yeso Group section here to the Torres Member because of its stratigraphic position and overall lithologic resemblance to the Torres Member outcrops at Massacre Gap and in the McLeod Hills. However, we note that at Hidden Tank the Torres Member lacks gypsum beds, though gypsum-filled vugs are present in many of the dolomite beds.

A particularly interesting bed at Hidden Tank is a collapse breccia that is 3.3 m thick and extends at least 6 m on strike, laterally pinching out into thin-bedded dolomite (Figs. 7, unit 23, 8F; also see Seager and Mack, 2003, fig. 33). Breccia blocks consist of dolomite and are up to 1.2 m in diameter. A similar, but finer breccia is present at almost the same stratigraphic level in the lower Torres Member at Broken House Tank (Fig. 5). This may suggest an area of dissolution and collapse that encompassed the two sections, which are about 10 km apart (Fig. 1).

YESO DEPOSITIONAL ENVIRONMENTS

Arroyo de Alamillo Formation

During deposition of the Arroyo de Alamillo Formation in early Yeso time, marine carbonates were deposited in the Delaware and Pedregosa basins in the south, grading into shallow-marine siliciclastic, carbonate and evaporate sediments with intercalated eolian deposits towards the northern and northwestern shelf, and into eolian sand sheets in west-central New Mexico, eolian dune fields in the northwest and ephemeral streams and eolian deposits in north-central New Mexico (Baars, 1974; Stanesco, 1991; Mack and Suguio, 1991; Mack and Dinterman, 2002). At all three locations in the Fra Cristobal and Caballo Mountains that we studied (Masacre Gap, Broken House Tank, McLeod Hills), the Arroyo de Alamillo Formation is thinner (42-87 m) than at the type section east of Socorro (106 m) (Fig. 10).

At Broken House Tank, the Arroyo de Alamillo Formation is of dominantly nonmarine origin. We interpret the mudstone to fine-grained siltstone and channel-form sandstone as floodplain deposits and shallow, broad channel fills. The horizontally and ripple laminated, massive to indistinctly laminated and crossbedded sandstone are interpreted as eolian deposits (eolian ripples and small-scale dunes). The gypsiferous siltstone to fine-grained sandstone in the upper part formed in a sabkha environment. The dolomite intercalation (Fig. 5, units 79-80) in the upper part of the section shows a shallowing upward trend. Oncoids near the base indicate the first marine flooding and deposition in a shallow marine environment. Tepee structures, which in the dolomite are developed above, are typical of peritidal environments and form by desiccation in the upper intertidal and supratidal zones. The overlying gypsiferous dolomite was deposited in a coastal, supratidal sabkha environment.

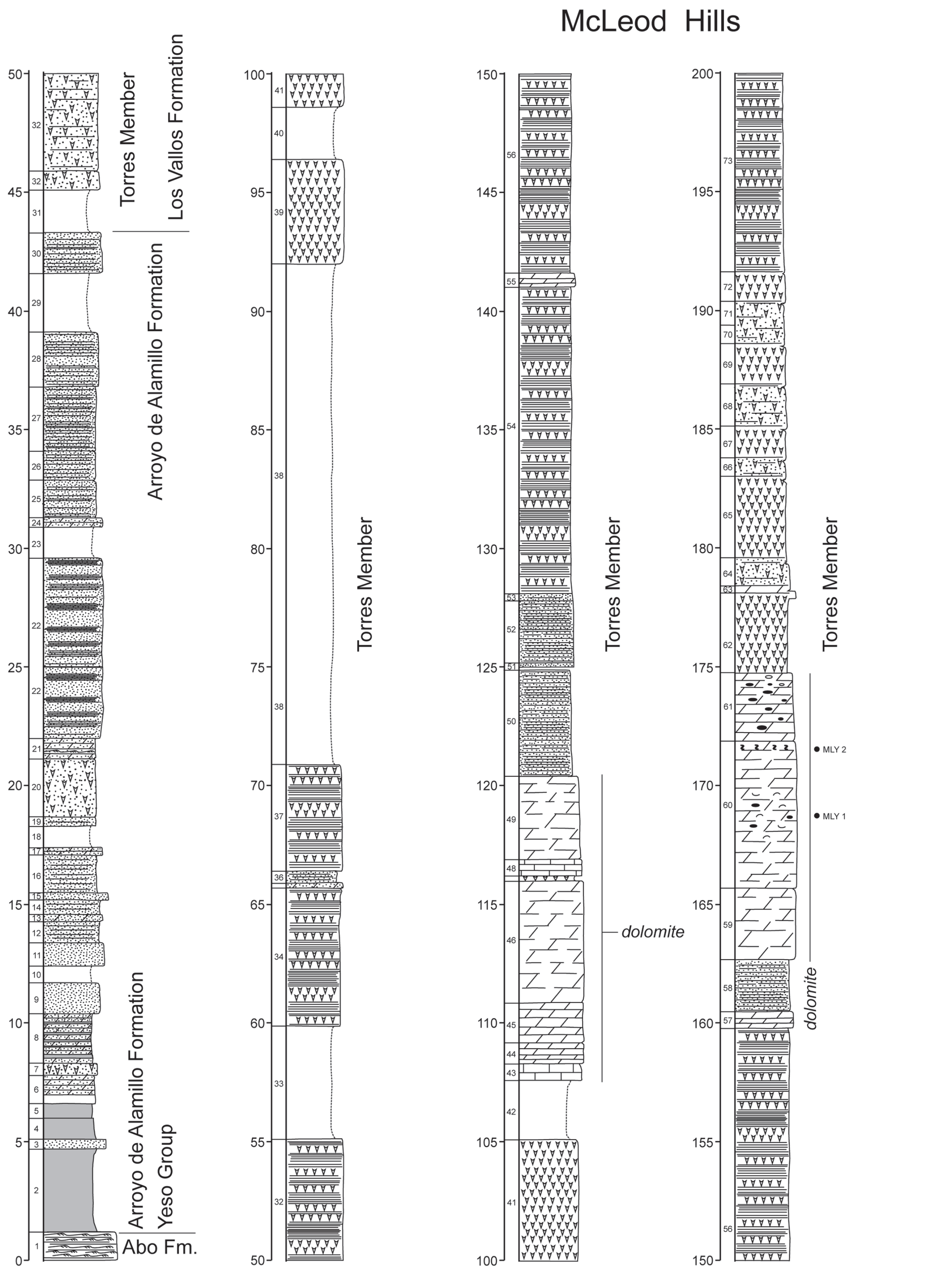

FIGURE 6. Measured stratigraphic section of the Yeso Group in the McLeod Hills in the southern Caballo Mountains. See Appendix for map coordinates of location, and Figure 4 for lithology symbols legend.

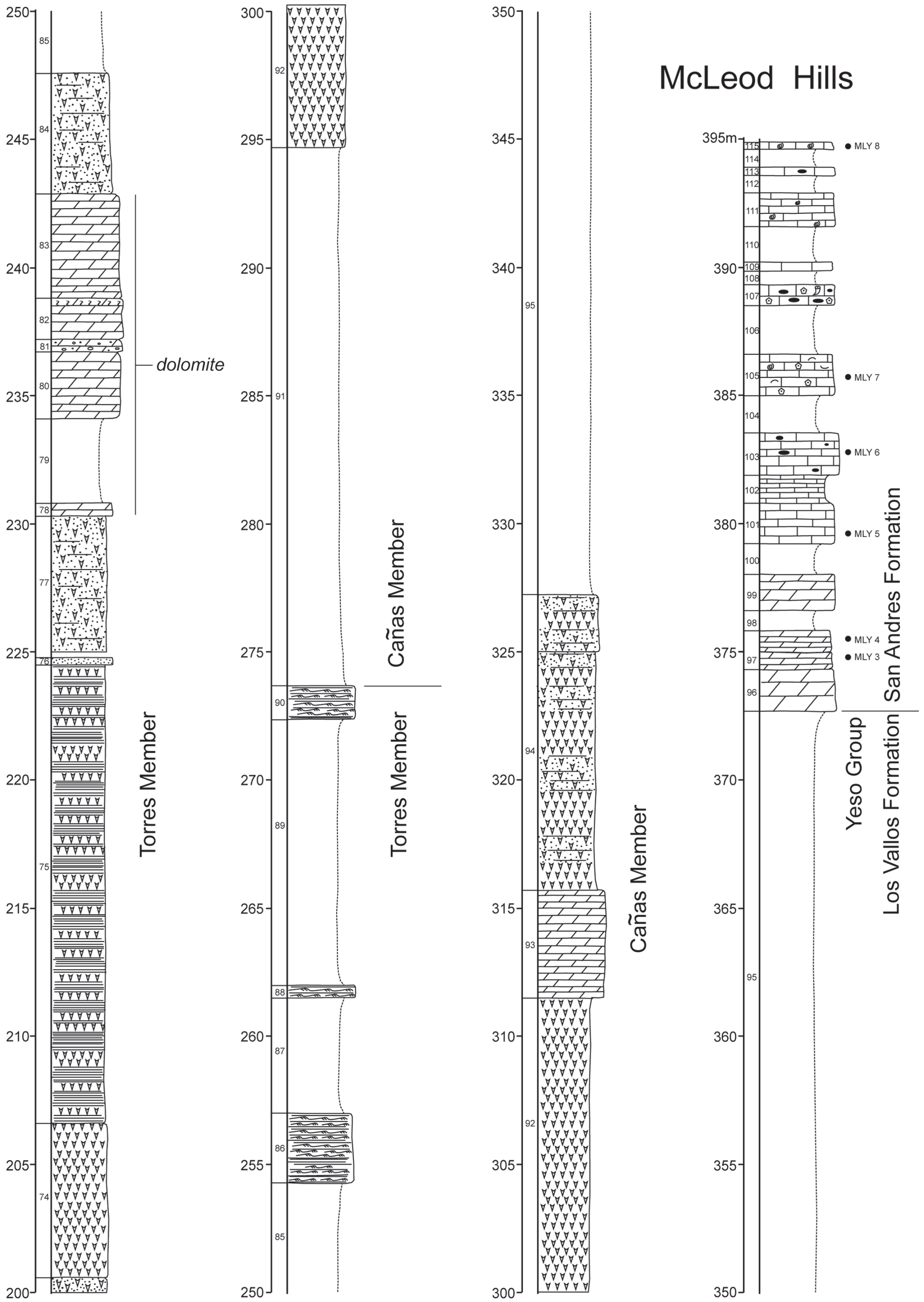

FIGURE 6. Cont.

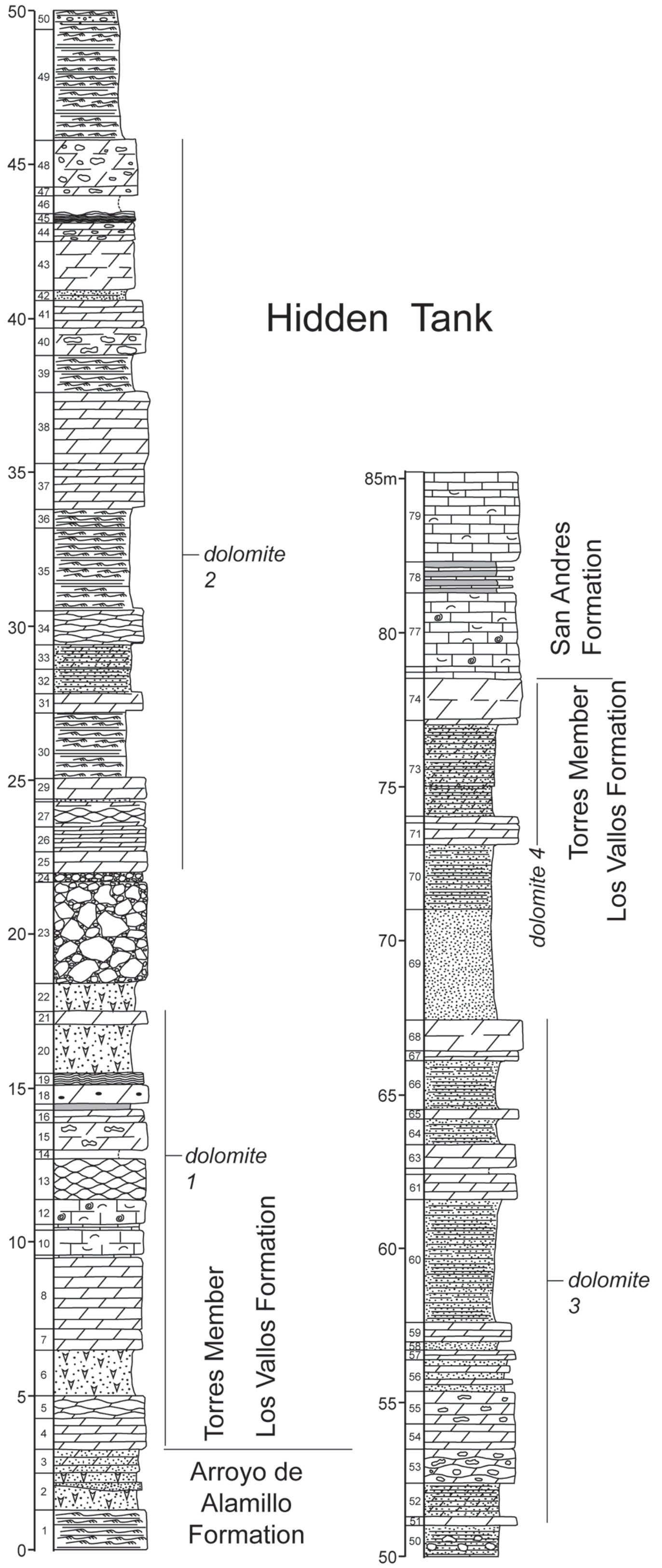

FIGURE 7. Measured stratigraphic section of the upper part of the Yeso Group at Hidden Tank in the southern Caballo Mountains. See Appendix for map coordinates of location, and Figure 4 for lithology symbols legend.

At Massacre Gap, the Arroyo de Alamillo Formation is dominantly nonmarine red beds where rare trough-crossbedded sandstone represents small channel fills of an ephemeral braided stream system. Ripple laminated siltstone to fine-grained sandstone probably represents eolian deposits (eolian sand sheets) or shallow channel fills (cf. Mack and Suguio, 1991). Crossbedded fine-grained sandstone with small ripples on foresets is interpreted to represent eolian dunes. Horizontally-laminated siltstone to fine-grained sandstone is either of eolian origin or represents sheetflood deposits. Red mudstone is interpreted as overbank fines deposited on an extensive coastal plain. Intercalated greenish mudstone, laminated green dolomitic siltstone and gypsiferous siltstone represent short periods of shallow marine flooding with partly evaporitic conditions.

In the McLeod Hills we interpret the greenish siltstone/shale of the Arroyo de Alamillo Formation as deposits of a coastal plain. The massive to indistinctly laminated siltstone to fine-grained sandstone probably represent eolian deposits. The dolomitic siltstone to silty dolomite formed in nearshore environments, and the gypsiferous siltstone to fine-grained sandstone represent deposits of a coastal sabkha. Thus, the Arroyo de Alamillo Formation at Broken House Tank and Massacre Gap represents dominantly nonmarine, eolian sand sheet deposits with minor fluvial sediments and thin intervals of fine-grained sediments resulting from short periods of marine flooding with partly evaporitic conditions. The Arroyo de Alamillo Formation in the McLeod Hills contains less eolian sediments, lacks fluvial deposits and contains a higher portion of sabkha and nearshore sediments compared to Broken House Tank and Massacre Gap.

Los Vallos Formation

In the Fra Cristobal and Caballo Mountains, the Torres and Cañas members of the Los Vallos Formation are composed of similar lithologies that are arranged to form six depositional cycles. Various types of dolomite formed in a shallow marine, mostly restricted environment, as indicated by a low-diversity biota, partly in evaporitic settings documented by vuggy dolomite containing gypsum and halite, and rarely under more normal, open marine conditions represented by dolomite containing a diverse fossil assemblage. Coquina layers are interpreted as storm deposits (tempestites).

Gypsiferous siltstone and gypsum formed in sabkha environments; siltstone to fine-grained sandstone are interpreted as eolian deposits. Hunter and Ingersoll (1981) interpreted the evaporitic sediments of the Cañas Member as deposits of a hypersaline lagoon which covered an area of approximately 25.000 km², though this is a minimum as the Canas Member has a much greater areal extent than recognized by Hunter and Ingersoll (1981).

During late Yeso time, during deposition of the Joyita Member, an extensive eolian sand sheet prograded towards the south overlying shallow marine, particularly evaporitic deposits (Mack and Dinterman, 2002). The Joyita Member is well exposed at Massacre Gap and composed of siltstone to fine-grained sandstone which are massive, horizontally laminated and ripple laminated. We interpret the succession as deposits of an eolian sand sheet

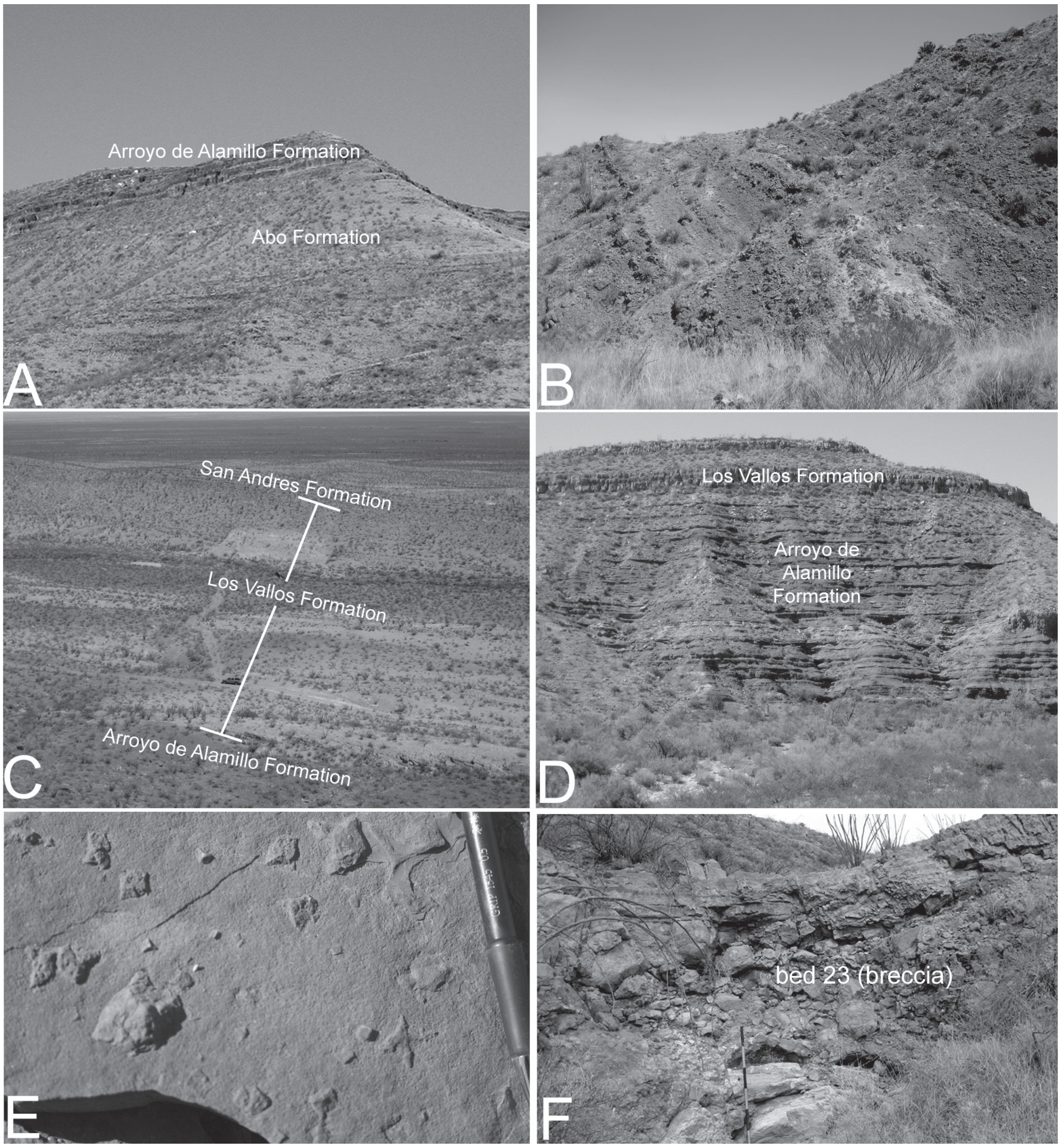

FIGURE 8. Selected photographs of Yeso Group outcrops in the Fra Cristobal and Caballo Mountains. A, Base of Yeso Group (Arroyo de Alamillo Formation) on Abo Formation at Massacre Gap section, segment A. B, Upper part of Torres Member showing characteristic interbedded dolomite, siltstone and gypsum at Massacre Gap section, segment B. C, Overview of upper part of McLeod Hills section. D, Complete section of Arroyo de Alamillo Formation at Broken House Tank. E, Halite pseudomorphs in sandstone bed of Arroyo de Alamillo Formation at Massacre Gap section, segment A. F, Dolomite breccia (bed 23) in Hidden Tank section of Torres Member.

facies. The Joyita Member at Masacre Gap is thick compared to the type section (see Lucas et al. 2005) and documents that the eolian sand sheet extended as far south as the southern Fra Cristobal Mountains. The Joyita Member is completely covered, if it is present, in the McLeod Hills.

CORRELATION

One of the most striking aspects of Yeso regional lithostratigraphy is the consistent architecture of the Los Vallos Formation from the Lucero uplift in Valencia County (Lucas and Zeigler, 2004), through the Yeso type section in Socorro County (Lucas et al., 2005) to Massacre Gap in the southern Fra Cristobal Mountains of Sierra County (Fig. 10). Thus, the Torres Member of the Los Vallos Formation at these three sections contains six obvious transgressive-regressive cycles marked by six intervals of dolomite separated by thicker intervals of siltstone, gypsum and minor carbonate and sandstone beds.

Minor differences are, however, present. Dolomite intervals at Massacre Gap are considerably thicker than at the Yeso type sec-

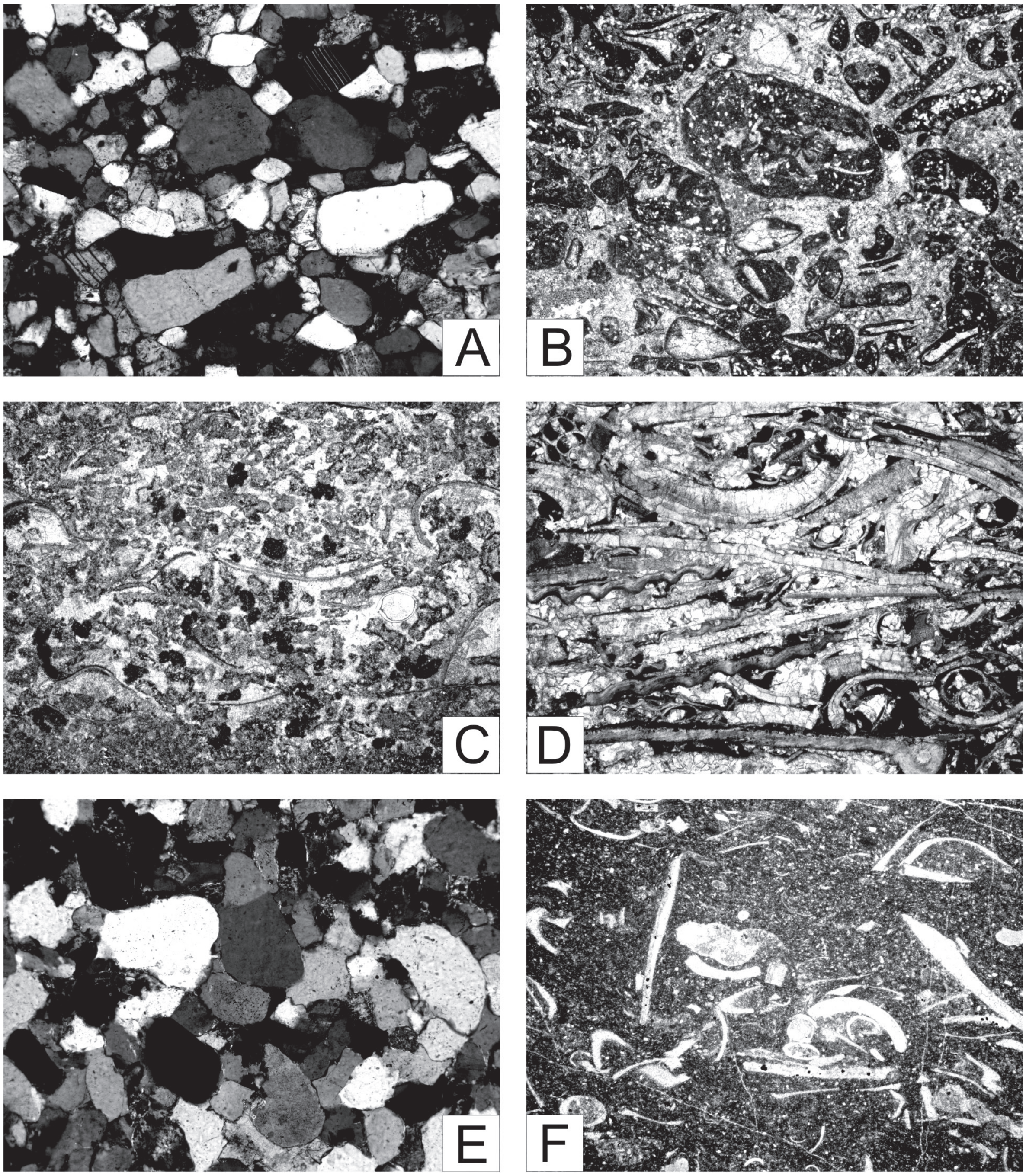

FIGURE 9. Thin section photographs of sandstone and dolomite of the Yeso Group. **A**, Fine-grained, moderately-sorted arkosic sandstone containing abundant quartz grains and many detrital feldspars (small grains, some displaying polysynthetic twins). Sandstone is cemented by quartz which occurs as authigenic overgrowths on detrital grains, and dark-colored carbonate cement. Massacre Gap, Arroyo de Alamillo Formation, sample MG 7. Crossed nicols, width of photograph is 1.2 mm. **B**, Oncoidal rudstone containing abundant oncoids that are up to 6 mm in diameter, and coated grains. Fossils are recrystallized skeletons that commonly form the nuclei of oncoids. Matrix is microspar with a few detrital small quartz grains. Abundant small authigenic, partly idiomorphic quartz grains occur in the oncoids. Masacre Gap, Torres Member, sample MG 10. Plane light, width of photograph is 6.3 mm. **C**, Thin rudstone layer containing many recrystallized shell fragments derived from bivalves or brachiopods, abundant peloids, rare ostracods and a few micritic intraclasts. The rudstone is well washed and carbonate cemented, and locally some micrite is present. Masacre Gap, Torres Member, sample MG 11. Plane light, width of photograph is 6.3 mm. **D**, Rudstone (coquina layer) composed of abundant brachiopod and bivalve shells, and subordinate small gastropods and ostracods. Shells are mostly oriented parallel to the bedding. The rudstone is well washed and carbonate cemented, and locally some micrite is observed. Masacre Gap, Torres Member, sample MG 13. Plane light, width of photograph is 6.3 mm. **E**, Moderately sorted arkosic sandstone composed of monocrystalline quartz and untwinned feldspar grains. The sandstone is cemented by quartz, which occurs as poorly visible authigenic overgrowths on detrital grains and carbonate. Masacre Gap, Joyita Member, sample MG 15. Crossed nicols, width of photograph is 1.2 mm. **F**, Wackestone containing ostracods and larger recrystallized shell fragments probably derived from brachiopods, rare echinoderm fragments and gastropods embedded in dark, peloidal micrite. McLeod Hills, Torres Member, sample MLY 1. Plane light, width of photograph is 6.3 mm.

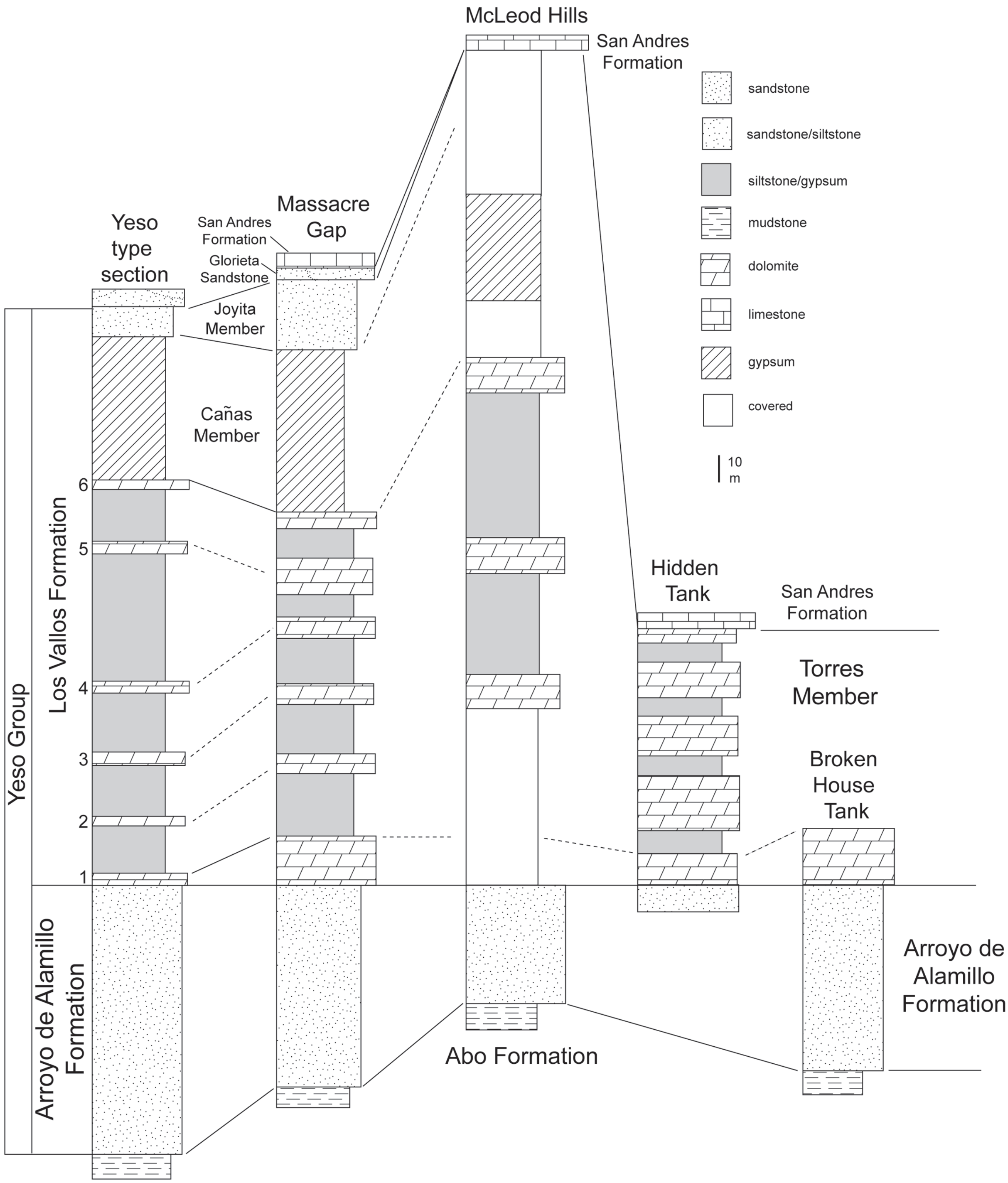

FIGURE 10. Correlation of Yeso Group sections including the type Yeso section in Socorro County and the Yeso Group sections in Sierra County described here. See text for discussion.

tion east of Socorro, the dolomite on top of the Cañas Member is not developed at the type section, and intercalated siltstone-sandstone is rare compared to the type section, suggesting a position closer to the coastline of the Los Vallos section in the Fra Cristobal Mountains. The dolomite intervals in the Torres Member represent periods of relatively high sea-level when large areas were covered by a shallow sea with locally increased salinity. During periods of lowered sea-level, evaporitic and eolian sediments were deposited. At the Yeso type section and at Massacre Gap, strata above the Torres Member are a relatively thick gypsum-dominated interval (the Cañas Member) overlain by red-bed sandstones and siltstones, the Joyita Member. This architectural similarity allows a straightforward correlation of the Yeso Group from the Yeso type section to Massacre Gap (Fig. 10).

However, in the southern Caballo Mountains, the architecture of the Torres Member has changed, so that fewer cycles can be recognized (Fig. 10). Furthermore, as first noted by Kelley and Silver (1952), total Yeso thickness in the Caballo Mountains varies substantially. We explain this thickness variation very simply, by arguing that there is a substantial amount of depositional thinning (loss of gypsum beds) within the upper Yeso and stratigraphic relief at the base of the San Andres Formation (Fig. 10).

The base of the San Andres Formation has long been recognized as a regional unconformity (see Sarg and Lehmann, 1986, Ross, 1987 and Lucas, 2004, and references cited therein). It marks the beginning of the Guadalupian (Middle Permian) marine cycle of deposition (culminated by a highstand around the Pangean periphery), which actually began during the latest Leonardian. The dramatic thinning of the Los Vallos Formation between our sections at Massacre Gap/McLeod Hills and Hidden Tank (Fig. 10) is readily explained as due to a combination of depositional thinning and erosion at the basal San Andres unconformity.

Kottlowski et al. (1956) documented Yeso Group stratigraphy in the San Andres Mountains of eastern Sierra County and northeastern Doña Ana County and showed similar dramatic thinning of the Yeso lithosome from north to south (Fig. 11). At Rhodes Canyon in the northern San Andres Mountains, the Yeso Group is 481 m thick and very similar to (though thicker than) the section we describe here at Massacre Gap: ~ 108 m of Arroyo de Alamillo Formation overlain by 373 m of Los Vallos Formation divisible into the Torres (~ 285 m), Cañas (~ 72 m) and Joyita (up to 33 m) members. Six dolomite intervals can be identified in the Torres Member at Rhodes Canyon (Kottlowski et al., 1956, figs. 10-11). Southward in the San Andres Mountains, at Hembrillo

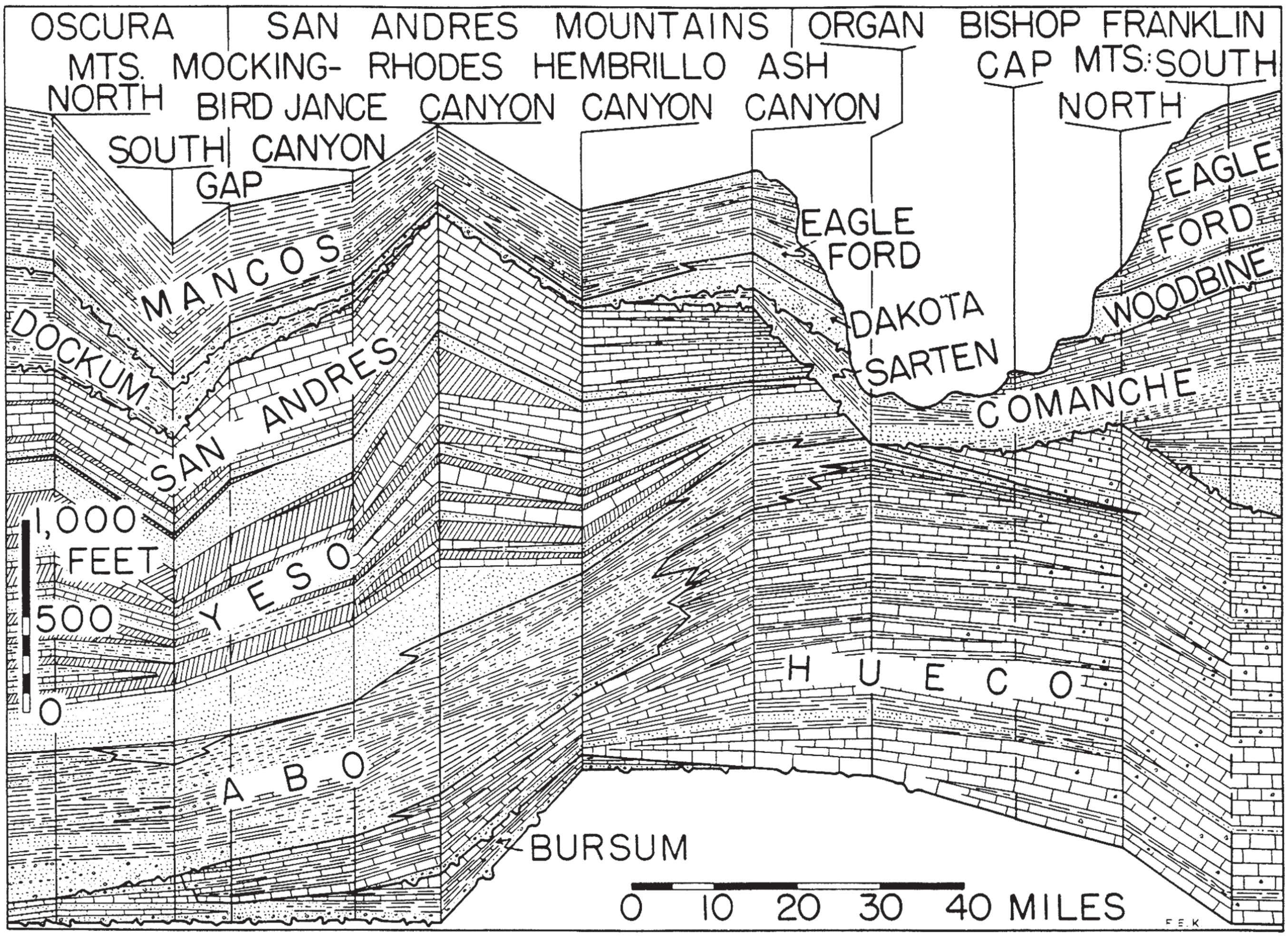

FIGURE 11. North-south diagrammatic section of Permian-Cretaceous strata in the San Andres Mountains (from Kottlowski and LeMone, 1994). Note the dramatic southward thinning of the Yeso lithosome due to loss of gypsum beds and the unconformity at the base of the San Andres Formation.

Canyon, the Yeso Group is ~ 272 m thick and contains much less gypsum than the section at Rhodes Canyon. Farther south, at Love Ranch, the Yeso Group is only ~ 99 m thick and contains little gypsum. Kottlowski et al. (1956) attributed this north-to-south thinning of the Yeso interval primarily to the loss of gypsum beds (Fig. 11). The dramatic thinning of the Yeso Group in the southern Caballo Mountains can also be attributed in large part to the loss of gypsum beds. However, we also believe the evident local absence of the Cañas and Joyita members and of the Glorieta Sandstone can be attributed to stratigraphic relief on the unconformity at the base of the San Andres Formation (Fig. 10).

In the Caballo Mountains, Seager and Mack (2003) assigned strata that Kelley and Silver (1952) mapped as San Andres Formation to the upper part of the Yeso Formation, as its limestone and sandstone-limestone members (Fig. 2). However, Kottlowski et al. (1956, p. 61, fig. 13) noted the presence of siltstones and sandstones in the San Andres Formation in their Love Ranch section in the San Andres Mountains, and clastic beds are common in many San Andres Formation sections (e.g., Kelley, 1971; Harbour, 1970; Lucas and Zeigler, 2004; Brose, 2011). Furthermore, the "limestone member of the Yeso" of Seager and Mack (2003) is remarkably similar to the lower part of the San Andres Formation in the San Andres Mountains (Kottlowski et al., 1956; Krainer et al., 2012). Therefore, we conclude that strata assigned by Seager and Mack (2003) to the upper part of the Yeso are, as Kelley and Silver (1952) concluded, correctly assigned to the San Andres Formation (Figs. 2, 10).

The cycles of deposition of the Torres and Cañas members of the Los Vallos Formation are striking in their areal extent. They may well correlate to at least some of the third-order cycles evident in the platform deposits of the Leonardian Hess Formation in West Texas (Ross and Ross, 1995). These cycles may be the product of glacio-eustatic sea-level fluctuations. Although the maximum extent of the Gondwana glaciation was during the Wolfcampian, smaller ice sheets existed in Australia and Siberia throughout the late Early Permian and Middle Permian (Isbell et al., 2003; Fielding et al., 2008), which may have caused minor sea-level fluctuations sufficient to drive the cyclic succession evident in the Los Vallos Formation of the Yeso Group.

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APPENDIX—LOCATIONS OF MEASURED STRATIGRAPHIC SECTIONS

All coordinates are UTM in zone 13 using datum NAD 83.

Massacre Gap—base at 305041E, 3090514N to 304935E, 3690587 (segment A); then offset to 304801E, 3689828N to top of section at 304892E, 3689543 (segment B).

Hidden Tank—base at 295614E, 3637592N, top at 295743E, 3637652N (SE ¼ sec. 6, T17S, R3W).

McLeod Hills—base at 301150E, 3636501N, top at 301648E, 3636726N (N1/2 sec. 11, T17S, R3W).

Broken House Tank—base at 291746E, 3635015N, top at 291708E, 3634901N (NW ¼ sec. 14, T17S, R4W).