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PENNSYLVANIAN STRATIGRAPHY IN THE FRA CRISTOBAL AND CABALLO MOUNTAINS, SIERRA COUNTY, NEW MEXICO

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Abstract—Pennsylvanian strata exposed in the Fra Cristobal and Caballo Mountains of central Sierra County, New Mexico, are assigned to the (ascending order) Red House, Gray Mesa, Bar B and Bursum formations. The terms Magdalena Group, Madera Group and Nakaye Formation are rejected for these rocks. The Morrowan-Atokan Red House Formation is 29-93 m thick and is a slope-forming succession of shale, limestone and minor conglomerate and sandstone. It unconformably overlies rocks of Proterozoic to Mississippian age. The Atokan-Desmoinesian Gray Mesa Formation conformably overlies the Red House Formation and is 118-210 m of mostly ledge- and cliff-forming beds of cherty limestone. In the southern Caballo Mountains (Green Canyon), the Gray Mesa Formation consists of three members, Elephant Butte, Whiskey Canyon and Garcia, but elsewhere in the Caballo and Fra Cristobal Mountains the formation is not subdivided. The Desmoinesian-Virgilian Bar B Formation conformably overlies the Gray Mesa Formation, is 72-107 m thick and is mostly a slope-forming unit of shale with relatively thin limestone beds. It is unconformably overlain by the lower Wolfcampian (Newwellian) Bursum Formation or by red beds of the middle Wolfcampian Abo Formation. Conodont and fusulinid biostratigraphy establishes the ages of the Pennsylvanian strata in the Fra Cristobal and the Caballo Mountains. These strata differ significantly from the Pennsylvanian section (especially Upper Pennsylvanian strata) in the nearby Mud Springs Mountains. Pennsylvanian tectonism – differential subsidence and tectonic activity of the Caballo uplift – best explains these differences.

INTRODUCTION

Pennsylvanian strata crop out in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico (Fig. 1) and form significant topography along the crests of these ranges. Studies of these Pennsylvanian rocks extend back more than a century, but only during the last 60 years have more detailed data become available. Here, our goal is to present an overview of the stratigraphy of the Pennsylvanian System in the Fra Cristobal and Caballo Mountains pending publication of a more complete treatment of the subject.

PREVIOUS STUDIES

The earliest descriptions of Pennsylvanian strata in the Fra Cristobal and Caballo Mountains were preliminary and very general, referring these strata to the Magdalena Group, or Limestone (Gordon, 1907; Lee, 1909; Darton, 1928; Harley, 1934) (Fig. 2). Kelley and Silver (1952) published the first detailed information on these rocks in their classic monograph on the geology of the Caballo Mountains. They divided the Magdalena Group into three formations (ascending order) – Red House, Nakaye and Bar B (Figs. 2-3). Earlier, Thompson (1942) had published a detailed lithostratigraphy and fusulinid biostratigraphy of the lower part of the Pennsylvanian section in the nearby Mud Springs Mountains and Derry Hills (Fig. 2). However, Kelley and Silver (1952) rejected Thompson's (1942) lithostratigraphy (as have other workers: Lucas et al., 2012) and made little use of his fusulinid biostratigraphy.

Most subsequent workers in the Caballo Mountains (Kottlowski, 1960, 1963; Kalesky, 1988; Singelton, 1990; Thompson, 1991; Lawton et al., 2002; Seager and Mack, 2003) have not altered the lithostratigraphy of Kelley and Silver (1952). In the Fra Cristobal Mountains, Cserna (1956) first made it clear that the Pennsylvanian section in that range is tripartite, but he

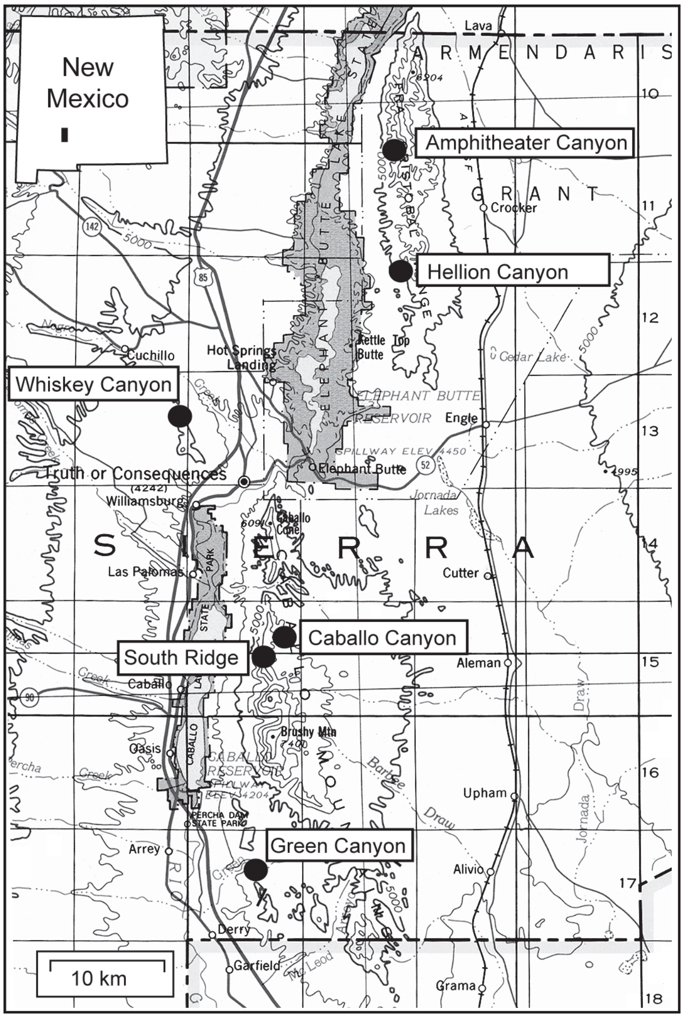

FIGURE 1. Map of Fra Cristobal and Caballo Mountains in Sierra County showing locations of the three principal sections discussed in the text and the Whiskey Canyon section in the Mud Springs Mountains.

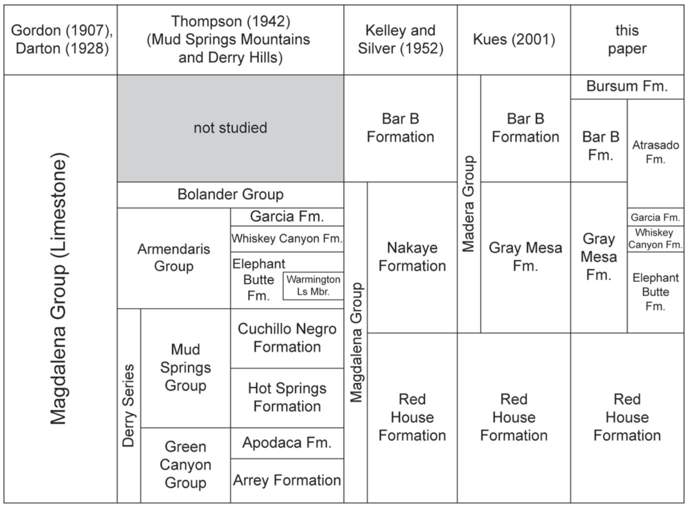

FIGURE 2. Development of lithostratigraphic nomenclature of the Pennsylvanian strata in the Fra Cristobal and Caballo Mountains.

applied no formal nomenclature to the three units. McCleary (1960), however, did use Kelley and Silver's (1952) formation names for Pennsylvanian strata in the Fra Cristobal Mountains (also see Nelson, 1986).

Kues (2001) first suggested modifications to the Pennsylvanian lithostratigraphic nomenclature in the Fra Cristobal and Caballo Mountains. He replaced the name Nakaye Formation with the older name Gray Mesa Formation (of Kelley and Wood, 1946). He abandoned the term Magdalena Group and united the Gray Mesa and Bar B formations in the Madera Group (Fig. 2). Lucas et al. (2009a) used the name Atrasado Formation for the upper part of the Pennsylvanian section in the Mud Springs Mountains. The Atrasado Formation is the name applied to that part of the section to the north, in Valencia and Socorro counties (Lucas et al., 2009b).

There have been just a few detailed studies of sedimentation of parts of the Pennsylvanian section in the Caballo Mountains (Kalesky, 1988; Singleton, 1990). Verville et al. (1986) presented a preliminary study of fusulinid biostratigraphy of most of the Pennsylvanian section in the Fra Cristobal Mountains. Detailed studies of Lower-Middle Pennsylvanian fusulinids have been undertaken in the Mud Springs Mountains and Derry Hills (Thompson, 1942; Lane et al., 1972; King, 1973; Clopine, 1990, 1991a, b, 1992; Clopine et al., 1991), and some conodont data (Kaiser, 1990; Kaiser and Manger, 1991; Barrick et al., 2012; Lucas et al., 2012) and brachiopod data (Gehrig, 1958; Sutherland, 1991) are also available. Thompson (1991) and Lawton et al. (2002) undertook a detailed study of fusulinid biostratigraphy of the upper part of the Pennsylvanian section in the Caballo Mountains.

DATABASE

We measured more than 20 sections in the Pennsylvanian strata in the Fra Cristobal and the Caballo Mountains. However, here we rely primarily on three complete Pennsylvanian sections: (1) a composite of sections at Amphitheater Canyon and Hellion Canyon on the western flank of the Fra Cristobal Mountains; (2) a section on South Ridge through Caballo Canyon in the central Caballo Mountains; and (3) the section at Green Canyon in the southern Caballo Mountains (in the Red Hills) (Figs. 4-10). The other sections we measured include one or more of the four Pennsylvanian formations we recognize in the Fra Cristobal and Caballo Mountains (see Lucas et al., 2012 for detailed discussion of the Red House Formation sections), some of which are presented here (Fig. 11).

LITHOSTRATIGRAPHY

Introduction

We recognize four formations of Pennsylvanian age in the Fra Cristobal and Caballo Mountains (in ascending order): Red House, Gray Mesa, Bar B and Bursum formations (Fig. 2). Here, we justify this nomenclature and describe the lithostratigraphy of these units.

Magdalena and Madera Groups

As noted above, Gordon's (1907) term Magdalena Group is synonymous with Pennsylvanian System in New Mexico. For that reason, Thompson (1942) and Kues (2001) recommended abandoning the term Magdalena Group, and we concur. Kues (2001) extended use of the term Madera Group into Sierra County to unite the Nakaye and Bar B formations. However, Krainer and Lucas (2004) argued that the Madera Group as used by Kues (2001) lacks lithologic unity, has arbitrary geographic boundaries, and its upper and lower boundaries are more chronostratigraphic than lithostratigraphic. Furthermore, the name Madera Group (or Formation or Limestone) has been inconsistently used by various workers. Therefore, Krainer and Lucas (2004) abandoned the term Madera Group, as do we.

Type Sections

The type sections of the Red House, Nakaye and Bar B formations are one section on South Ridge (sec. 10, T15S, R4W) in the Caballo Mountains (Fig. 1). Kelley and Silver (1952, p. 253-256) described this section (Fig. 3), determining the following thicknesses: Red House Formation, 362 ft (110 m); Nakaye Formation, 419 ft (128 m); and Bar B Formation, 339 ft (103 m). However, two modifications of the type sections of Kelley and Silver (1952) need to be made:

1. As discussed by Lucas et al. (2012) in this guidebook, the approximately lower 10 m of the original type section of the Red House Formation (units 23-24 of the Kelley and Silver, 1952 section: Fig. 3) are Devonian Percha Formation overlain by Mississippian Lake Valley Formation. Thus, the Red House Formation, at its type section, is ~92 m thick by our measurement and rests disconformably on the Lower Mississippian Lake Valley Formation (Fig. 8).

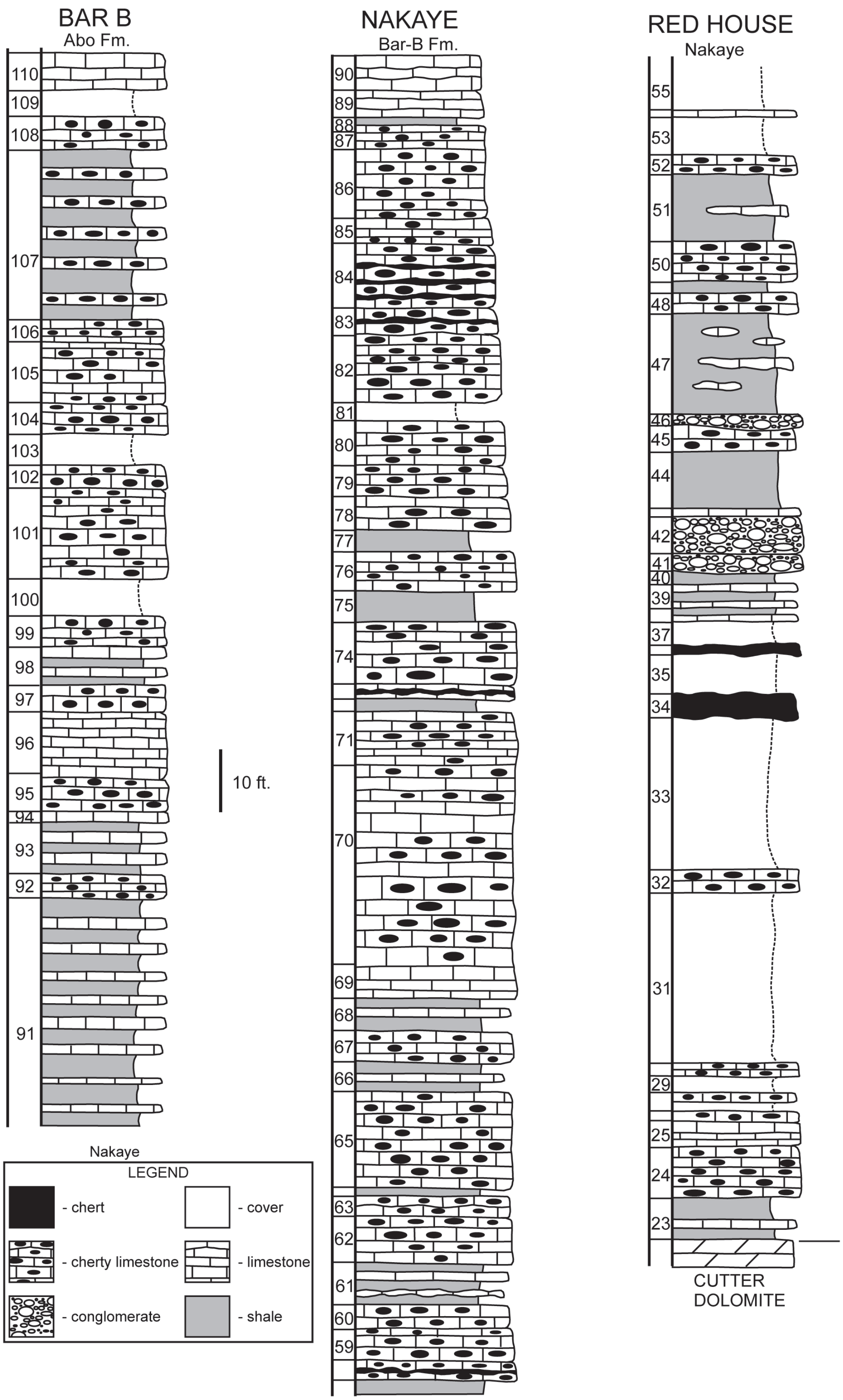

FIGURE 3. Type section of the Red House, "Nakaye" and Bar B formations, drawn from the description provided by Kelley and Silver (1952, p. 253-256).

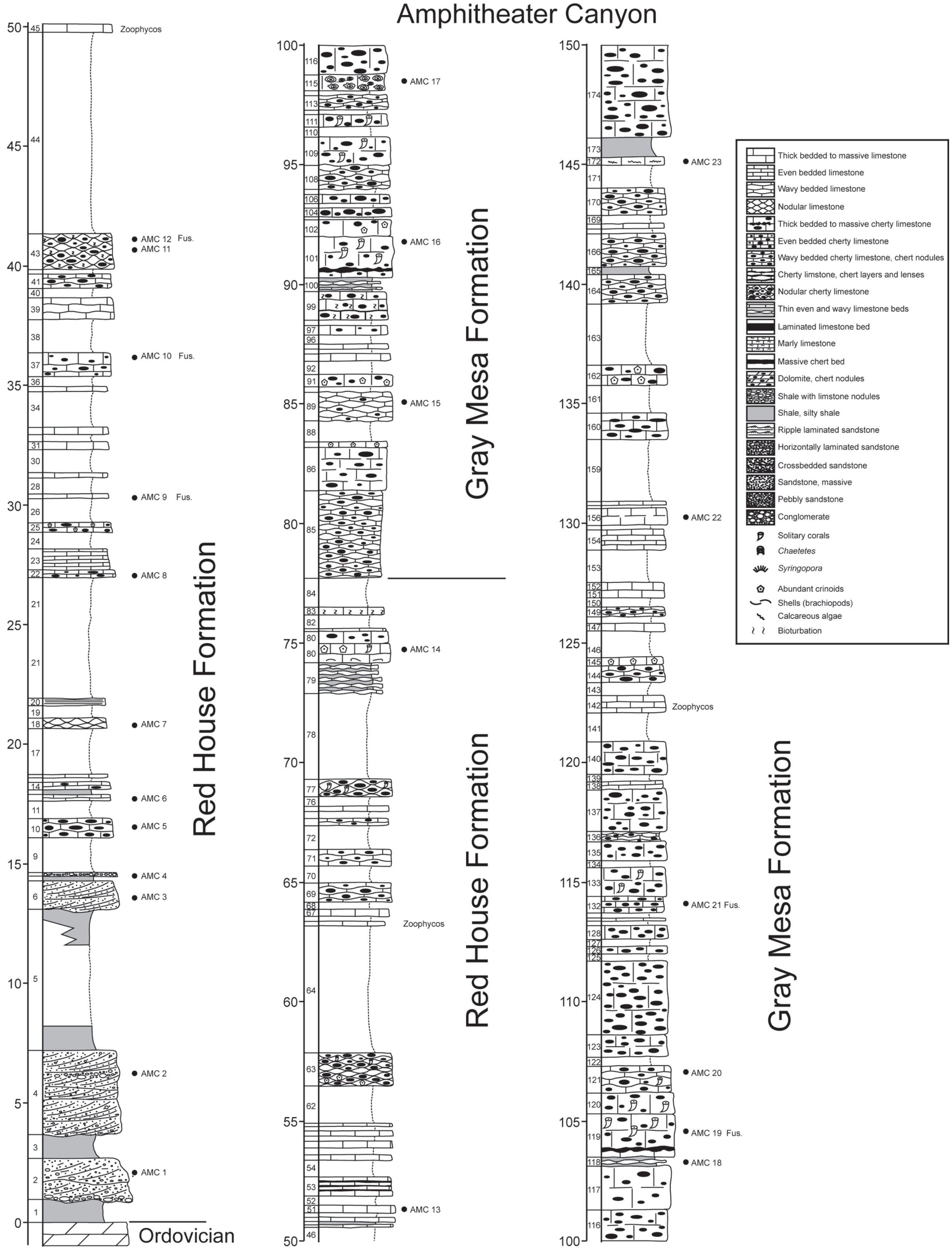

FIGURE 4. Measured stratigraphic of Red House and lower part of Gray Mesa Formation at Amphitheater Canyon in the northern Fra Cristobal Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

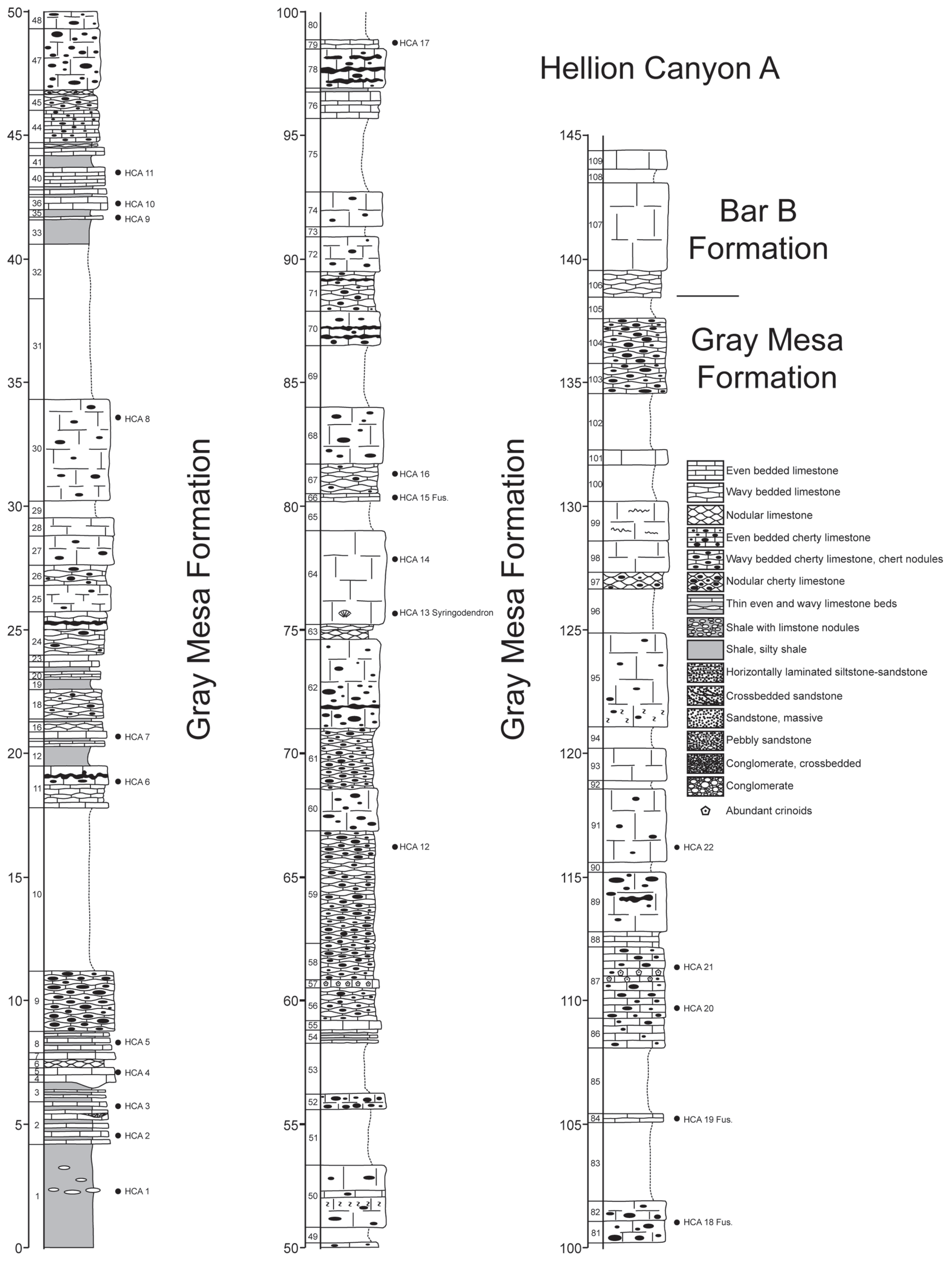

FIGURE 5. Measured stratigraphic section of the majority of the Gray Mesa Formation and base of the Bar B Formation at Hellion Canyon (A) on the western flank of the Fra Cristobal Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

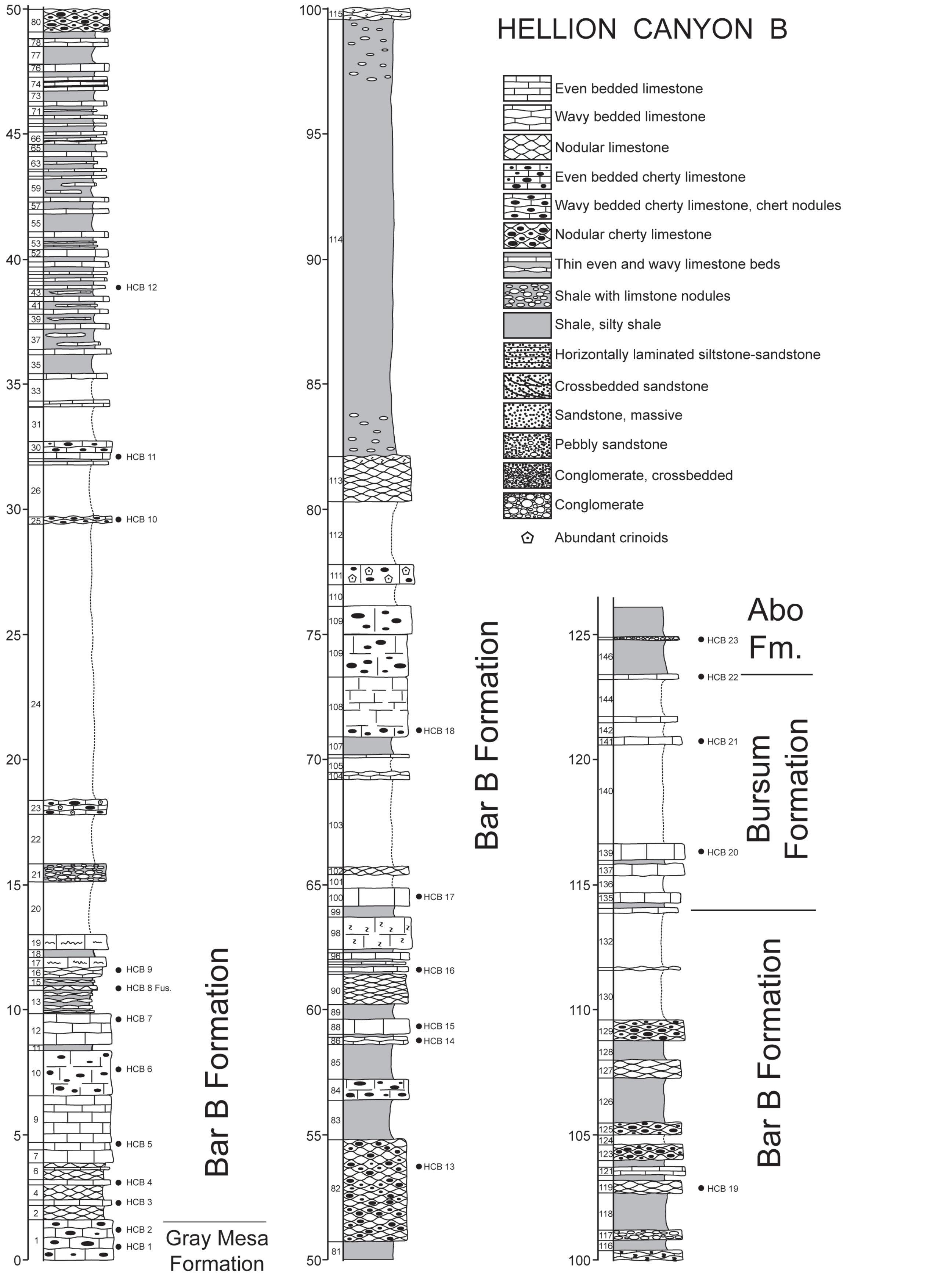

FIGURE 6. Measured stratigraphic section of the Bar B and Bursum formations at Hellion Canyon (B) on the western flank of the Fra Cristobal Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

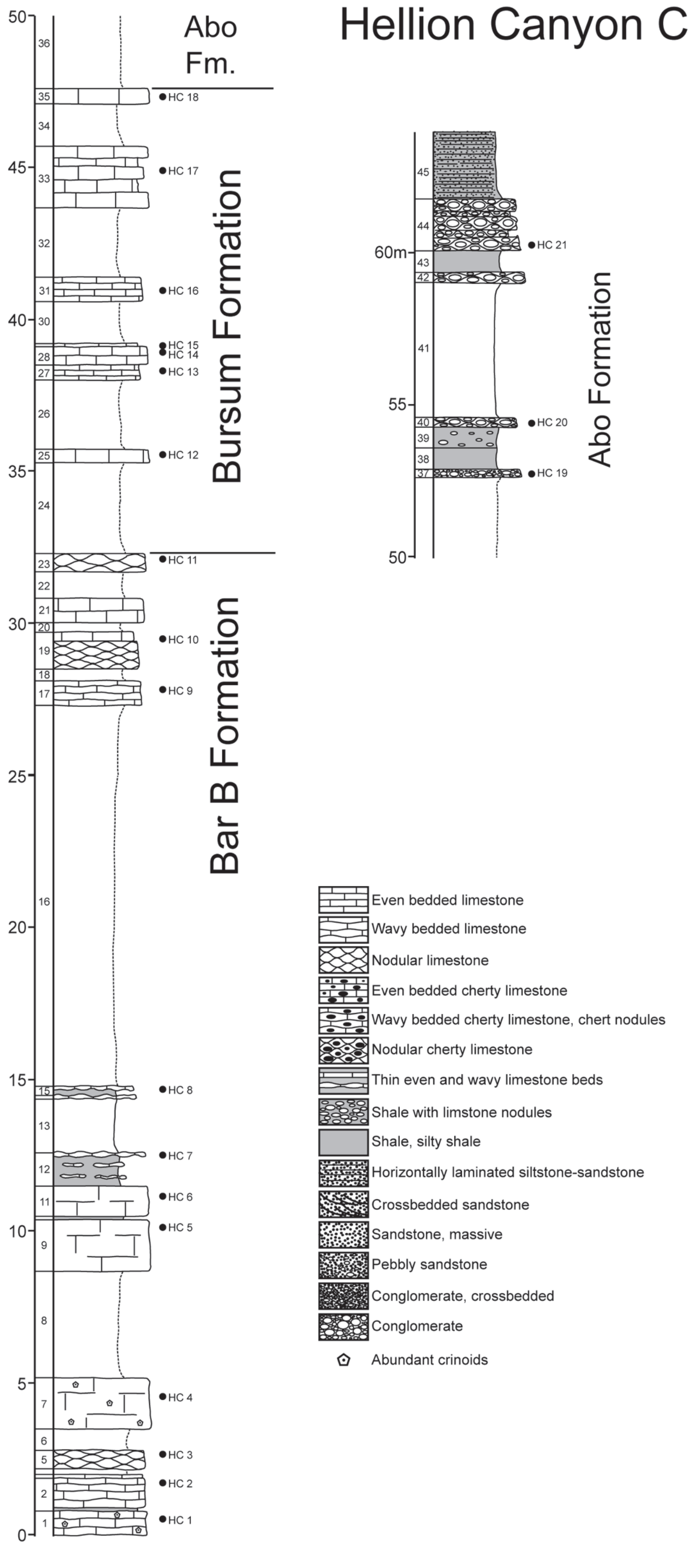

FIGURE 7. Measured stratigraphic section of the upper part of the Bar B Formation, Bursum Formation and lower part of the Abo Formation at Hellion Canyon (C) on the western flank of the Fra Cristobal Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

2. Kelley and Silver (1952) concluded that the top of South Ridge (the topographic crest of the Caballo Mountains at this location) is approximately the Bar B/Abo formational contact. This is not the case. Instead, the topographic crest here is within the upper Gray Mesa Formation, very close to the Gray Mesa/Bar B formational contact. What this means is that the "type section of the Bar B Formation" of Kelley and Silver (1952) is actually a section of Gray Mesa Formation.

To verify this, compare Kelley and Silver's (1952) type sections of the Nakaye and Bar B formations (Fig. 3) to our sections at South Ridge and Caballo Canyon (Figs. 8-9). There is a reasonable match of Kelley and Silver's (1952) Red House Formation section to our Red House section at the same locality, both about 100 m thick (compare Figures 3 and 8). Our composite section of South Ridge and Caballo Canyon indicates a thickness of the Gray Mesa (Nakaye) Formation of ~100 m, close to the thickness of Kelley and Silver's (1952) type Nakaye Formation thickness of ~128 m (compare Figures 3, 8 and 9). Also, their type Nakaye section is mostly cherty limestone with an uppermost limestone interval lacking chert, and thus broadly resembles our section. The type Bar B Formation of Kelley and Silver (1952), however, bears little resemblance to the Bar B Formation section we measured at Caballo Canyon (compare Figures 3 and 9). Furthermore, we have examined the outcrops at the top of South Ridge, and no Abo Formation is preserved there. Indeed, total thickness of the Pennsylvanian strata exposed on the western face of South Ridge cannot be more than about 230 m (estimated trigonometrically), much less than the total thickness of ~340 m of Kelley and Silver's (1952) section (Fig. 3). In addition, we found the upper part of the South Ridge section to be unclimbable cliffs, so we believe the upper part of Kelley and Silver's (1952) section was an estimate made using the topographic map and binoculars. Whether or not that was the case, there is no Bar B Formation section overlain by Abo Formation at the top of South Ridge. Instead, there is Gray Mesa Formation at the top of the ridge, locally overlain by the base of the Bar B Formation.

Clearly, Kelley and Silver (1952) understood that a relatively shaley unit is at the top of the Pennsylvanian section in the Caballo Mountains, and they named it the Bar B Formation. To remedy the problem produced by their type section of the Bar B Formation, we designate units 74-117 of our Caballo Canyon section (Fig. 9) as the principal reference section of the Bar B Formation. This is a section consistent with Kelley and Silver's (1952) original concept of the Bar B Formation, with clear upper and lower contacts, that is relatively accessible. It well characterizes the Bar B Formation in the Caballo and Fra Cristobal Mountains.

Red House Formation

The stratigraphically lowest unit in the Pennsylvanian section in the Fra Cristobal and Caballo Mountains is the Red House Formation of Kelley and Silver (1952). The lithostratigraphic names created by Thompson (1942) for his Derry Series were based on outcrops of the Red House Formation in the Mud Springs Mountains and the Derry Hills. As Kelley and Silver (1952) first

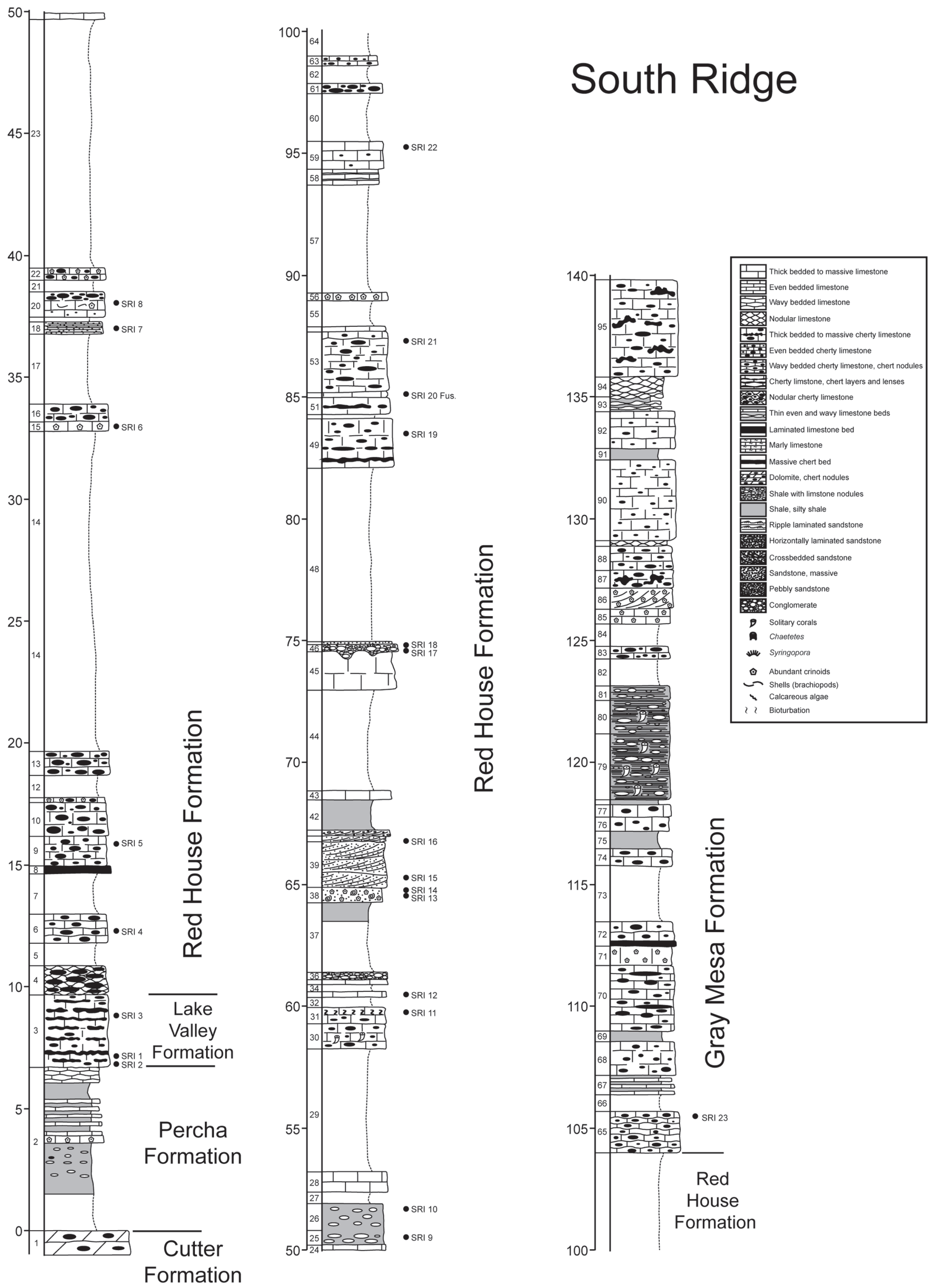

FIGURE 8. Measured stratigraphic section of the Red House Formation and lower part of the Gray Mesa Formation at South Ridge in the central Caballo Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

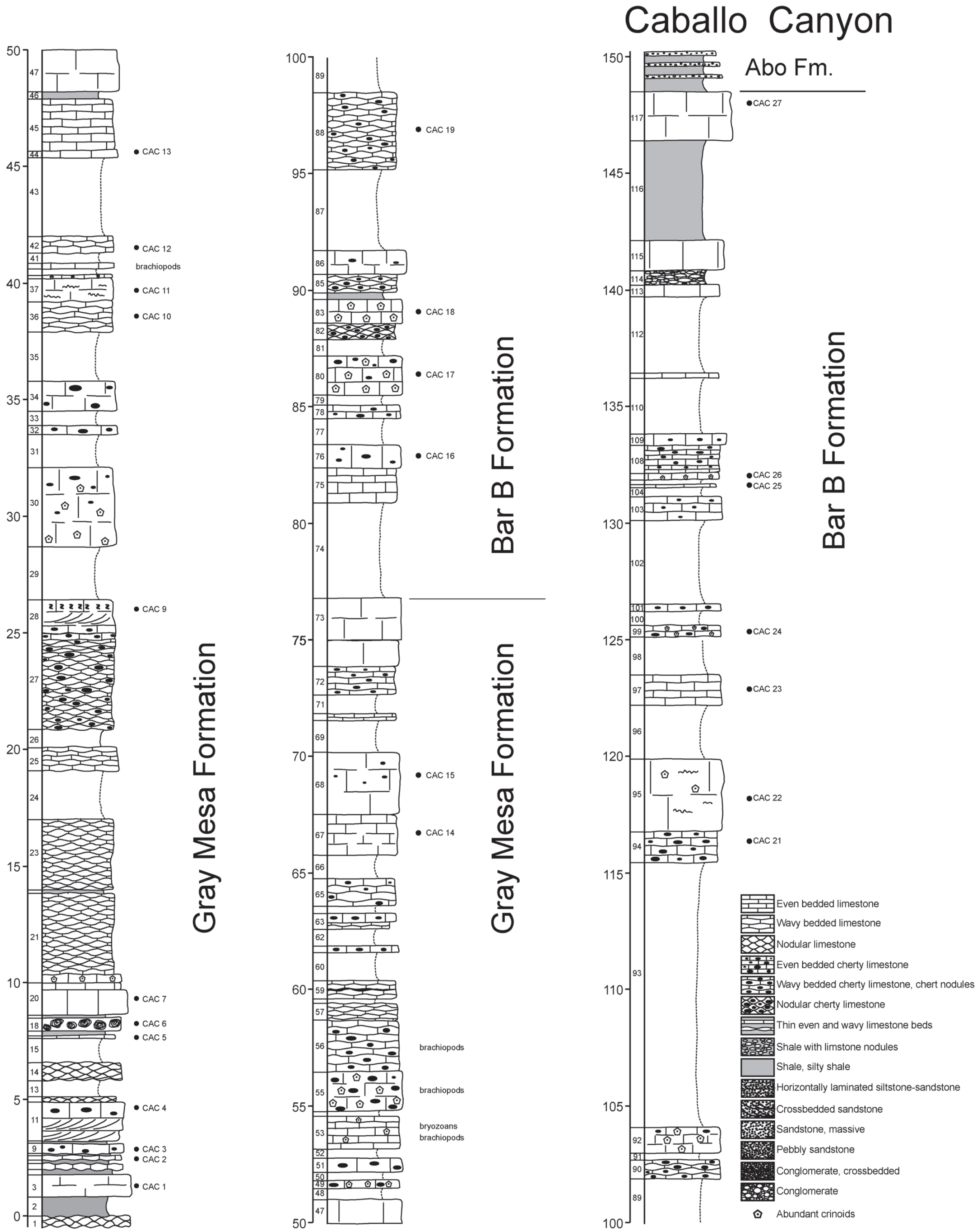

FIGURE 9. Measured stratigraphic section of most of the Gray Mesa Formation and the entire Bar B Formation at Caballo Canyon in the central Caballo Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

observed, these units (two groups and four formations: Fig. 2) are biostratigraphic units, not lithostratigraphic units, and should be abandoned (also see Lucas et al., 2012, this guidebook). Kalesky (1988), working in the southern Caballo Mountains, recognized four informal units of the Red House Formation, but these are genetic sedimentological facies, without consistent boundaries, not formal lithostratigraphic units. Therefore, we advocate no lithostratigraphic subdivisions of the Red House Formation in the Fra Cristobal and Caballo Mountains.

We offer only a brief review of Red House Formation lithostratigraphy here; for more detailed information see Kalesky (1988) and Lucas et al. (2012). Thus, the Red House Formation in the Fra Cristobal and Caballo Mountains is 29-93 m thick and is a slope-forming succession of shale (gray, black or green), limestone (mostly cherty wackestone, nodular wackestone and crinoidal packstone) and minor conglomerate and sandstone (Figs. 4, 8, 10). At many sections, the base of the Red House Formation is conglomerate or sandstone, and a medial sandstone complex is present in the formation in the southern Caballo Mountains. The base of the Red House Formation is a profound unconformity on rocks of Proterozoic, Ordovician, Silurian, Devonian or Mississippian age. The upper contact is conformable with the Middle Pennsylvanian Gray Mesa Formation.

Gray Mesa Formation

We follow Kues (2001) in abandoning the name Nakaye Limestone (Kelley and Silver, 1952) and replacing it with the name Gray Mesa Formation (Kelley and Wood, 1946). Both names are for the limestone- (especially cherty limestone-) dominated lithostratigraphic unit that is the medial (or near medial) Pennsylvanian formation-rank unit across much of central New Mexico. Besides their essentially identical lithology and stratigraphic position, the type Gray Mesa and type Nakaye are the same age – largely Desmoinesian – which demonstrates their stratigraphic equivalence. Therefore, the name with priority – Gray Mesa Formation – is used here.

Our measured sections indicate a Gray Mesa Formation thickness in the Caballo and Fra Cristobal Mountains that ranges from about 118 m (at Green Canyon: Fig. 10) to ~210 m (estimated from the composite of the Amphitheater Canyon and Hellion Canyon A sections: Figs. 4-5). Our sections for South Ridge and Caballo Canyon (Figs. 8-9) indicate a Gray Mesa Formation thickness of ~100 m. Seager and Mack (2003) stated the Nakaye Formation ranges in thickness from 140 to 200 m, which is close to our measurements. However, note that in their measured section between Green Canyon and Red Hill Tank (Seager and Mack, 2003, fig. 21), which is the same as our Green Canyon section (Fig. 10), they include strata we assign to the Garcia Member of the Gray Mesa Formation in the Bar B Formation.

In the Fra Cristobal Mountains, the Gray Mesa Formation is dominated by relatively thick (>1 m) ledge- and cliff-forming limestone units. These limestone units are commonly wavy bedded to nodular and indistinctly bedded to massive. Rarely, thin limestone beds alternate with covered (shale) units. These limestones are mostly cherty, although non-cherty limestones are also present. The limestone textures are mostly muddy (mudstone and wackestone), though a few packstones are evident. Fossils observed on outcrop include echinoderm fragments (mostly crinoids), bryozoans, brachiopods, fusulinids, solitary corals and rare *Zoophycos*. Fossils are locally silicified. Some limestone beds are bioturbated.

Although the Gray Mesa Formation can be divided into three lithologically distinct members in Socorro County to the north (Rejas, 1965; Lucas et al., 2009b), and in the Mud Springs Mountains to the southwest (Thompson, 1942; Lucas et al., 2009a), these subdivisions are not evident in the Fra Cristobal Mountains. Therefore, we treat the Gray Mesa Formation as an undivided unit in the Fra Cristobal Mountains (Figs. 4-5).

Similarly, at South Ridge-Caballo Canyon in the Caballo Mountains, no subdivisions of the Gray Mesa Formation are evident. Particularly striking here is the lack of a distinct, medial, chert-rich zone (Figs. 8-9), which is the Whiskey Canyon Member in the Mud Springs Mountains and in Socorro County. However, ~20 km to the south, at Green Canyon, we do recognize three members of the Gray Mesa Formation (Fig. 10):

1. Lower, relatively shaley interval ~ 33 m thick with many limestone beds and units intercalated, the Elephant Butte Member. These limestones are thin- to medium- to wavy-bedded, rarely thick-bedded, and both cherty and non-cherty. Fossils include brachiopods, fusulinids, gastropods, solitary corals and rare *Chaetetes*.
2. Medial interval, with thicker beds of limestone and much chert, the Whiskey Canyon Member. This member is ~ 34 m thick and composed of thin- to medium-, mostly wavy-bedded and thick-bedded to massive, mostly cherty to very cherty limestones with a few thin covered (shale) intervals. The fossil assemblage from the unit is similar to the underlying Elephant Butte Member, and rare *Syringopora* are present.
3. The upper, Garcia Member, with its base marked by a prominent sandstone, which is more shaley and less cherty than the underlying Whiskey Canyon Member. The carbonate sandstone at the base is 1.7 m thick and crossbedded. Above the base, 0.2-1.4 m-thick limestone beds and up to 6.5 m thick, indistinctly bedded to massive limestone units alternate with covered intervals. Limestone is cherty and non-cherty, and partly bioturbated.

We thus see substantial facies and thickness change in the Gray Mesa Formation moving from south to north along the Caballo and Fra Cristobal Mountains. Simply put, the Gray Mesa Formation becomes thicker from south to north, although there is no significant facies change observed, and the facies indicate a deeper shelf environment.

Bar B Formation

We measured three complete sections of the Bar B Formation (Figs. 6, 9, 10), and it ranges in thickness from ~72 m (at Caballo Canyon: Fig. 9) to ~96 m (at Green Canyon: Fig. 10) to ~107 m (at Hellion Canyon B: Fig. 6). The majority of the unit is slope-forming beds of shale, which are often covered and up to 17.5 m thick; in our measured sections, shale/cover ranges from 59% to 65% of the thickness of the Bar B Formation. The remainder of the formation is beds of limestone, most of which are <1 m thick. Nodular and wavy-bedded wackestones are the most characteristic limestone lithology of the Bar B Formation, but cherty wackestones, crinoidal packstones and lime mudstones (some beds dolomitized) are also present, although the Bar B Formation is less cherty than the Gray Mesa Formation. Characteristic fossils are echinoderm fragments (mostly crinoids), brachiopods, bryozoans, gastropods, fusulinids, rare solitary corals, *Chaetetes* and phylloid algae. Typically, because of its high content of shale, the Bar B Formation is a slope or valley former.

It is important to note that at many locations in the Fra Cristobal and Caballo Mountains we have removed the upper part of the Bar B Formation from the unit, and recognize it as the Bursum Formation (see below). Nevertheless, there are widely varying thicknesses of the Bar B Formation reported in the Caballo Mountains, with the unit stated to be as thick as 206 m in the McLeod Hills (Singleton, 1990). Some of the differences in reported thicknesses definitely reflect different choices of the Gray Mesa-Bar B contact and inclusion/exclusion of Bursum Formation strata in the Bar B Formation. In general, our data suggest that the Bar B Formation in the Fra Cristobal and Caballo Mountains is about 100 m thick. Furthermore, the Bar B Formation variably encompasses strata of Desmoinesian, Missourian and Virgilian age (see discussion below, Thompson, 1991 and Lawton et al., 2002), so one or more unconformities is present within the formation. We currently lack the data to precisely locate those unconformities, and to resolve variably reported Bar B thicknesses, so these are topics for further study.

Indeed, we do not believe that the Bar B Formation base we chose in the three sections we measured is necessarily the same lithostratigraphic horizon. Thus, on the western slope of the Fra Cristobal Mountains, a light-colored interval of dolomitic lime mudstone is an obvious mapping base of the Bar B Formation (Fig. 6). It divides cliffy, limestone-dominated outcrops of the Gray Mesa Formation below from slope-forming, shaley Bar B Formation above. However, at Caballo Canyon, we chose the base of the Bar B Formation at a 4-m-thick shale/cover bed (our bed 74: Fig. 9), above which limestones are much thinner bedded and less cherty than those of the Gray Mesa Formation below. We note, however, that the Bar B base could, perhaps, have been chosen stratigraphically lower (base of bed 29: Fig. 9) or higher (base of bed 87: Fig. 9), depending on the criteria chosen. Furthermore, none of these possible bases is obviously correlative (or homotaxial) to the base of the Bar B Formation we chose in the Fra Cristobal Mountains. Similar issues can be raised (see earlier discussion) about choosing the base of the Bar B Formation in the Green Canyon section (Fig. 10).

Note that Soreghan (1992, 1994) described an ~260 m thick section of "Missourian-Virgilian" strata in the southern Caballo Mountains not far (about 6 km northeast) from our Green Canyon section. Soreghan (1994, fig. 6), used fusulinid data and cyclostratigraphy to interpret the section (which appears to us to be entirely Bar B Formation) as a complete record of Missourian-Virgilian glacio-eustatically driven depositional cycles. We have not examined this section, but as interpreted by Soreghan (1992, 1994) it differs substantially in thickness and age from nearby Bar B Formation sections. These discrepancies will be the subject of future research.

Bursum Formation

In naming the Bar B Formation, Kelley and Silver (1952) suggested that its uppermost beds may be equivalent to the Bursum Formation. Indeed, at many outcrops in the Fra Cristobal and Caballo Mountains, we identify the Bursum Formation between the Bar B and overlying Abo Formation (Figs. 7, 10-11), and these Bursum strata of our usage were included in the Bar B Formation by previous workers. These strata were termed the "upper conglomerate member" of the Bar B Formation by Lawton et al. (2002).

Across much of New Mexico, the Bursum Formation is generally less than 100 m of interbedded siliciclastic red beds and marine limestone and shale (e.g., Lucas and Krainer, 2004; Krainer and Lucas, 2009). The Bursum Formation is distinguished from underlying Pennsylvanian strata by its substantial content of red-bed shale and mudstone and the presence of beds of limestone-pebble conglomerate and trough-crossbedded sandstone. The base of the Bursum Formation is chosen as the base of the first siliciclastic bed of these kinds. Unlike the immediately overlying lower Permian Abo Formation, the Bursum Formation contains beds of marine limestone and shale. Typically, the highest marine limestone bed is chosen as the uppermost bed of the Bursum Formation.

In the Fra Cristobal and Caballo Mountains, we use these criteria to identify the Bursum Formation as a generally thin unit (<25 m) locally present between the Bar B and Abo formations (Figs. 7, 10-11). However, in the McLeod Hills, the Bursum Formation is as much as 107 m thick according to Singleton (1990). As elsewhere, the Bursum Formation in the Fra Cristobal and Caballo Mountains is a mixture of red-bed mudstone and shale, limestone-cobble conglomerate, marine limestone and shale (Figs. 7, 10-11). Our measured sections indicate the Bursum Formation is as much as 80 m thick and that it is locally absent where the Abo Formation rests directly on the Bar B Formation (Fig. 11).

We regard the Bursum Formation as a syntectonic unit with a regionally unconformable base (e.g., Krainer and Lucas, 2009). The Bursum Formation in the Fra Cristobal and Caballo Mountains supports these conclusions (Lawton et al., 2002; Krainer and Lucas, 2009). In the southern Caballo Mountains (e.g., McLeod Draw), several sandstone and conglomerate beds that are 0.1-0.7 m thick are characteristic of the Bursum Formation. Conglomerate beds are poorly sorted, clasts are mostly well rounded, measure up to 10 cm in diameter and are mostly < 3 cm. Conglomerate beds are composed of various types of carbonate clasts and, subordinately, chert clasts. Quartz is very rare. Some conglomerate and sandstone beds are well washed, calcite cemented and contain abundant fragments of echinoderms (crinoids), brachiopods, bryozoans and fusulinids, indicating a high-energy, nearshore shallow marine depositional environment (cf. Singleton, 1990).

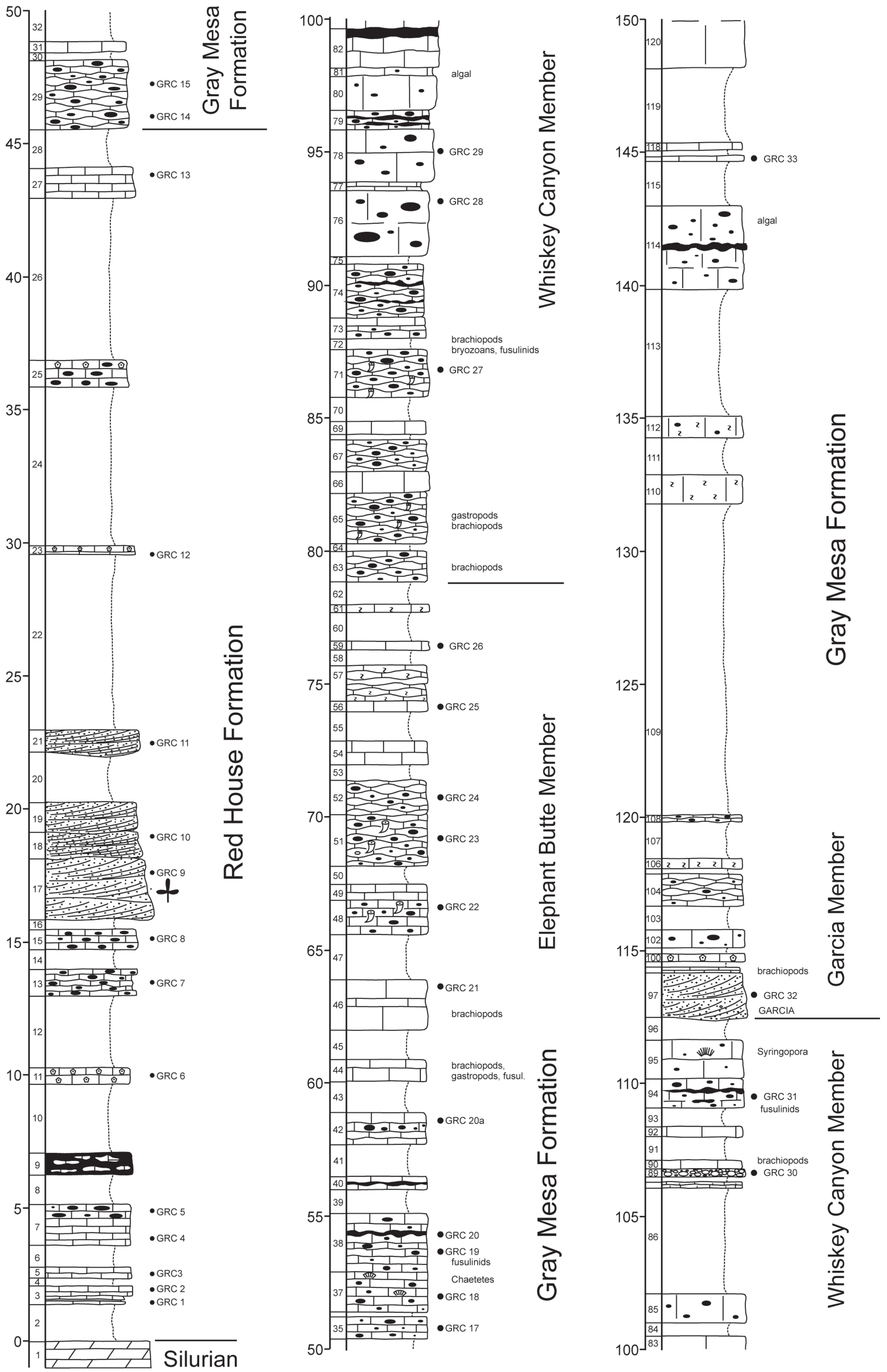

FIGURE 10. Measured stratigraphic section of the Red House, Gray Mesa, Bar B and Bursum formations at Green Canyon in the southern Caballo Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

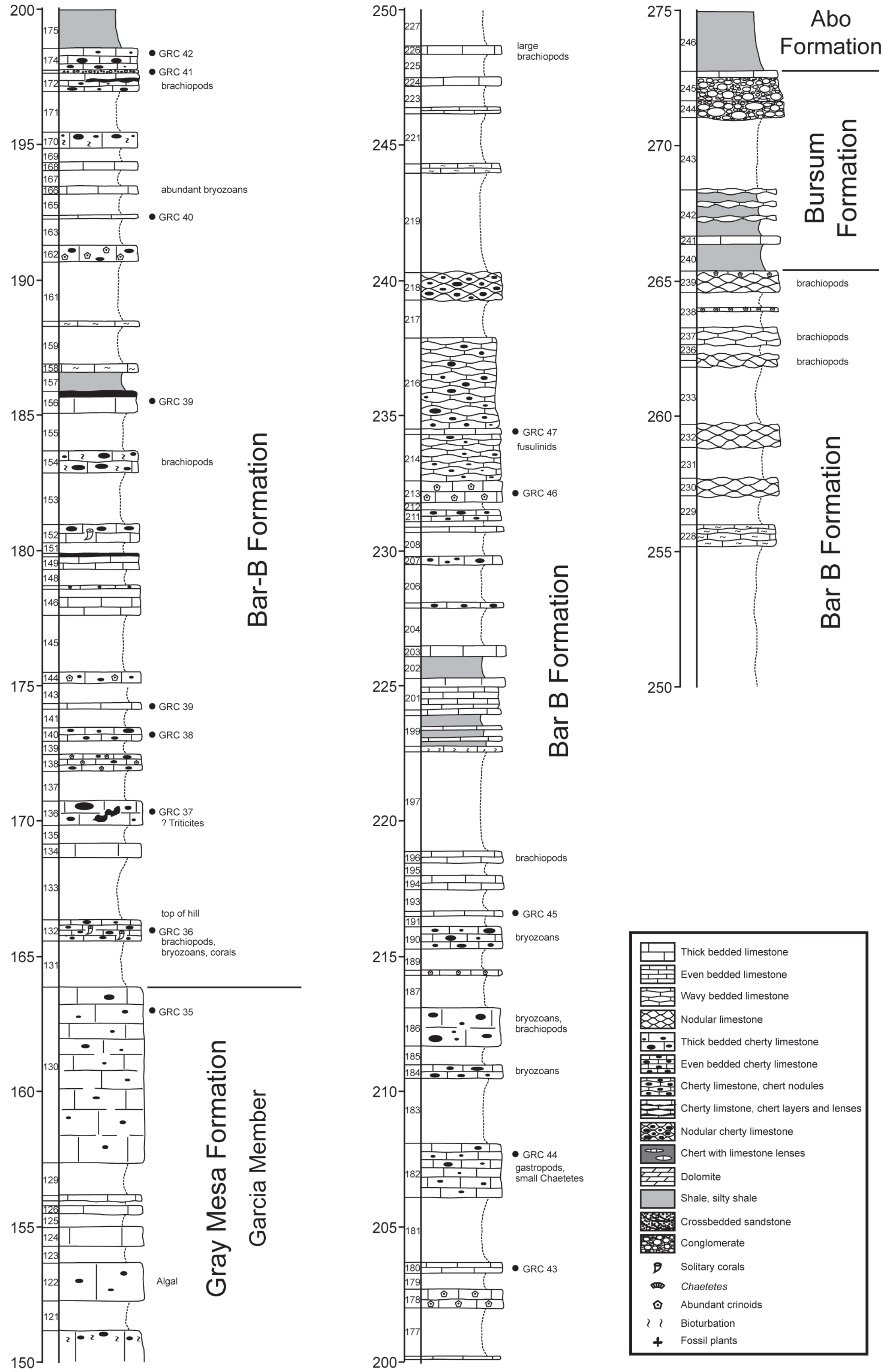

FIGURE 10. Cont..

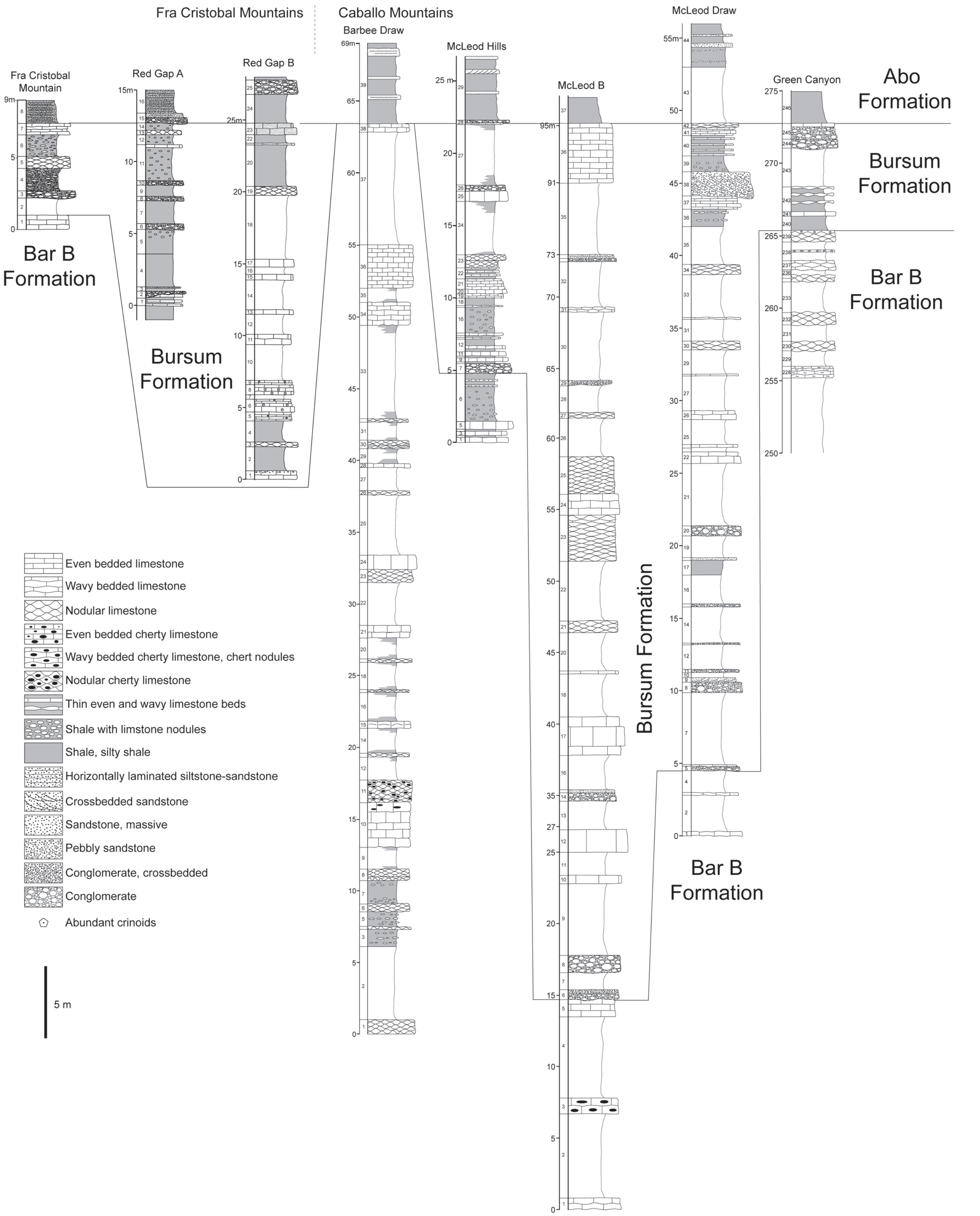

FIGURE 11. Selected measured stratigraphic sections of the Bursum Formation in the Fra Cristobal and Caballo Mountains. See Appendix for map coordinates of measured section. Vertical scale in meters.

BIOSTRATIGRAPHY AND AGE

Although invertebrate macrofossils (mostly crinoids, brachiopods, bryozoans and some mollusks) are common in the Pennsylvanian strata in the Fra Cristobal and Caballo Mountains, they have received little to no study. Instead, the focus has been on studying microfossils – fusulinids and conodonts – from these rocks to determine their age (Fig. 12).

Brachiopods indicate that the lowermost ~3 m of the Red House Formation is of Morrowan age at the type Derryan section in the Derry Hills (Sutherland and Manger, 1984; Manger et al., 1987; Sutherland, 1991). This is the only locality at which Morrowan fossils have been recovered at the base of the Red House Formation. However, given that the base of the Red House is a complex unconformity on rocks of Proterozoic to Mississippian age, it is possible, but unlikely that some Morrowan-age strata maybe present at the base of the Red House Formation everywhere across its outcrop belt.

Gehrig (1958) identified distinctive Red House (his “Derry”) and Gray Mesa (his “Des Moines”) brachiopod assemblages at Whiskey Canyon in the Mud Springs Mountains. However, no study of the Pennsylvanian brachiopods (or other invertebrate macrofauna) has been undertaken in the Fra Cristobal or Caballo Mountains to extend these observations.

In this guidebook, Barrick et al. (2012) and Lucas et al. (2012) present the preliminary results of conodont biostratigraphy of the Pennsylvanian strata in the Caballo Mountains, primarily focused on the Red House Formation. These data indicate that the Red House and lowermost Gray Mesa Formation are of Atokan age. The remainder of the Gray Mesa Formation is of early-middle Desmoinesian age. The lower-middle Bar B Formation yields middle-late Desmoinesian conodonts, and the upper Bar B Formation yields early Missourian conodonts (Fig. 12).

Fusulinid data are much more extensive for the Pennsylvanian strata in the Fra Cristobal-Caballo Mountains, and the nearby Mud Springs Mountains and Derry Hills (Thompson, 1942, 1948; Lane et al., 1972; King, 1973; Verville et al., 1986; Singleton, 1990; Clopine, 1990, 1991a, b, 1992; Lawton et al., 2002). They agree with the conodont data in assigning the Red House to the Morrowan-Atokan, Gray Mesa to the Atokan-middle Desmoinesian, and the Bar B Formation to the middle Desmoinesian-Missourian. However, they also indicate that the Bar B Formation at some sections preserves strata of Virgilian age (Verville et al., 1986; Singleton, 1990; Lawton et al., 2002). They also indicate an early Wolfcampian (Newwellian) age of the Bursum Formation (Singleton, 1990; Lawton et al., 2002).

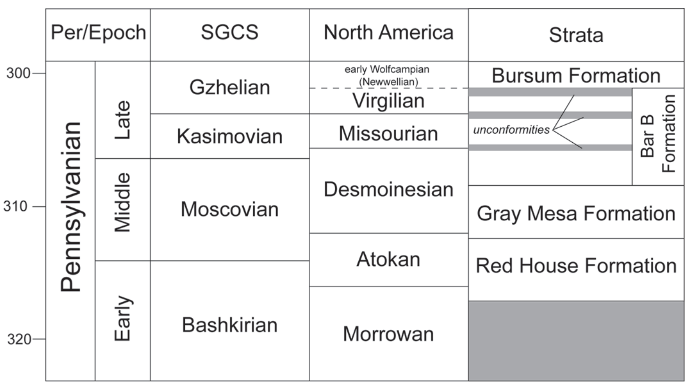

FIGURE 12. Summary of biostratigraphically-based ages of the Pennsylvanian strata in the Caballo and Fra Cristobal Mountains.

More data are needed to refine the Pennsylvanian biostratigraphy in the Fra Cristobal and Caballo Mountains, especially within the Bar B Formation. Nevertheless, the brachiopod, conodont and fusulinid data are consistent with each other in the ages assigned to these strata (Fig. 12).

COMPARISON TO PENNSYLVANIAN SECTION IN THE MUD SPRINGS MOUNTAINS

Across the Rio Grande, the Mud Springs Mountains are only about 10-20 km northwest-west-southwest of the Fra Cristobal and Caballo Mountains (Fig. 1). Despite the geographic proximity, the Pennsylvanian section in the Mud Springs Mountains (best exposed along Whiskey Canyon: Thompson, 1942; Gehrig, 1958; Lucas et al., 2009a) differs from the Pennsylvanian sections in the Fra Cristobal-Caballo Mountains (Fig. 13):

1. The Red House Formation is finer grained in the Mud Springs Mountains than it is to the east – it lacks substantial beds of conglomerate or sandstone at its base or in the middle of the formation (Lucas et al., 2012).
2. The Gray Mesa Formation in the Mud Springs Mountains is relatively thick (~170 m) and readily divisible into three members. It thus does not match the Gray Mesa Formation sections we measured in the Fra Cristobal or central Caballo Mountains. Closest similarity is to the Green Canyon section, where the Gray Mesa Formation section can be divided into the same three members seen at the Whiskey Canyon section. However, at 118 m thick at Green Canyon, the Gray Mesa Formation is about two thirds of the thickness of the formation in the Mud Springs Mountains.
3. The most substantial difference is the thick (~185 m) section of strata between the Gray Mesa and Bursum formations in the Mud Springs Mountains. This section bears little resemblance to Bar B Formation sections in the Fra Cristobal and Caballo Mountains, even though it has been termed Bar B Formation by some workers (Maxwell and Oakman, 1990; Kues, 2001). Thus, not only is the Mud Springs Atrasado Formation section thicker and has a very different stratigraphic architecture than the Bar B Formation, but it is of Missourian-Virgilian age, not the Desmoinesian-Virgilian or Desmoinesian-Missourian age of the Bar B Formation. Indeed, we assign the strata between the Gray Mesa and Bursum formations in the Mud Springs Mountains to the Atrasado Formation, which they resemble more than the Bar B Formation (Lucas et al., 2009a).

How can we explain the differences between the Pennsylvanian sections in the Mud Springs and in the Fra Cristobal-Caballo

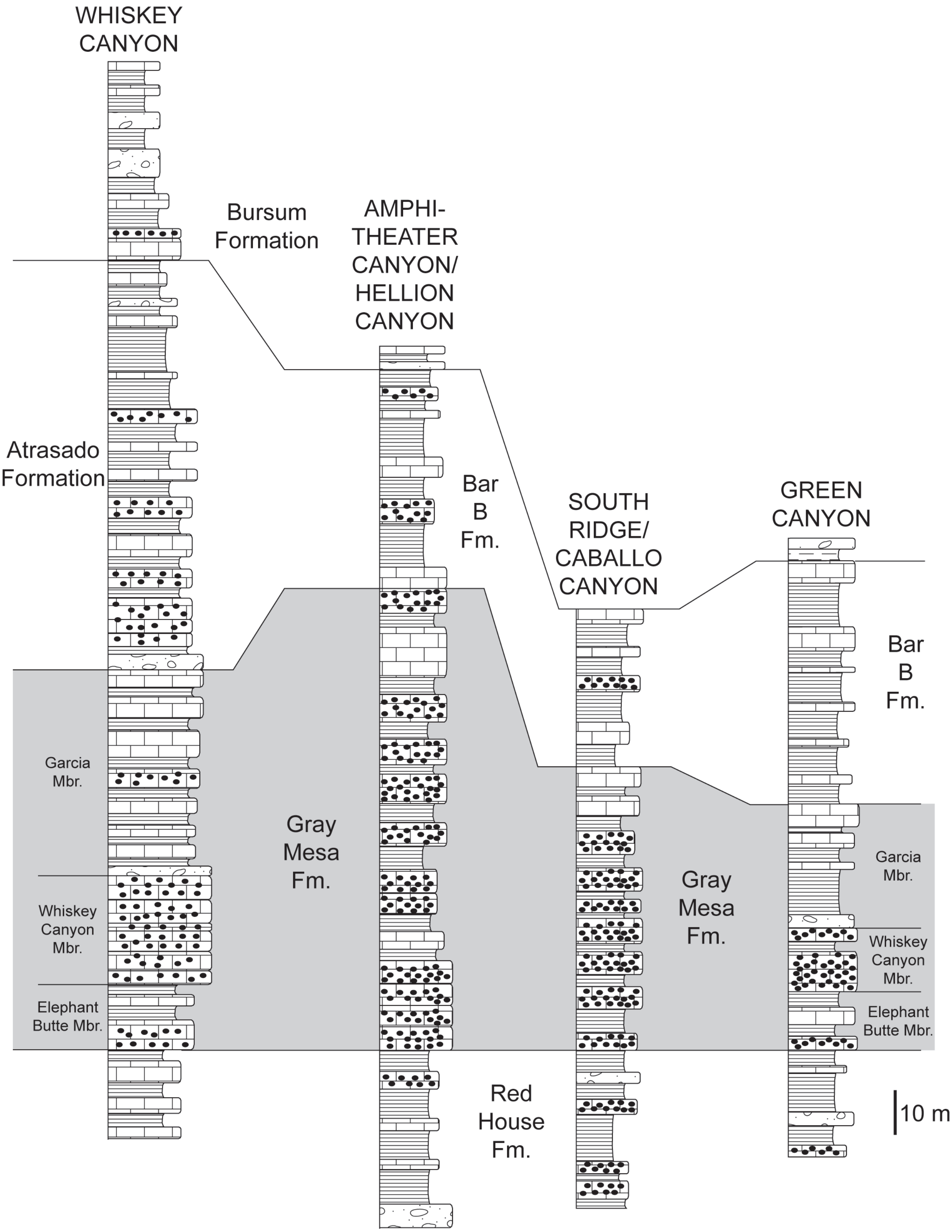

FIGURE 13. Comparison of Pennsylvanian stratigraphic sections (lithology generalized) in the Mud Springs (Whiskey Canyon), Fra Cristobal (Amphitheater Canyon/Hellion Canyon) and the Caballo (South Ridge/Caballo Canyon, Green Canyon) Mountains.

Mountains? One possibility is post-Pennsylvanian fault offset, which would have moved the Mud Springs outcrop from its original depositional location, where it should resemble other outcrops of Pennsylvanian strata that were in depositional proximity.

Cather and Harrison (2002) presented such a fault mechanism, arguing that ~26 km of dextral slip on the Hot Springs fault system (cf. Seager and Mack, 2003) moves the current location of the Mud Springs Mountains southward, thus matching up lower Paleozoic isopachs. They posited this movement as mostly of Laramide (Late Cretaceous-Eocene) age. However, the evident mismatch of the upper part of Pennsylvanian stratigraphic sections in the Mud Springs and the Fra Cristobal-Caballo Mountains demonstrated here (Fig. 13) does not support Cather and Harrison's (2002) ideas about Laramide dextral slip. Indeed, Cather and Harrison (2002, p. 97), lacking detailed data, used the summary of Kottlowski (1960) to conclude that the entire Truth or Consequences area "was located on the relatively stable western shelf of the Orogrande basin" during the Pennsylvanian.

If this were the case, we should be able to explain the differences between the Pennsylvanian sections in the Mud Springs and the Fra Cristobal-Caballo Mountains as due to lateral facies changes on a shallow marine shelf. This may explain the relatively minor differences in the Red House Formation sections, and it could explain some of the differences in the Gray Mesa Formation sections. However, the differences between the Atrasado Formation section in the Mud Springs Mountains and the Bar B Formation sections in the Fra Cristobal-Caballo Mountains are not readily seen as lateral facies change on a marine shelf. If nothing else, the thickness differences between correlative Desmoinesian, Missourian and Virgilian strata in both areas imply differential local subsidence, which indicates active tectonism.

Note how relatively consistent the thickness and lithofacies of the Bar B Formation are from Green Canyon in the southern Caballo Mountains and Hellion Canyon in the central Fra Cristobal Mountains, a distance of about 55 km. Yet, only 10-20 km to the west the correlative section is about twice as thick and encompasses many different lithofacies, too many to simply be explained by lateral facies change. If we accept the argument that at least some of the Atrasado Formation in the Mud Springs Mountains records glacio-eustatically forced cycles (Soreghan, 1992, 1994), then it must be recording more and/or different cycles than the much thinner Bar B Formation. Indeed, hiatuses within the Bar B Formation indicate substantial unconformities with a likely tectonic cause (Singleton, 1990; Lawton et al., 2002).

Therefore, we conclude that local Pennsylvanian tectonism is the most probable cause of the evident differences between the Pennsylvanian sections in the Mud Springs and the Fra Cristobal-Caballo Mountains, especially in the Atrasado and Bar B intervals. Differential subsidence and activity on the Caballo uplift, located in the present location of the Red Hills in the southern Caballo Mountains (and partly buried under the Rio Grande rift?), are the most obvious sources of this tectonic activity.

ACKNOWLEDGMENTS

We are grateful to Ted Turner and Tom Waddell of the Armendaris Ranch for access to the Fra Cristobal Mountains. James Barrick and John Nelson collaborated with us on some of our field studies of Pennsylvanian stratigraphy in the Fra Cristobal and Caballo Mountains. Bruce Allen and Jim Barrick provided helpful reviews of the manuscript.

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APPENDIX – GPS LOCATION OF MEASURED SECTIONS

All UTM coordinates, zone 13.

Amphitheater Canyon – base at 303636E, 3697032N; top at 303792E, 3697247N (NAD 83).

Hellion Canyon (A) – base at 304006E, 3693059N; top at 303995E, 3692861N (NAD 83).

Hellion Canyon (B) – base at 304817E, 3692940N; top at 305022E, 3692669N (NAD 83).

Hellion Canyon (C) – base at 304355E, 3691947N; top at 304680E, 3692030N (NAD 83).

South Ridge – base at 291508E, 3656226N; top at 291809E, 3656148N (NAD 83).

Caballo Canyon – base at 292817E, 3655983N; top at 293637E, 3656605N (NAD 83).

Green Canyon – base at 289680E, 3635754N; top at 289840E, 3634882N (NAD 83).

Red Gap A – section at 304723E, 3691285N (NAD 27).

Red Gap B – section at 305681E, 3691368N (NAD 27).

McLeod Draw – base at 29944E, 3632220 N; top at 299377E, 3632427N (NAD 27).

McLeod B – base at 302073E, 3633493N; top at 302073E, 3633602N (NAD 27).