New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/63



The Pennsylvanian Red House Formation, central Sierra County, New Mexico

Spencer G. Lucas, Karl Krainer, James E. Barrick, and Justin A. Spielmann
2012, pp. 305-326. https://doi.org/10.56577/FFC-63.305

in:

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

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

Annual NMGS Fall Field Conference Guidebooks

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

Free Downloads

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

Copyright Information

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

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

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

New Mexico Geological Society Guidebook, 63rd Field Conference, Warm Springs Region, 2012, p. 305-326.

THE PENNSYLVANIAN RED HOUSE FORMATION, CENTRAL SIERRA COUNTY, NEW MEXICO

SPENCER G. LUCAS[1], KARL KRAINER[2], JAMES E. BARRICK[3] AND JUSTIN A. SPIELMANN[1]
[1] New Mexico Museum of Natural History and Science, 1801 Mountain Rd. NW, Albuquerque, NM 87104 spencer.lucas@state.nm.us
[2]Institute of Geology and Paleontology, Innsbruck University, Innrain 52, Innsbruck, A-6020 AUSTRIA, karl.krainer@uibk.ac.at
[3]Department of Geosciences, Texas Tech University, Box 41053, Lubbock, Texas 79409, jim.barrick@ttu.edu;

Abstract—The Lower-Middle Pennsylvanian Red House Formation is the lowermost Pennsylvanian lithostratigraphic unit exposed in central Sierra County, New Mexico. We studied 15 measured stratigraphic sections of the Red House Formation in the Fra Cristobal, Mud Springs, and Caballo Mountains and in the Derry Hills in Sierra County and one section in the Rincon Hills of Doña Ana County. The Red House Formation unconformably overlies rocks that range in age from Proterozoic to Mississippian, is 29-93 m thick, and is overlain conformably by the Middle Pennsylvanian Gray Mesa (= Nakaye) Formation. The Red House Formation is almost equal amounts of gray, green or black shale and limestone (mostly cherty wackestone, nodular wackestone and crinoidal packstone) with subordinate sandstone and conglomerate. We recognize three main lithofacies in the Red House Formation: coarse-grained siliciclastic sediments (sandstone, pebbly sandstone, conglomerate), limestone and shale. We interpret the coarse siliciclastics as tidal and fluvial deposits, the limestones as open, normal marine strata deposited below fair weather wave base but slightly above the storm wave base, and the shale as deposits of the deeper shelf environment below storm wave base. The Derryan Series was originally based on fusulinid biostratigraphy of the Red House Formation, but lithostratigraphic subdivisions of the Derryan are biostratigraphic units that are not mappable or lithostratigraphically useful and can be abandoned. The Red House Formations yields fusulinids, conodonts and brachiopods of Atokan age, and at one location the lowermost Red House Formation is of Morrowan age. Red House Formation conodonts documented here indicate the formation encompasses most of the time commonly assigned to the Atokan Stage. The Red House Formation records the onset of the ancestral Rocky Mountain orogeny in Sierra County and represents deeper marine shelf deposition than the shallow marine and nonmarine deposits of the homotaxial Sandia Formation to the north.

INTRODUCTION

During the Carboniferous, the collision of Gondwana and Laurussia amalgamated the Pangean supercontinent. Along and near the zone of the collision – a megasuture – various orogenies took place during the Late Carboniferous-Permian (e.g., Zeigler, 1988). In western North America, this was the time of the ancestral Rocky Mountain (ARM) orogeny, a complex and amagmatic basement deformation almost certainly driven by the Gondwana-Laurussia collision (e.g., Kluth and Coney, 1981; Dickinson and Lawton, 2003). The ARM orogeny produced a series of north- to west-trending elongate basins and adjacent basement-cored uplifts in New Mexico, Colorado, Oklahoma, Texas, Arizona and Utah, long referred to as the "ancestral Rocky Mountains" (e. g., Eardley, 1951). Synorogenic sediments shed from these uplifts formed alluvial facies that fringed them, adjacent to (mostly) shallow marine basins.

In Sierra County, south-central New Mexico, the onset of the ARM orogeny is marked by strata assigned to the Red House Formation of Kelley and Silver (1952). The Red House Formation also includes an important microfossil (fusulinid) record that Thompson (1942) used to define the Derryan Series, a now disused subdivision of Middle Pennsylvanian time. Thus, the Red House Formation has been studied primarily for the insight it provides into the sedimentary history of the early phase of the ARM orogeny in south-central New Mexico, and for its fusulinid biostratigraphy (e.g., Thompson, 1942; Kalesky, 1988; Clopine, 1992). Here, we present data on and interpretation of the lithostratigraphy, lithofacies, petrography, deposition and micropaleontology of the Red House Formation outcrops in central Sierra County.

DATABASE

Fieldwork for this project was undertaken during 2008-2011. We measured 15 detailed stratigraphic sections of the Red House Formation in the Fra Cristobal, Mud Springs and Caballo Mountains, and in the Derry and Rincon Hills (Fig. 1, Table 1). Samples were collected for the preparation of petrographic and carbonate thin sections, as were microfossil samples for the extraction of conodonts and fusulinids.

PREVIOUS STUDIES

The first work on Pennsylvanian stratigraphy that made specific reference to outcrops in Sierra County is Gordon (1907), who coined the term Magdalena Group to refer to the entire Pennsylvanian section (Fig. 2). To the north, in Socorro, Valencia and Bernalillo counties, he divided the Magdalena Group into the lower, Sandia Formation (of Herrick, 1900) and upper, Madera Formation (of Keyes, 1904), but Gordon (1907, p. 809) noted that "the data at hand concerning these formations in Sierra County are insufficient to warrant an attempt to subdivide the [Magdalena] [G]roup." For the next 30 years geologists (e.g., Lee, 1909; Darton, 1928; Harley, 1934) simply referred to the Pennsylvanian strata in Sierra County as the Magdalena Group or Limestone (Fig. 2).

Thompson (1942) presented an ambitious and detailed subdivision of some of the Pennsylvanian section in Sierra County based on outcrops in the Mud Springs Mountains and the Derry Hills (Fig. 2). This led Thompson (1942) to propose the Derry Series as a North American provincial chronostratigraphic term,

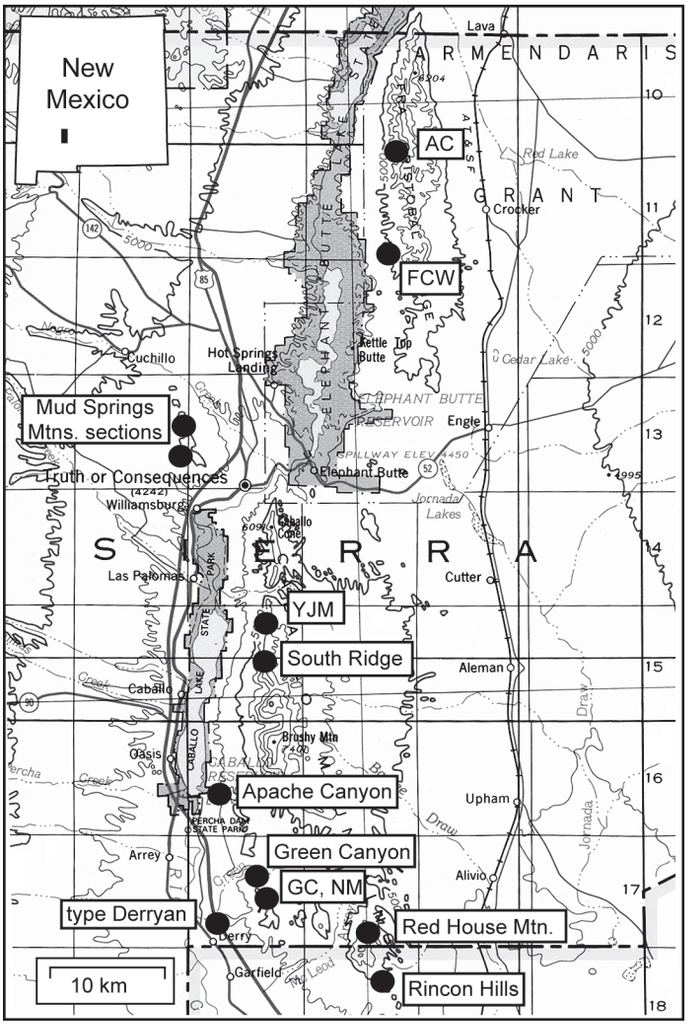


FIGURE 1. Map of part of Sierra and northern Doña Ana counties, New Mexico, showing location of measured sections of the Red House Formation (Table 1). Abbreviations are: AC = Amphitheater Canyon, FCW = Fra Cristobal West; GC = Garfield Crest; NM = Nakaye Mountain; and YJM = Yellowjacket Mine.

TABLE 1. Map (UTM) locations of Red House Formation measured stratigraphic sections. All UTM coordinates are zone 13, NAD 83 datum.

Locality Name	UTM Base	UTM Top	Thickness (m)
Fra Cristobal Mountains:			
1. Amphitheater Canyon	303636E, 3697032 N	303792E, 3697247N	75
2. Fra Cristobal West	303192E, 3694062N	303234E, 3694089N	44+
Mud Springs Mountains:			
3. Whiskey Canyon	283719E, 3675991N	283908E, 3676010N	34+
4. Mud Springs N	284017E, 3675428N	284167E, 3675379N	58
5. Mud Mountain	285315E, 3671449N	258365E, 3671647N	68
6. Type Cuchillo Negro	285920E, 3670334N	285984E, 3670380N	45
Derry Hills:			
7. Type Derryan	286797E, 3630875N	386865E, 3630925N	36
Caballo Mountains:			
8. Yellowjacket Mine	292168E, 3663449N	292298E, 3663507N	65
9. South Ridge*	291508E, 3656226N	291809E, 3656148N	91
10. Apache Canyon	288185E, 3641858N	288173E, 3641875N	27
11. Nakaye Mountain	291540E, 3633029N	291426E, 3633028N	41
12. Red House Mountain	301335E, 3628717N	301313E, 3628814N	33
13. Green Canyon	289680E, 3635754N		47
14. Garfield Crest	290032E, 3634180N	290027E, 3634080N	48
Rincon Hills:			
15. Rincon Hills	301970E, 3623726N	302093E, 3623734N	71

* type section of Red House Formation.

based on its distinctive fusulinid assemblages, which are dominated by *Fusulinella*, *Profusulinella* and *Eoschubertella*. Thompson's (1942) Derryan fusulinids came from strata he assigned to two groups divided into four formations (Fig. 2).

Kelley and Silver (1952, p. 89) were dismissive of Thompson's (1942) Derryan stratigraphy, referring to his groups and formations as "not mappable in the Caballo Mountains." Instead, Kelley and Silver (1952) named three mappable lithostratigraphic units in the Caballo Mountains, in ascending order, the Red House, Nakaye and Bar B formations, and united them in the Magdalena Group (Fig. 2). They described the Red House Formation as "dominantly…thin-bedded limestone and shale or claystone with limestone nodules and lenses" that is "gray to dark gray and usually slope-forming" (Kelley and Silver, 1952, p. 92). They also noted that "locally massive limestone beds that are commonly very cherty are present" as are "some beds of sandstone and coarse-grained/conglomeratic sandstone." Kelley and Silver (1952, p. 92) described the Red House Formation limestone and shale beds as "abundantly fossiliferous" and stated that conglomerates in the lower part of the formation contain clasts derived from Mississippian or older rocks.

The Red House Formation takes its name from Red House Mountain in the southern Caballo Mountains (Fig. 1). The type section of the Red House Formation designated and described by Kelley and Silver (1952, p. 91, 255) is on South Ridge in the Caballo Mountains (Fig. 3). Here, according to Kelley and Silver (1952), the Red House Formation rests on the Ordovician Cutter Member of the Montoya Formation and is 372 ft (~113 m) thick. They noted that the Red House Formation is present in the Caballo, Mud Springs and Fra Cristobal Mountains.

It is fair to say that subsequent workers have not altered the

concept of the Red House Formation of Kelley and Silver (1952) (e.g., Kottlowski, 1960; Seager and Hawley, 1973; Kues, 2001; Seager and Mack, 2003). In the Fra Cristobal Mountains, Cserna (1956) recognized three divisions of the Pennsylvanian section, but did not use formal names, though his lower division is evidently the Red House Formation. McCleary (1960) used the stratigraphic terminology that Kelley and Silver (1952) developed in the Caballo Mountains: lower Red House Formation, middle Nakaye Limestone, and upper Bar B Formation.

In the Mud Springs Mountains, Maxwell and Oakman (1990) mapped the Red House Formation, though in an earlier publication they called it "Sandia Formation" (Maxwell and Oakman, 1986; also see Hill, 1956). Also note that Gehrig (1958) used Thompson's (1942) stratigraphic nomenclature in his monograph on Middle Pennsylvanian brachiopods from the Mud Springs Mountains and Derry Hills.

King (1973) studied some of the Derryan fusulinids at the type Derry section, using Thompson's (1942) lithostratigraphic units. Fusulinid studies by Clopine (1991a, b, 1992; Clopine et al., 1991) acknowledged the use of Red House Formation in the Mud Springs Mountains and the Derry Hills, but preferred to refer to the rocks primarily in terms of biostratigraphic units (fusulinid zones) and chronostratigraphic units (Morrowan, Atokan and Desmoinesian "Series"). A study of Pennsylvanian fusulinids in the Fra Cristobal Mountains by Verville et al. (1986) did the same, but Nelson (1986), in a review of the geology of the Fra Cristobal Mountains, explicitly referred to the lower part of the "Magdalena Group" as the Red House Formation.

Working primarily in the Caballo Mountains, Kalesky (1988) undertook a detailed study of sedimentation of the Red House Formation. However, other than an abstract (Kalesky, 1987), this work was not published, so we restudied many of the sections first described by Kalesky (1988). In brief, Kalesky (1988) reached the following conclusions: (1) the Red House Formation is ~30-110 m thick, consists of limestone, pebbly sandstone and black shale and unconformably overlies rocks ranging in age from Proterozoic to Mississippian (also see Seager, 1986); (2) the formation can be divided into four units (ascending order): basal terrigenous, lower limestone, middle terrigenous and upper limestone; (3) asymmetric mixed carbonate and siliciclastic cycles of the Red House Formation are evidence of glacioeustatically-driven sedimentation; and (4) the varied subcrop and thickness of the Red House Formation reflect re-activation of pre-Pennsylvanian structures.

As alluded to above, Nelson (1986, p. 86) briefly described the Red House Formation in the Fra Cristobal Mountains as a "poorly exposed slope-former that rests unconformably on all pre-Pennsylvanian units" and contains a basal conglomerate. Verville et al. (1986) reported late Atokan fusulinids (*Fusulinella juncea* Thompson) from strata we identify as the upper part of the Red House Formation in Amphitheater Canyon in the northern Fra Cristobal Mountains. They suggested that the absence of older Atokan fusulinids "substantiates the presence of a topographic high during most of Atokan time" (Verville et al., 1986, p. 215).

In the 1980s, a group of paleontologists headed by Patrick K. Sutherland of the University of Oklahoma, restudied the type

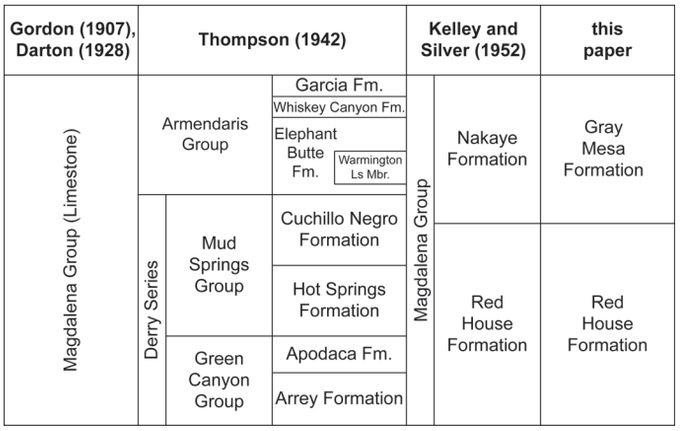


FIGURE 2. Development of lithostratigraphic nomenclature of the Red House Formation.

Derryan section. Thompson (1942) had concluded that at this section Derryan (Middle Pennsylvanian) strata rest unconformably on Upper Devonian strata of the Percha Formation. However, Sutherland and collaborators found a Morrowan brachiopod assemblage in the basal bed of the type Derryan, just above the Percha Formation (Sutherland and Manger, 1984; Manger et al., 1987; Sutherland, 1991). They also reported the first record of conodonts from the type Derryan strata (Kaiser, 1990; Kaiser and Manger, 1991). Most extensive, though, was the work of Clopine (1990, 1991a, b, 1992), who restudied the Derryan fusulinid assemblages in the Mud Springs Mountains (Whiskey Canyon) and the Derry Hills (type Derryan section). In these strata he recognized five fusulinid zones (in ascending order), the Morrowan zone of *Millerella*, the lower Atokan zone of *Eoschubertella* and *Profusulinella munda* range zone and the upper Atokan *Fusulinella acuminata* lineage zone overlain by the *Fusulinella devexa* interval zone.

Seager and Mack (1991, 1998, 2005) mapped the Red House Formation in the Caballo Mountains as the stratigraphically lowest formation of the Magdalena Group. Seager and Mack (2003) provided a brief description of the Red House Formation in the Caballo Mountains, presenting a characteristic measured section of the formation at Green Canyon in the southern Red Hills (Seager and Mack, 2003, fig. 18). They described the Red House Formation as 35 to 86 m thick and consisting primarily of fossiliferous "packstone" and gray or green shale. They also noted the presence of a medial sandstone interval (also see Kalesky, 1988) and a basal sandstone/conglomerate at most locations. They concluded that the Red House was deposited on a shallow marine shelf.

Only a small portion of the work reported by us here has already been published. Thus, Lucas et al. (2009a) presented a brief review of the Pennsylvanian section exposed in Whiskey Canyon in the Mud Springs Mountains. Krainer et al. (2011a) presented an overview of Red House stratigraphy and sedimentation in the southern Caballo Mountains. Elsewhere in this guidebook, Barrick et al. (2012) summarize the Red House Formation conodont assemblage from the Green Canyon section.

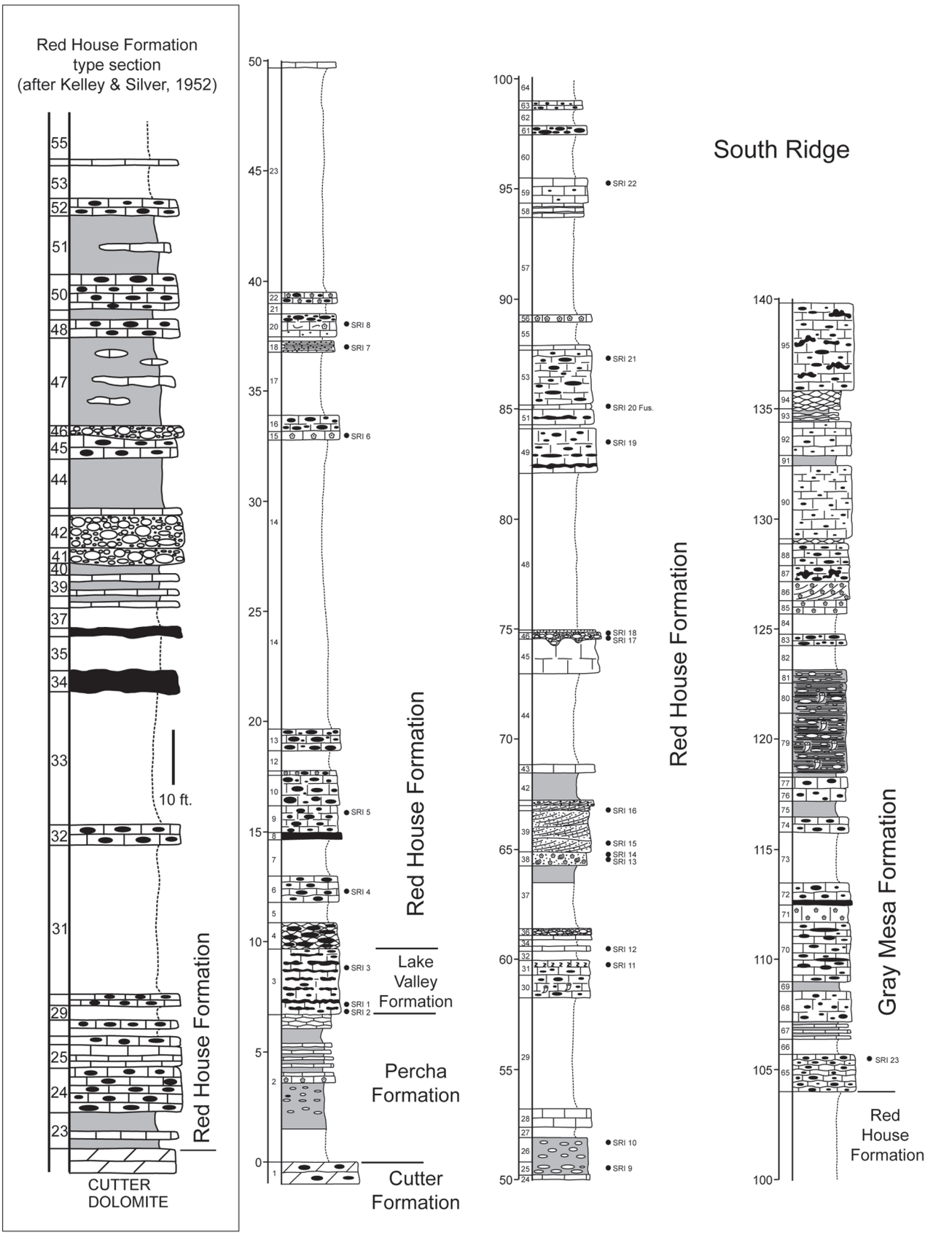


FIGURE 3. Type section of the Red House Formation, based on description of Kelley and Silver (1952), compared to our measured stratigraphic section at the same locality. Lithologic legend of our section is the same as Figure 9; thickness of units is in meters.

LITHOSTRATIGRAPHY

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 Red House, 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, 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.

Thompson's Lithostratigraphy

Thompson (1942) divided the stratigraphic interval now termed Red House Formation into two lithostratigraphic groups and four formations (Figs. 2, 4). However, no subsequent workers have mapped or otherwise used these units, and we believe they have no lithostratigraphic utility. Kelley and Silver (1952, p. 89) reached the same conclusion.

The two groups – Green Canyon and Mud Springs – are clearly biostratigraphic units. The Green Canyon Group is the part of the lower Derryan in which *Profusulinella* is present without *Fusulinella*, whereas the Mud Springs Group is the upper Derryan without *Profusulinella* and with *Fusulinella*. Thus, the Green Canyon Group is early Atokan, whereas the Mud Springs Group is middle-late Atokan (e.g., Wilde, 1990, 2006). There is no lithologic integrity to either group (Fig. 4), so both can be abandoned.

Thompson's (1942) Arrey Formation is the lower part of the Red House Formation at the type Derryan section (Figs. 5, 6D). Here, it is about 14 m thick and mostly thin beds of wackestone and massive beds of cherty limestone. This unit might serve as a local, basal, limestone-dominated member of the Red House Formation in the Derry Hills and Mud Springs Mountains. However, in the Fra Cristobal and Caballo Mountains, several Red House sections have a basal clastic interval (sandstone and conglomerate) very different from the Arrey Formation of Thompson (1942). In fact, the Arrey Formation is essentially the basal fusulinid zone of the Derryan, now called the *Eoschubertella* zone

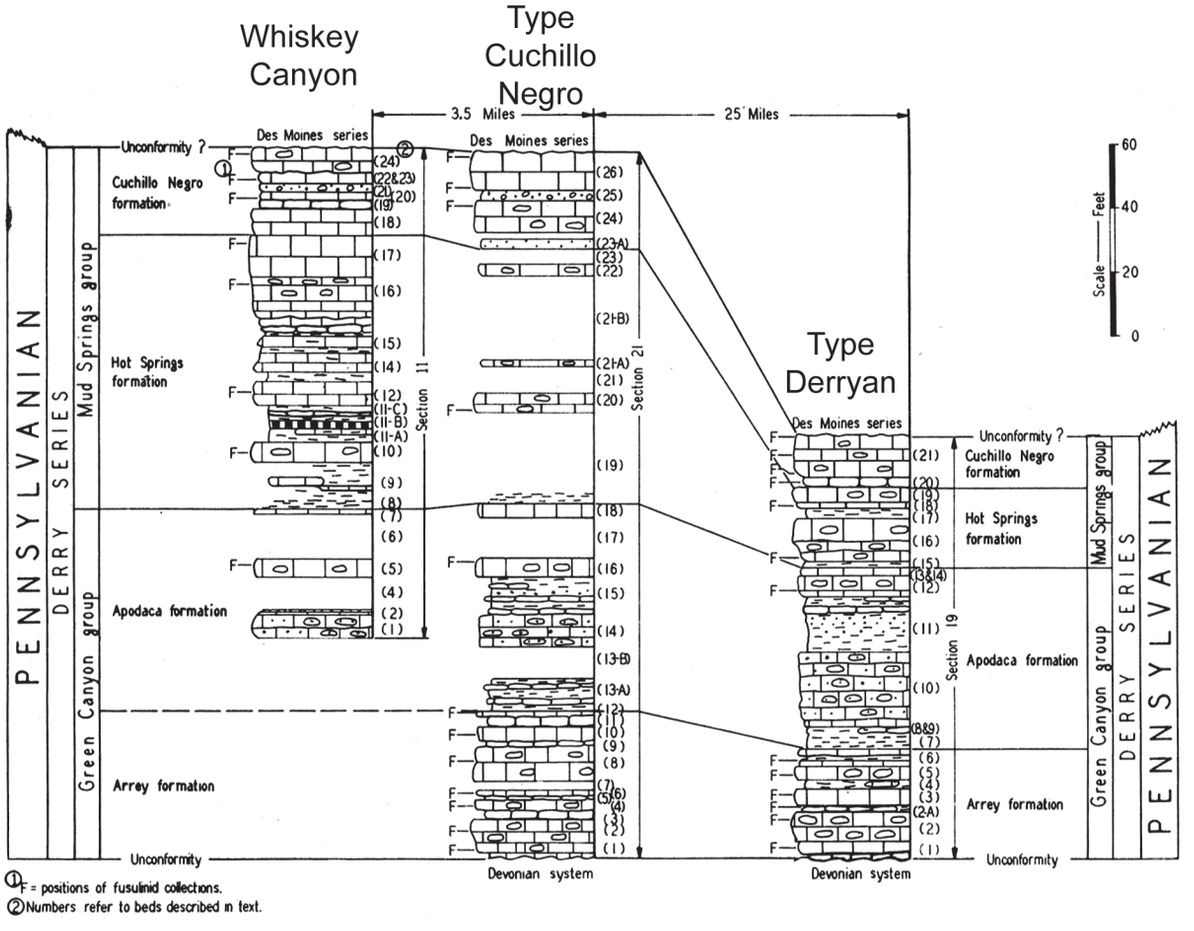


FIGURE 4. Thompson's measured stratigraphic sections of Derryan strata (from Thompson, 1942, fig. 2). Section on the left is at Whiskey Canyon, section in middle is the type Cuchillo Negro section and section at right is the type Derryan section.

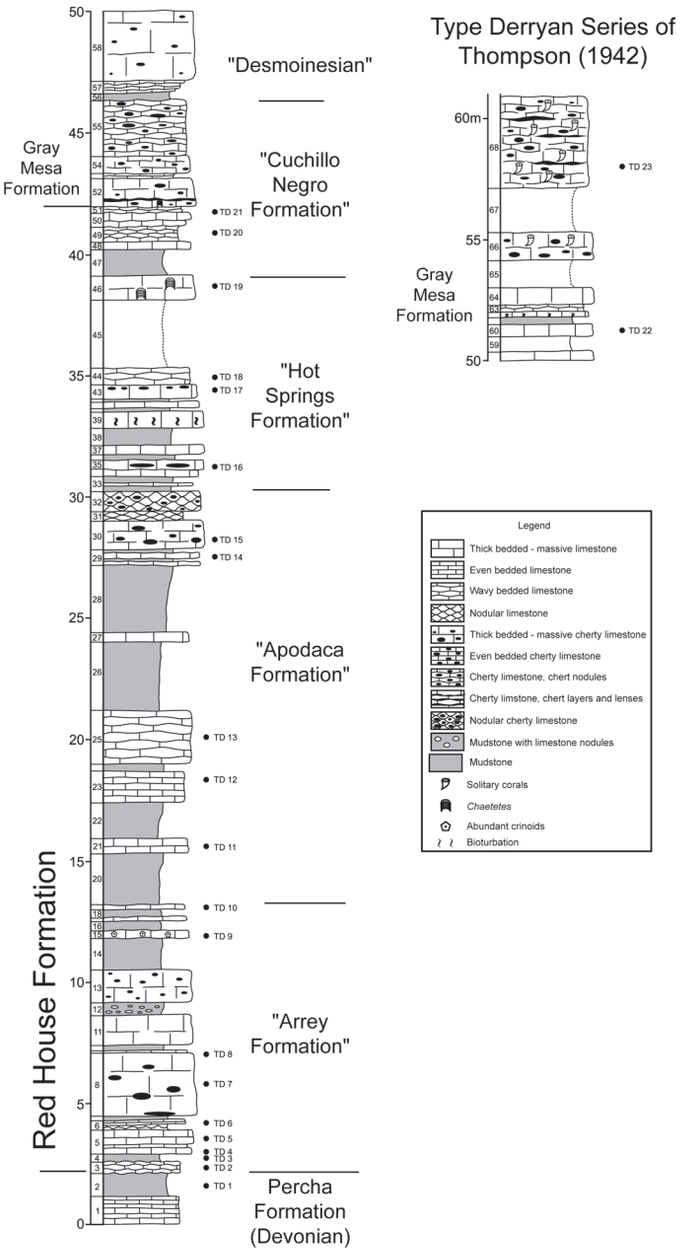


FIGURE 5. Type Derryan section in the Derry Hills. Thompson's (1942) formation boundaries are indicated. See Table 1 for location of section.

(Clopine, 1991b, 1992). Its overlying contact with the Apodaca Formation is not a mappable boundary (a surface of lithologic contrast). Therefore, we abandon the term Arrey Formation and do not even attempt to redefine it as a member- or bed-level unit in the lower Red House Formation.

The overlying Apodaca Formation of Thompson (1942) also has its type section at the Derryan type section, where it is ~20 m of slope-forming shale and interbedded limestones (Figs. 4-5, 6D). Our evaluation of this unit is similar to that of the underlying Arrey Formation: the Apodaca Formation lacks lithologic integrity, mappable boundaries and cannot be distinguished (even as a bed or member) in the Caballo and Fra Cristobal Mountains. Again, the Apodaca Formation is essentially a fusulinid zone, the *Profusulinella munda* range zone of Clopine (1991b, 1992). We abandon it as a lithostratigraphic unit.

The Hot Springs Formation of Thompson (1942) has its type section in Whiskey Canyon in the Mud Springs Mountains, where it is ~ 26 m thick (Figs. 4, 10). It is a more limestone-dominated unit than the underlying Apodaca Formation, but there is no real lithostratigraphic basis for drawing its upper boundary with the overlying Cuchillo Negro Formation. Significantly, the base of the Hot Springs Formation is the lowest occurrence of *Fusulinella* in the Derryan section, and it corresponds to a fusulinid zone, the *Fusulinella acuminata* lineage zone of Clopine (1991b, 1992). Hot Springs Formation thus is not a lithostratigraphic unit and can be abandoned.

The top of Thompson's (1942) Derryan section is his Cuchillo Negro Formation, which has its type section in the Mud Springs Mountains (Figs. 4, 10). Here, it is ~8 m of mostly cherty limestone. At the type Derryan section, we actually draw the contact of the Red House and Gray Mesa formations within the Cuchillo Negro Formation (Fig. 5). The Cuchillo Negro Formation is a biostratigraphic construct, the interval zone of *Fusulinella devexa* (Clopine, 1991a, 1992), not a lithostratigraphic unit, so it can be abandoned.

Red House Formation

Type Section

Kelley and Silver (1952) designated a section on South Ridge in the Caballo Mountains as the type section of the Red House Formation (Fig. 3). We remeasured this section (Fig. 3), and it is a relatively well-exposed, characteristic and fossiliferous Red House Formation section with unambiguous lower and upper contacts. However, we differ from Kelley and Silver (1952, p. 256) in their placement of the lower contact of the Red House Formation at this section. Thus, we identify their bed 23 as Devonian Percha Formation (green shale), and their bed 24 as Mississippian Lake Valley Formation (it yields Mississippian-age conodonts), instead of assigning these beds to the lowermost Red House Formation.

Therefore, the Red House Formation at its type section is ~ 92 m thick, and is mostly slopes (71% of the measured section) that are largely covered, but where exposed are black and gray shale. Limestone is the next most common lithology (25% of the section) and is mostly cherty wackestone, although crinoidal and fusulinid packstones and nodular wackestones are also common. A few prominent but relatively thin beds of sandstone and conglomerate also are present.

Lower Contact

The base of the Red House Formation is a profound unconformity where it overlies rocks that range in age from Proterozoic to Mississippian. At some sections, the basal bed of the Red House Formation is shale, but at other locations it is sandstone or conglomerate that has a sharp or scoured contact with underlying limestone or dolomite (Figs. 7A, 9, 11). Seager (1986) and

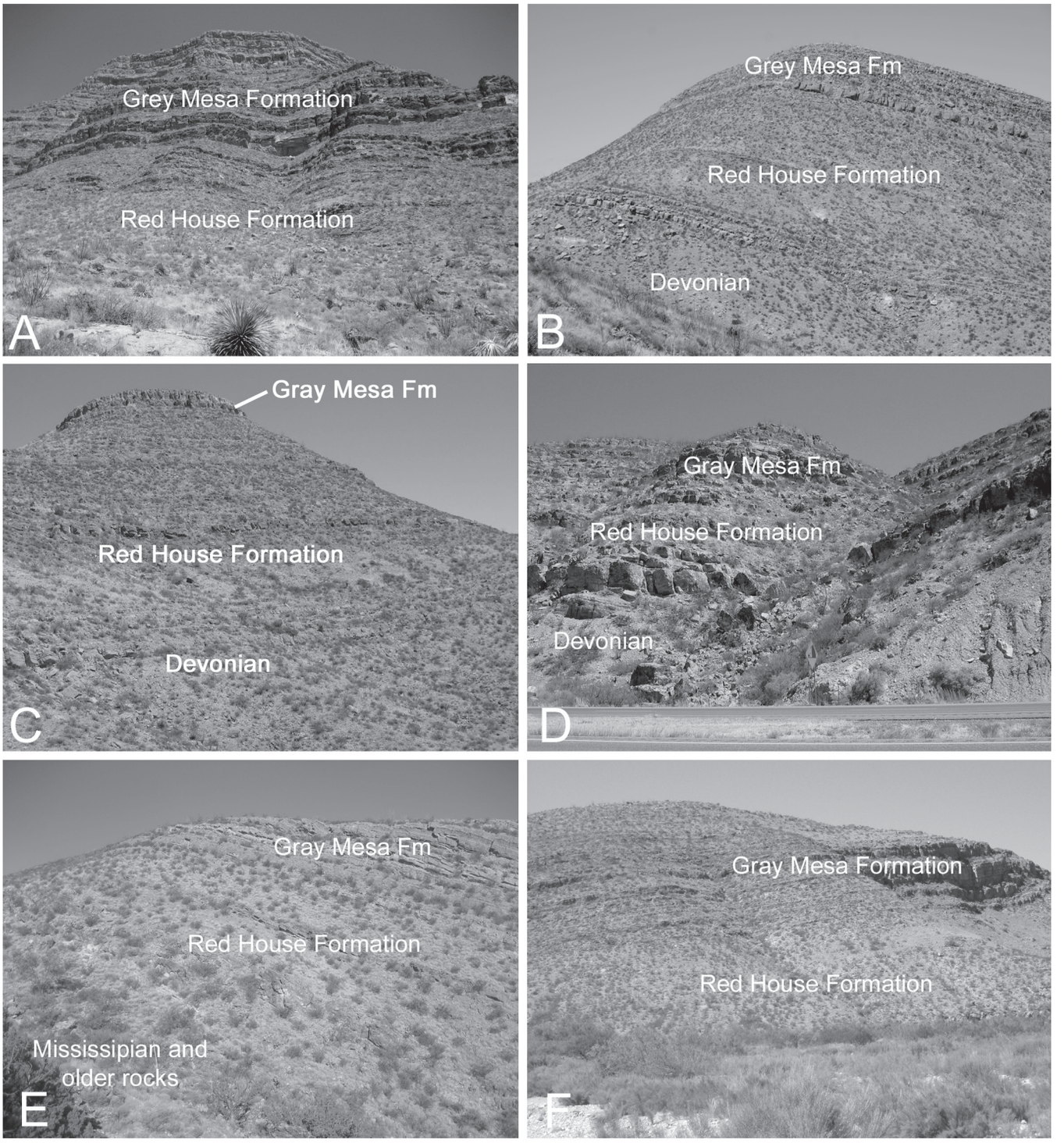


FIGURE 6. Photographs of selected Red House Formation outcrops in the Fra Cristobal and Mud Springs Mountains, Derry Hills and southern Caballo Mountains. **A**, Section at Amphitheater Canyon in northern Fra Cristobal Mountains. **B-C**, Mud Mountain (**B**) and type Cuchillo Negro (**C**) sections in the Mud Springs Mountains. **D**, Type Derryan section in Derry Hills. **E-F**, Apache Canyon (**E**) and Green Canyon (**F**) sections in southern Caballo Mountains. See Table 1 for location of sections.

Kalesky (1988) documented the angular nature of this unconformity in the southern Caballo Mountains (Fig. 8). Maxwell and Oakman (1986) also drew attention to the stratigraphic relief on the Red House-Ordovician contact in the northern Mud Springs Mountains.

Upper Contact

The Red House Formation is everywhere conformably overlain by the Gray Mesa Formation (= Nakaye Formation: Lucas et al., 2012 in this guidebook). The Gray Mesa Formation typically

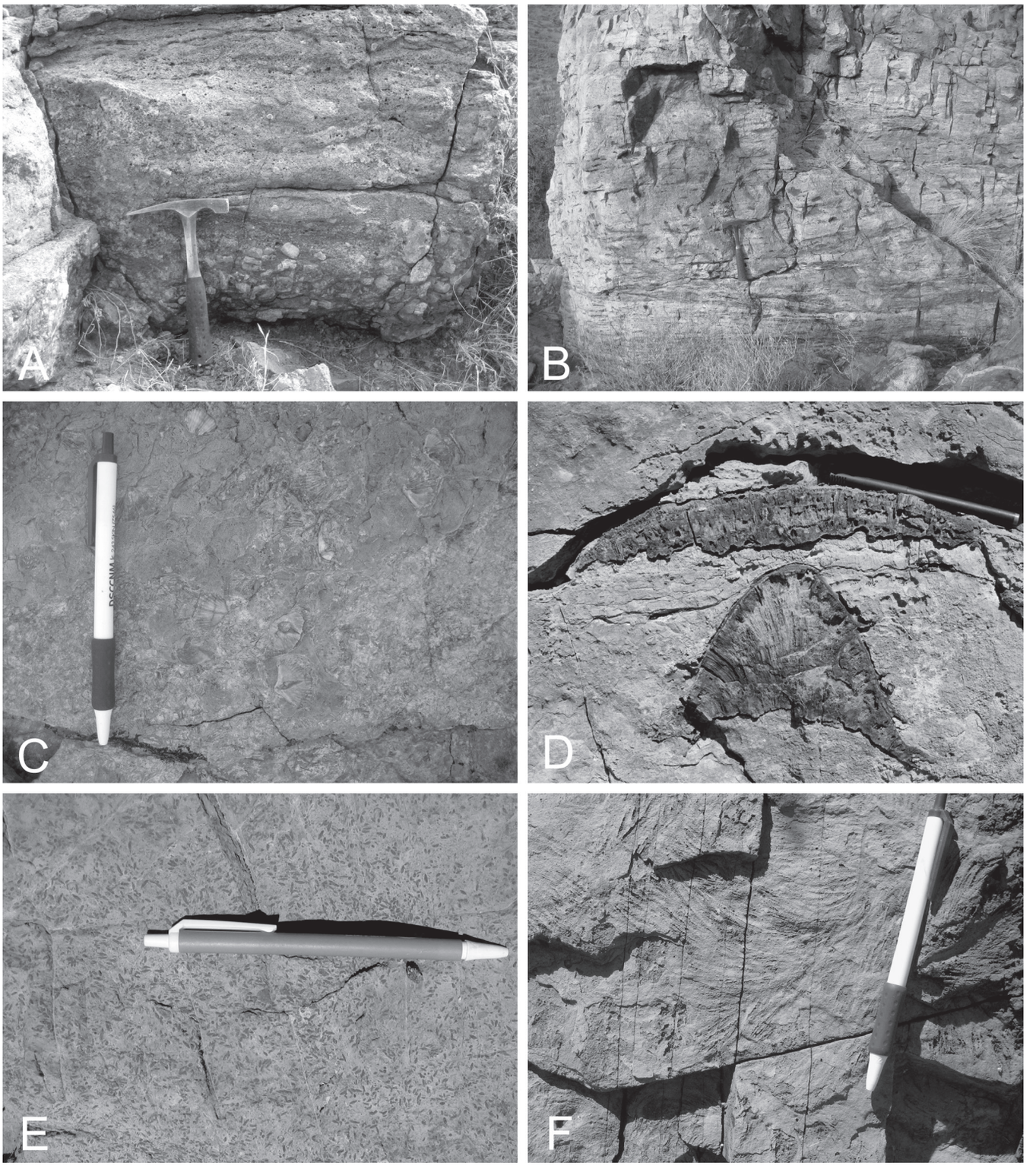


FIGURE 7. Photographs of selected lithofacies of the Red House Formation. **A**, Quartz-pebble conglomerate of lowermost Red House Formation at Amphitheater Canyon section. **B**, Crossbedded sandstone, Amphitheater Canyon section. **C**, Brachiopod coquina, Fra Cristobal West section. **D**, Silicified *Chaetetes,* type Derryan section. **E**, Fusulinid wackestone, South Ridge section. **F**, *Zoophycos*, Amphitheater Canyon section.

erodes to bold ledges and cliffs, whereas the Red House underlies valleys and slopes. We have chosen the base of the Gray Mesa Formation where thick beds of cherty limestone, usually with *Chaetetes*, with lesser interbeds of shale or nodular limestone, have their stratigraphically lowest occurrence (Figs. 3, 5, 9-11). An important example of this placement is at the type Derryan

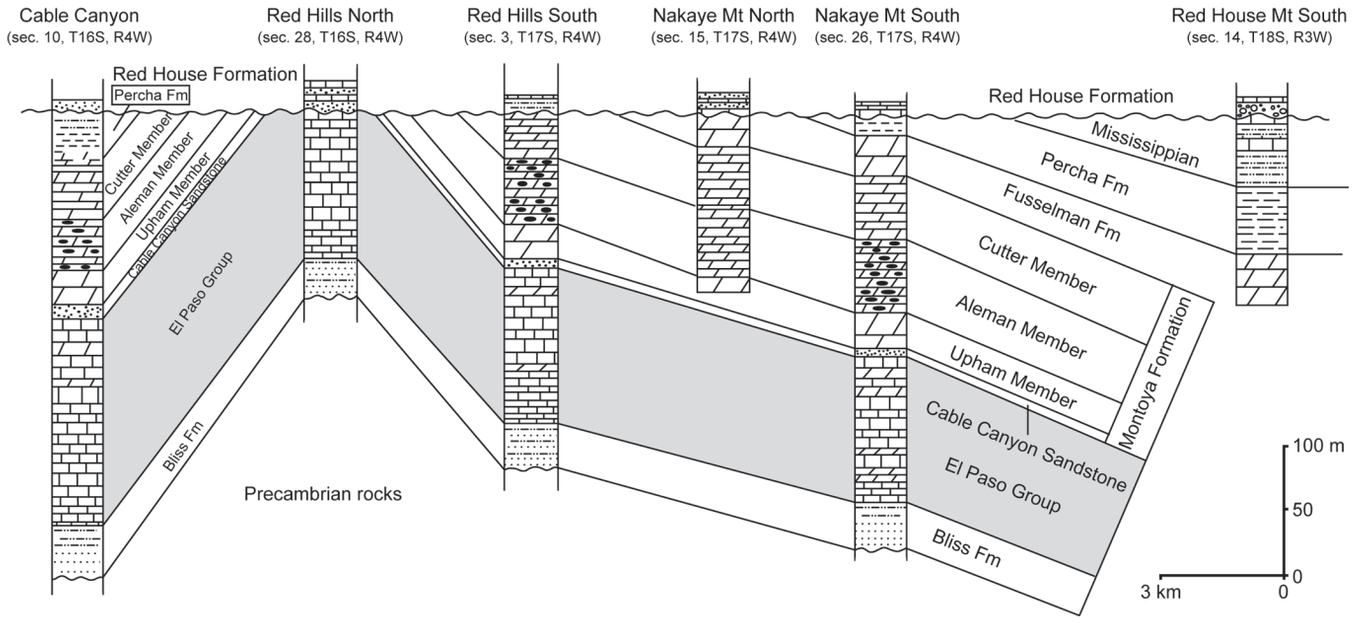


FIGURE 8. Generalized Paleozoic stratigraphic sections in the southern Caballo Mountains showing erosional truncation of pre-Pennsylvanian strata, which indicates a domal ARM uplift in the area of the Red Hills (redrawn from Seager, 1986).

section, where we draw the base of the Gray Mesa Formation within the Cuchillo Negro Formation of Thompson (1942) (Fig. 5). Therefore, the lowermost Gray Mesa Formation is of Atokan (= Derryan) age, so the Red House-Gray Mesa formational contact is not a chronostratigraphic boundary.

Lithology

The Red House Formation can generally be described as a slope-forming succession of gray, green or black shale, intercalated with limestone beds that are mostly cherty wackestones, nodular wackestones or crinoidal packstones (Figs. 3, 5-6, 9-11). The base of the formation at some locations is sandstone or conglomerate containing clasts of older carbonate rocks. Other sandstone beds are a minor lithology in the formation, though a medial sandstone interval up to 4 m thick is present in the southern Caballo Mountains (Fig. 11).

Thickness

Thickness of the Red House Formation at the sections we measured (Table 1) ranges from 29 to 93 m. The thickest section (93 m) is the type section of the formation at South Ridge in the Caballo Mountains. The thinnest section (29 m) is at Apache Canyon in the Red Hills. Kalesky (1988) presented a thickness map of the Red House Formation (Fig. 16).

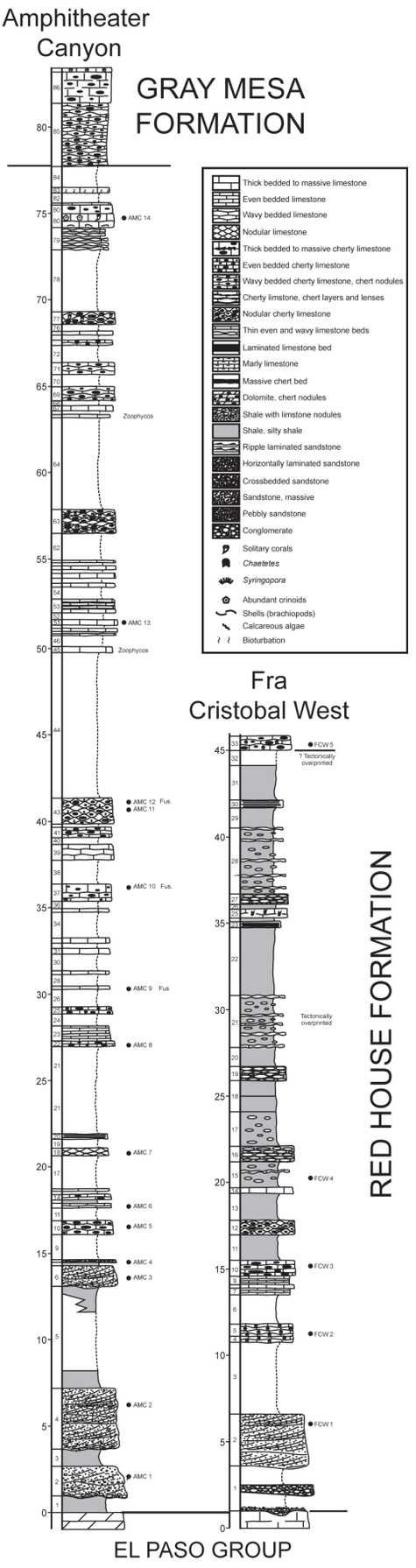
LITHOFACIES

The main lithotypes of the Red House Formation are: (1) coarse-grained siliciclastic sediments (sandstone, pebbly sandstone, conglomerate), (2) various types of limestone and (3) shale and covered intervals (inferred to be shale).

Coarse-grained Siliciclastic Sediments

The proportion of coarse siliciclastic sedimentary rocks in the Red House Formation is highest at Apache Canyon, comprising 24% of the total section (which is the thinnest section). At Amphitheater Canyon, Fra Cristobal West (incomplete section), Green Canyon, Garfield Crest and Rincon Hills, 8 to 12%, and at Yellowjacket Mine, South Ridge, Nakaye Mountain and Type Cuchillo Negro and Whiskey Canyon, 0.5 to 5% of the total section is composed of coarse, siliciclastic sedimentary rocks. Such rocks are absent at Cuchillo Tank, Mud Mountain, the type Derryan and Red House Mountain. Coarse siliciclastics occur: (a) at the base of the Red House Formation (Amphitheater Canyon, Fra Cristobal W, Apache Canyon and Rincon Hills) and (b) approximately in the middle of the Red House Formation (Apache Canyon, Green Canyon, Garfield Crest, Nakaye Mountain, Yellowjacket Mine, South Ridge, Whiskey Canyon and Type Cuchillo Negro).

At Amphitheater Canyon in the northern Fra Cristobal Mountains (Fig. 9), the siliciclastic succession of the lowermost Red House Formation overlies Ordovician dolomite (El Paso Group), is approximately 15 m thick and is composed of shale with four intercalated coarse siliciclastic intervals. The lowermost interval is 1.7 m thick and is composed of pebbly, trough-crossbedded sandstone containing quartz pebbles and rip-up clasts up to 3 cm in diameter and a poorly-sorted lag conglomerate at the base containing clasts up to 6 cm in diameter (Figs. 7A, 9). The second interval is 3.5 m thick and composed of trough-crossbedded, poorly sorted, coarse-grained pebbly sandstone (Figs. 7B, 9) with an intercalated channel-fill conglomerate bed in the upper part containing quartz pebbles and rip-up clasts up to 10 cm in diameter. Both intervals display an erosional lower contact. The upper



two intervals are 1.2 and 0.1 m thick and composed of coarse-grained, partly pebbly, crossbedded, quartzose sandstone. These coarse-grained siliciclastic intervals are separated by greenish shale and covered (shale) intervals.

At Fra Cristobal West (Fig. 9), thick-bedded carbonate rocks of the El Paso Group are overlain by poorly-exposed polymict conglomerate that is mud supported, poorly sorted and contains abundant carbonate clasts up to 10 cm in diameter floating in a sandy matrix. Above a covered interval, 3 m of coarse-grained, crossbedded quartzose sandstone is exposed that laterally thins to 0.5 m.

At Apache Canyon (Fig. 11), the lowermost 7 m of the Red House Formation are composed of crossbedded, quartzose sandstone, pebbly sandstone, conglomerate and minor fine-grained sandstone. Shale and marly shale is intercalated. The maximum grain size of the conglomerate is 3 cm. The succession rests on marly, greenish-gray limestone of the Mississippian Lake Valley Formation.

In the Rincon Hills section (Fig. 11), the lowermost 6 m of the Red House Formation are composed of fine-grained sandstone displaying trough crossbedding, horizontal lamination and ripple cross lamination. Fossil plant fragments occur in the upper part.

Thus, the thickest and coarsest siliciclastic sediments at the base of the Red House Formation occur in the northernmost section (Amphitheater Canyon in the Fra Cristobal Mountains), and are also present at Fra Cristobal West and Apache Canyon. These are the Red House sections most proximal to ARM uplifts (see below). Farther south, coarse siliciclastic sediments are only present at the Rincon Hill section, although they are fine-grained there. At all other sections in the Caballo Mountains, at the type Derryan section and in the Mud Springs Mountains, coarse-grained sediments are absent at the base of the Red House Formation (Figs. 5, 10).

In the middle of the Red House Formation, coarse siliciclastic sedimentary rocks are trough-crossbedded, pebbly sandstone and sandstone that are exposed at Yellowjacket Mine (1.2 m), South Ridge (two horizons, 7.5 and 0.4 m), Apache Canyon (2 m), Green Canyon (4.4 and 0.8 m separated by 1.9 m cover, probably shale), Garfield Crest (4.3 m), Nakaye Mountain (0.7 to 2 m), type Cuchillo Negro (0.3 to 3 m) and Whiskey Canyon (2 horizons, 0.6 and 0.3 m thick). In all other sections, coarse siliciclastic sediments are absent in the middle of the Red House Formation. The thickest coarse-grained siliciclastic intercalations are present at South Ridge, Green Canyon and Garfield Crest, containing fossil plant fragments.

At South Ridge (Fig. 3, units 36-41) this interval is approximately 7.5 m thick, starts with a thin, poorly-sorted polymict conglomerate containing marine fossil fragments (crinoids, brachiopods, corals), overlain by shale, a very fossiliferous rudstone bed containing a few quartz grains and intraclasts up to 5 cm, over-

FIGURE 9. Red House sections in the Fra Cristobal Mountains—complete section of the formation at Amphitheater Canyon and incomplete section of the lower part of the formation at Fra Cristobal West. Thickness of units in meters. See Table 1 for location of sections.

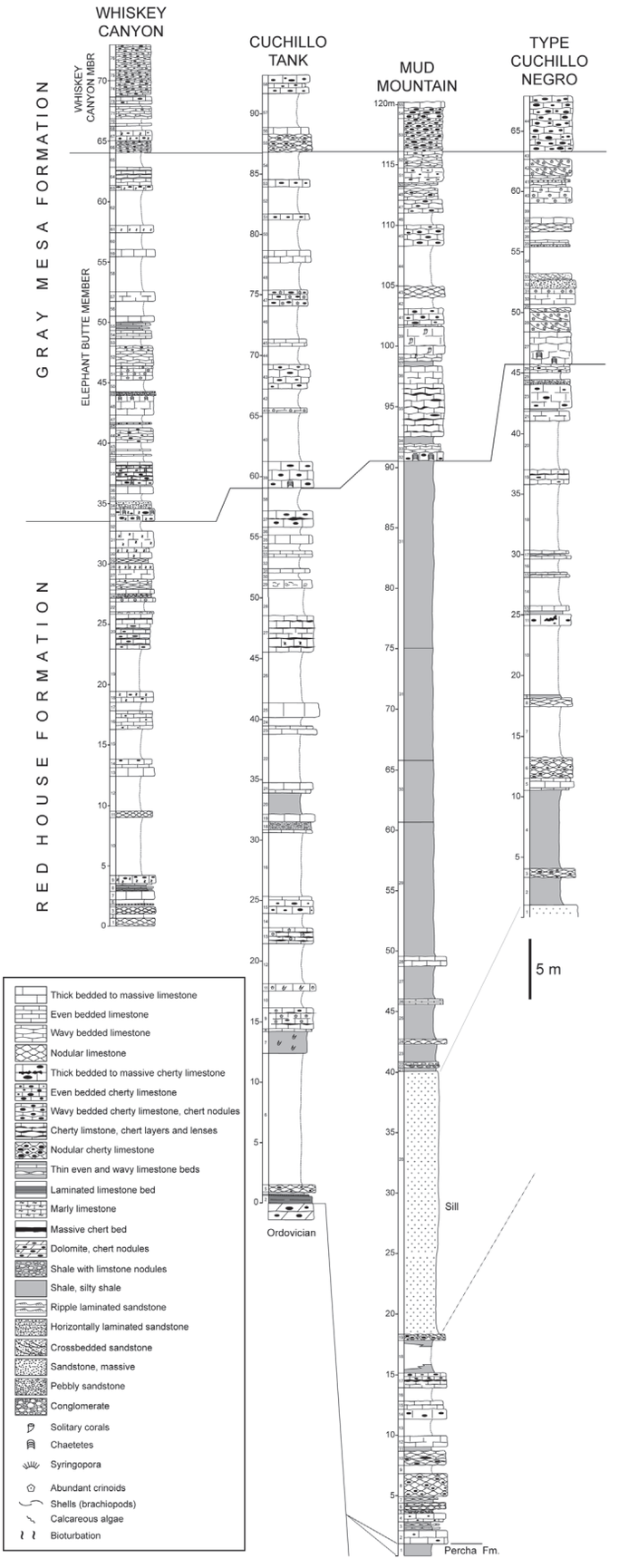


FIGURE 10. Red House sections in the Mud Springs Mountains. See Table 1 for location of sections.

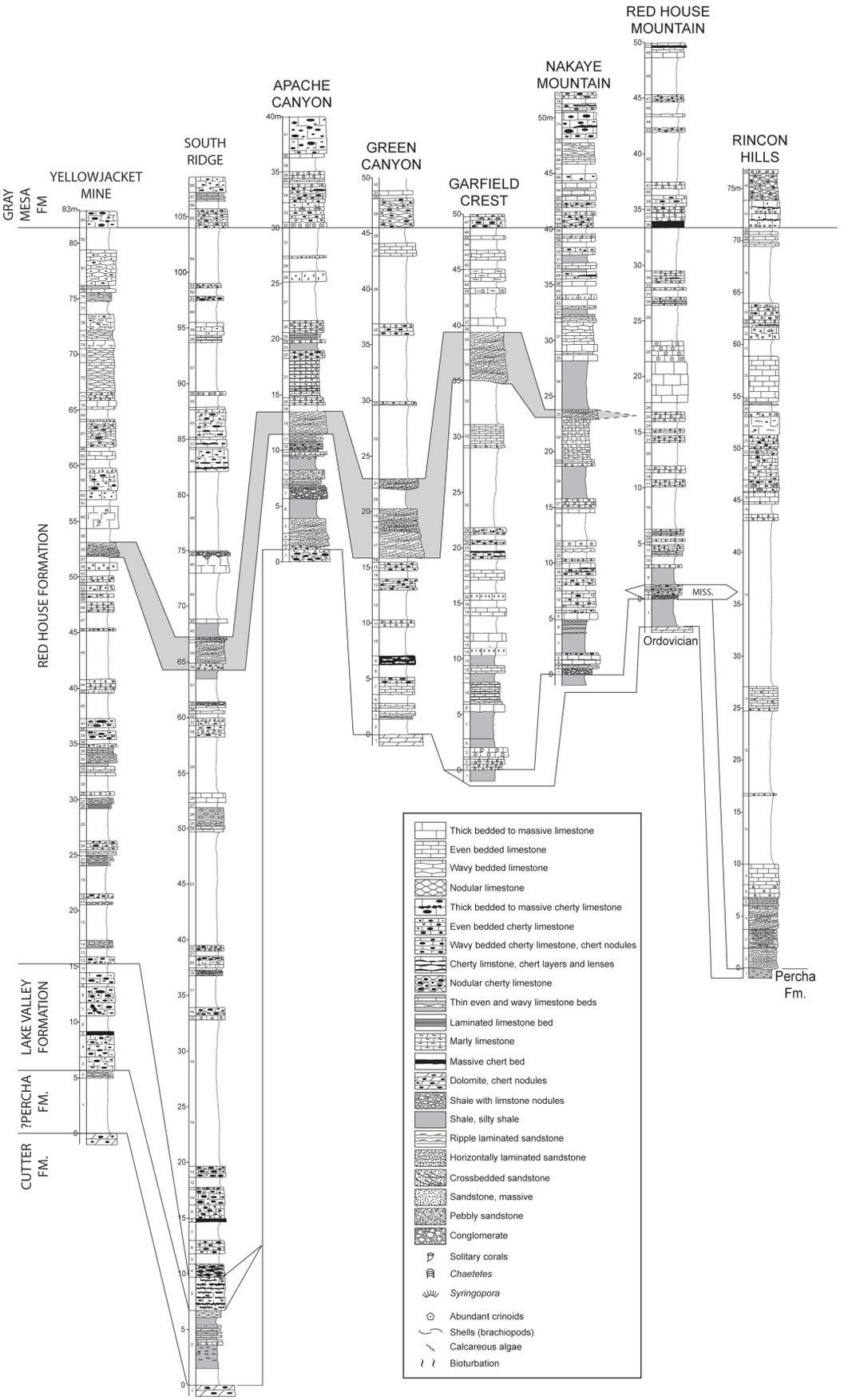


FIGURE 11. Red House sections in the Caballo Mountains and Rincon Hills. See Table 1 for location of sections.

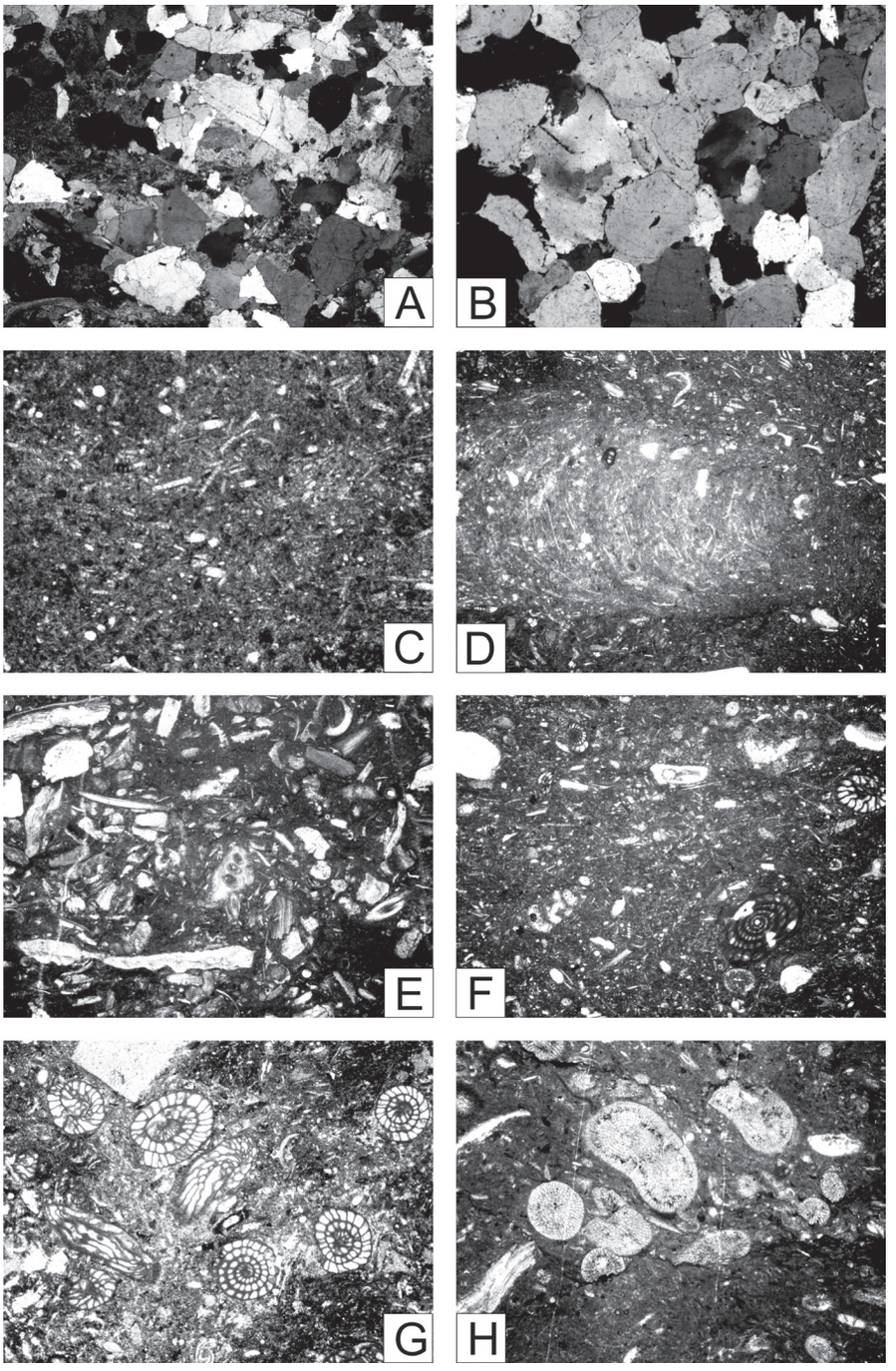


FIGURE 12. Thin section photographs of sandstone and limestone of the Red House Formation. **A**, Coarse-grained sandstone, calcite cemented, containing abundant detrital quartz grains and subordinate fossil fragments (echinoderms, brachiopods, bryozoans). Sample TCU 4, type Cuchillo Negro section, polarized light, width of photograph is 6.3 mm. **B**, Coarse-grained sandstone composed of mono- and polycrystalline quartz grains that are cemented by quartz in the form of authigenic overgrowths on detrital grains. Sample GRC 9, Green Canyon section, polarized light, width of photograph is 3.2 mm. **C**, Fine-grained bioclastic mudstone to wackestone containing spicules, some ostracods and recrystallized small skeletal grains embedded in micrite. Sample TD 7, type Derryan section, plane light, width of photograph is 3.2 mm. **D**, Fine-grained bioclastic wackestone containing abundant small skeletal grains embedded in micrite. A burrow is visible. Sample TCU 1, type Cuchillo Negro section, plane light, width of photograph is 6.3 mm. **E**, Wackestone, locally grading into packstone, containing a diverse fossil assemblage of echinoderms, bryozoans, brachiopods, ostracods, foraminiferans, trilobites, and micritic matrix. Sample TD 16, type Derryan section, plane light, width of photograph is 6.3 mm. **F**, Fine-grained wackestone containing spicules, echinoderms, ostracods, brachiopods and fusulinids floating in micrite. Sample CT 11, Cuchillo Tank section, plane light, width of photograph is 6.3 mm. **G**, Fusulinid wackestone composed of abundant fusulinid tests, subordinate echinoderms and other skeletal grains, embedded in micritic matrix. Sample TCU 5, type Cuchillo Negro section, plane light, width of photograph is 6.3 mm. **H**, Wackestone containing many *Komia* and subordinate fusulinids, echinoderms, bryozoans, brachiopods and other skeletal grains embedded in micrite. Sample CT 14, Cuchillo Tank section, plane light, width of photograph is 6.3 mm.

lain by crossbedded, coarse-grained rudstone to pebbly sandstone containing fossils, fine-grained, crossbedded sandstone, pebbly sandstone and shale.

Limestone

Limestone comprises 16% (Green Canyon) to 52% (type Derryan) of the total Red House Formation section and occurs as intercalated thin limestone beds to thicker limestone units (Figs. 3, 5, 9-11). Thickness commonly ranges from 0.1 to 3 m, and a few limestone intervals up to 8 m thick are present. Limestone beds and intervals alternate with shale or covered intervals, most of which probably also represent shale units. The following lithotypes are recognized: thin, even to wavy limestone beds; thin- to medium-bedded limestone with even bedding; thin- to medium-bedded limestone with wavy bedding; thick-bedded limestone; indistinctly bedded to massive limestone; and nodular limestone.

The limestone of the Red House Formation is mostly micritic, and gray to dark gray and both non-cherty and cherty. Cherty limestone contains dark gray-black chert nodules that may be up to 30 cm in diameter, but are usually 5 to 10 cm. Rarely, chert lenses and thin chert layers occur in the limestone. Silicified fossils may also occur, particularly brachiopods and solitary corals.

Fossils observed in the field are crinoid fragments that may be abundant in individual limestone beds, brachiopods (Fig. 7C), fusulinids (Fig. 7E), solitary corals and *Chaetetes* (Rincon Hills, type Derryan, Mud Mountain upper part, type Cuchillo Negro, Cuchillo Tank and Whiskey Canyon in the upper part) (Fig. 7D). Rarely, *Syringopora* is present (Rincon Hills). *Zoophycos* occurs at Whiskey Canyon (Lerner et al., 2011) and Amphitheater Canyon (upper part) (Fig. 7F).

In all sections wackestone to packstone containing a diverse fossil assemblage is by far the most common microfacies type, constituting more than 80% of all limestones (Fig. 12D, F-H). Subordinate bioclastic mudstone, locally grades into wackestone (Fig. 12C), packstone (Fig. 12E), floatstone (Fig. 13D), rudstone (Fig. 13C, E) and rare grainstone (Fig. 13F-H). The most common fossils are echinoderm fragments (mostly crinoids, locally forming crinoidal wackestone to packstone), brachiopod shell fragments and spines, bryozoans (rarely forming floatstone; Fig. 13D), fusulinids (locally forming fusulinid wackestone to packstone: Fig. 7E, 12G, 13B), and smaller foraminiferans (most common are *Bradyina, Climacammina, Endothyra, Globivalvulina, Hemigordius, Spireitlina, Tetrataxis, Tuberitina*). Phylloid algae are present in some limestone beds as completely recrystallized and fragmented algal plates forming phylloid algal floatstone (for example, at Whiskey Canyon). *Komia* (ungdarellacean red alga: Fig. 12H) is present in many samples and locally abundant. Rare fossils include trilobites, gastropods, corals and *Efluegelia* (stacheinacean red alga).

In the Whiskey Canyon section, peloidal wackestone containing abundant *Donezella* (problematical branching red alga) and other fossils is present in the lower part of the Red House Formation. Spicules derived from siliceous sponges are present in many samples, are locally abundant but rarely form spiculite. Spicules are usually calcified. Recrystallized and fragmented skeletons are present in most samples in moderate amounts. Rarely, skeletons are encrusted by cyanobacteria. In some limestone beds, echinoderm fragments are partly replaced by chert. Mudstone and wackestone are locally bioturbated, and a few mm-size burrows are present (Fig. 12D). Non-skeletal grains are peloids that, in some limestone beds, are abundant, forming peloidal wackestone. Micritic intraclasts are rare. The matrix is micrite, which often is peloidal or fine-bioclastic. Grainstone, packstone and rudstone are calcite cemented, but also contain small amounts of micrite as matrix.

Shale

In most Red House Formation sections, coarse-grained siliciclastic intervals and limestone alternate with covered intervals, which most likely represent shale intervals. Shale is rarely exposed. Shale and covered intervals constitute 34 to 72% of the sections, in most cases > 50%. Almost no shale (only covered intervals) is exposed at Rincon Hills, Green Canyon, Red House Mountain, South Ridge, Cuchillo Tank and Whiskey Canyon. Shale is quite well exposed at Mud Mountain, the type Derryan and Fra Cristobal West. Shale intervals range in thickness from a few cm to approximately 42 m (Mud Mountain), mostly ranging from 20 cm to a few meters. Most common are greenish- to gray-colored shale and marly shale; subordinate dark gray, black, brown or red shale is exposed. Fossils (brachiopods) are very rare in shale (Fra Cristobal West).

Petrography

Sandstone from the Green Canyon, Whiskey Canyon and type Cuchillo Negro sections was studied petrographically (Figs. 12-13). Medium-to coarse-grained sandstone from Green Canyon is poorly to moderately sorted, and the grains are mostly subangular to subrounded. Monocrystalline quartz is the most abundant grain type; subordinate are polycrystalline quartz grains of granitic origin, rarely of metamorphic origin, and chert grains (Fig. 12B). Very rare are carbonate grains (sedimentary rock fragments), detrital muscovite and feldspar grains (potassium feldspar). Sandstone is cemented by quartz that occurs as authigenic overgrowths on detrital quartz grains. Locally, large amounts of brownish carbonate cement are present.

Sandstone at Whiskey Canyon shows a similar composition and textural maturity. It is partly well sorted, grains are subrounded and the sandstone is cemented by quartz occurring as thin, authigenic overgrowths and by coarse blocky calcite.

The coarse-grained sandstone at the type Cuchillo Negro section contains abundant quartz grains, mainly monocrystalline quartz, a few fine-grained metamorphic rock fragments and rare detrital feldspars. Additionally, the sandstone consists of approximately 10% strongly fragmented fossils, particularly skeletons of echinoderms, brachiopod shells and spines, bryozoans and fusulinids. The sandstone is cemented by thin quartz overgrowths and coarse blocky calcite (Fig. 12A).

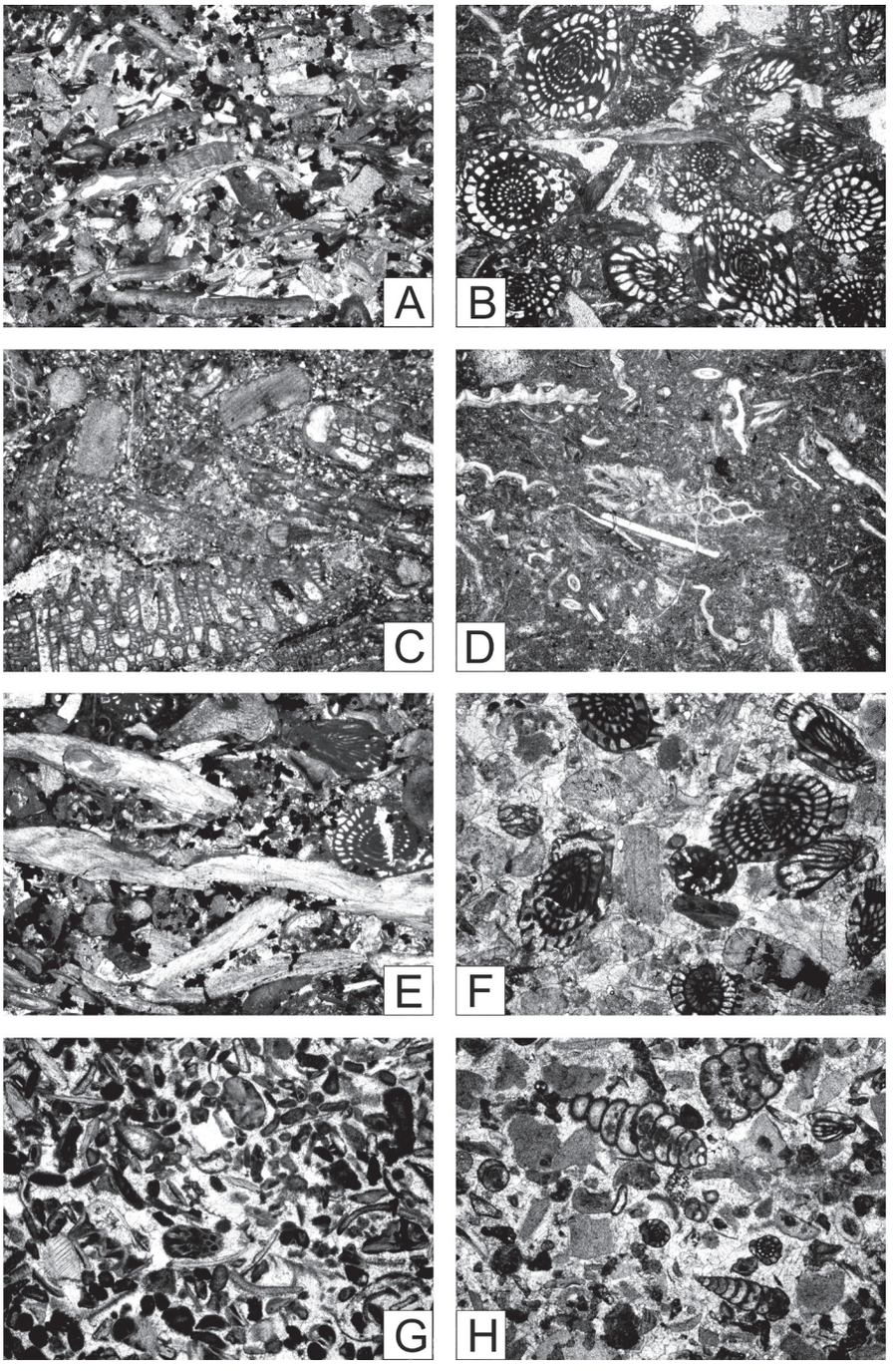


FIGURE 13. Thin section photographs showing microfacies types of limestone of the Red House Formation. All photos under plane light, width of photograph is 6.3 mm. **A**, Packstone containing abundant fragments of echinoderms, brachiopods, bryozoans, subordinate fusulinids and other fossils. Fossils are strongly fragmented. Sample CT 10, Cuchillo Tank section. **B**, Fusulinid packstone containing partly abraded fusulinid tests. Other skeletal grains are mainly echinoderms, brachiopods and bryozoans, and micritic matrix; calcite cement is also present. Sample MM 7, Mud Mountain section. **C**, Rudstone containing abundant large bryozoans, echinoderm and brachiopod fragments embedded in siltitic matrix. Sample CT 7, Cuchillo Tank section. **D**, Floatstone containing large fragments of brachiopods, echinoderms and bryozoans floating in fine-bioclastic micritic matrix. Sample WHC 17, Whiskey Canyon section. **E**, Rudstone containing fragments of brachiopods, echinoderms, fusulinids and other fossils. Shell fragments are oriented parallel to the bedding plane. Sample CT 10, Cuchillo Tank section. **F**, Grainstone to packstone, coarse-grained, composed of abundant echinoderm fragments and fusulinid tests (partly abraded), and a few other skeletal grains, cemented by coarse blocky calcite. Sample WHC 6, Whiskey Canyon section. **G**, Grainstone composed of peloids, coated grains, micritic intraclasts and mostly recrystallized skeletal grains, cemented by calcite. Sample MM 1, Mud Mountain section. **H**, Grainstone containing abundant echinoderm fragments, foraminiferans and a few other skeletal grains, cemented by calcite. Sample MM 9, Mud Mountain section.

DEPOSITIONAL ENVIRONMENTS

Kalesky (1988) concluded that Red House Formation deposition took place on a shallow marine platform in the southern part of the late Paleozoic Orogrande basin. He saw the principal mechanisms by which clastic sediments were distributed as waves, longshore currents and storms. Kalesky (1988) argued that the source of the quartzose clastics in the Red House Formation was a quartzite basement terrain to the northwest, in the current area of Catron County. He also inferred that limestone-shale couplets in the Red House Formation likely reflect glacio-eustatically-driven cycles of deposition. Here, we present our interpretation of Red House deposition, which differs in some details from that of Kalesky (1988).

Coarse siliciclastic sediments alternate with shale in the lowermost part of the Red House Formation at the Amphitheater Canyon, Fra Cristobal West and Apache Canyon sections and document a marine regression followed by transgression, producing an erosional surface. At Amphitheater Canyon this surface is overlain by shale, which we interpret as marine, probably estuarine basin mud, overlain by coarse-grained, siliciclastic sediments that we interpret as tidal-fluvial channel deposits. At Amphitheater Canyon four parasequences composed of coarse-grained, crossbedded channel deposits and overlying shale are exposed that may be interpreted as retrogradational parasequences of an estuarine facies formed during transgression.

At Fra Cristobal West and Apache Canyon the erosional surface is overlain by fine-grained conglomerate and crossbedded sandstone intercalated with shale. We interpret these deposits also as estuarine deposits. At Fra Cristobal West, the erosional surface on top of the Ordovician El Paso Group is particularly well exposed.

The thin, coarse-grained siliciclastic interval in the middle of the Red House Formation indicates another regression and formation of an erosional surface, overlain by coarse-grained, partly pebbly, crossbedded tidal-fluvial channel fill deposits that accumulated during transgression. The marine influence of the crossbedded sandstone is well documented by the occurrence of marine fossils at the Type Cuchillo Negro section.

At South Ridge, the thin polymict conglomerate at the base of this interval is interpreted to represent a marine lag deposit that formed during transgression. The lag deposit is overlain by marine shale. The fossiliferous rudstone bed and overlying crossbedded rudstone to fossiliferous sandstone, crossbedded sandstone and pebbly sandstone is interpreted to represent a tidal channel or tidal inlet channel, overlain by tidal mudstone.

This thin sandstone interval, which occurs approximately in the middle of the Red House Formation, at Yellowjacket Mine, South Ridge, Apache Canyon, Green Canyon, Garfield Crest, Nakaye Mountain, Whiskey Canyon and Type Cuchillo Negro is probably related to one regressional event (Fig. 11). A second thin siliciclastic intercalation occurs 8 to 10 m higher at Whiskey Canyon and South Ridge. At both sections an erosional surface on top of limestone (ravinement surface) is overlain by thin conglomerate and pebbly sandstone.

Limestone of the Red House Formation is characterized by the dominance of low-energy, micritic microfacies types (various types of wackestone to packstone), belonging to standard microfacies types (SMF) 8, 9 and 10, which were originally defined by Wilson (1975) (see also Flügel, 2004). All microfacies types contain a diverse fossil assemblage including abundant stenohaline biota such as echinoderms and brachiopods. Mudstone and wackestone are often bioturbated. Limestone is well bedded, commonly displaying wavy bedding, and the limestone is partly nodular. Locally, limestone contains abundant spicules derived from siliceous sponges, and chert nodules, lenses and thin layers. Calcareous algae are rare and allochthonous. Limestone alternates with marine shale. All these features indicate deposition of the limestone in an open, normal marine deeper shelf environment below fair weather wave base but slightly above the storm wave base as indicated by the presence of grainstone layers that can be interpreted as distal tempestites. The depositional environment belongs to the standard facies zone 2 (deep shelf) of the Wilson model (Flügel, 2004).

Interpretation of the depositional environment of the shale intervals is difficult due to the lack of diagnostic features. Fossils are extremely rare and intercalated shale, which is dominantly of gray to greenish, locally dark gray to black color, is poorly exposed or mostly covered in most sections. We interpret the shale to represent deposits of the deeper shelf environment below storm wave base ("offshore shale") except for the shale with intercalated coarse siliciclastic sediments at the base of the Red House Formation at Amphitheater Canyon, Fra Cristobal West and Apache Canyon.

BIOSTRATIGRAPHY

Introduction

The Red House Formation is a very fossiliferous stratigraphic unit, particularly rich in fusulinids, conodonts and brachiopods. Indeed, its fusulinid record was the basis of Thompson's (1942) Derryan Series, a subdivision of the Pennsylvanian now equated to (and subsumed under) the Atokan Stage. Here, we review Red House Formation biostratigraphy (Fig. 14) and report some newly collected conodonts (Fig. 15).

Fusulinid Biostratigraphy

The extensive record of fusulinids in the Red House Formation became the basis for Thompson's (1942) Derryan Series. The beginning of Derryan time is a turning point in fusulinid evolution when the non-fusiform fusulinids that are characteristic of the Morrowan (notably *Eostaffella* and *Millerella*) are replaced by fusiform taxa, beginning with *Profusulinella* and *Eoschubertella*. The end of the Derryan also marks another substantial change in the fusulinid fauna.

Studies of fusulinids from the Red House Formation have been published by Thompson (1942, 1948), Lane et al. (1972), King (1973), Verville et al. (1986) and Clopine (1990, 1991a, b, 1992). Originally, the Derryan encompassed two fusulinid zones,

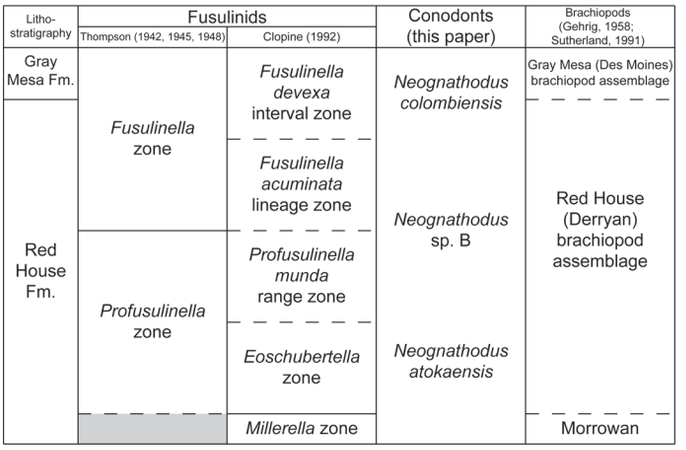


FIGURE 14. Summary of Red House Formation biostratigraphy.

Profusulinella (lower) and *Fusulinella* (upper) zones (Thompson, 1945, 1948). Clopine (1990, 1991a, b, 1992) presented a five-fold fusulinid biostratigraphy of the Red House Formation in the Derry Hills and Mud Springs Mountains (Fig. 14):

1. Morrowan *Millerella* zone found only in the basal Red House Formation at the Derryan type section.
2. Lower Atokan *Eoschubertella* zone documented in the lower part of the Red House Formation at Whiskey Canyon and at the type Derryan section.
3. Lower Atokan *Profusulinella munda* range zone, also known in the lower Red House at Whiskey Canyon and at the type Derryan section.
4. Upper Atokan *Fusulinella acuminate* lineage zone in the upper Red House Formation at Whiskey Canyon and at the type Derryan.
5. Upper Atokan *Fusulinella devexa* interval zone, from the uppermost Red House Formation, and locally, lowermost Gray Mesa Formation.

After Thompson (1942) proposed the Derry Series, Spivey and Roberts (1946), working in central Texas, proposed that the Atokan Series refer to post-Morrowan and pre-Desmoinesian strata that fit into a post-*Millerella* and pre-*Fusulina (= Beedeina)-Wedekindellina* interval in the fusulinid zonation. When Moore and Thompson (1949) used Atokan as a stage it was clear that the Derryan had been abandoned. The type Atokan strata are sparsely fossiliferous, but, based on their fusulinid record, they became the basis of the widely used Atokan Stage (see articles in Sutherland and Manger, 1984). Thus, the Atokan has long been perceived to encompass three fusulinid zones (in ascending order), the Zones of *Eoschubertella-Pseudostaffella*, *Profusulinella* and *Fusulinella* (Douglass, 1977; Wilde, 1990). Conodont and ammonoid correlations indicate that the Atokan is equivalent to the late Bashkirian-early Moscovian on the standard global chronostratigraphic scale.

Although Thompson's (1942) Derry Series had priority and was based on beautifully exposed and richly fossiliferous strata, Derryan never gained more currency than as a little-used alternative to the Atokan Series. Thus, Derryan has faded from the scene. Its boundaries with adjoining units posed intractable problems and its relatively thin type section (< 60 m) were perceived of as drawbacks of the Derryan that made it inferior to the Atokan as a chronostratigraphic unit (Lane and West, 1984; Sutherland and Manger, 1984).

Conodont Biostratigraphy

Based on preliminary sampling, conodont faunas from the Red House Formation vary greatly in abundance and diversity based on preliminary sampling. Finer-grained beds yielded small faunas, and the best samples were those from fine- to medium-grained carbonate packstones, or packstone lenses in finer-grained carbonate beds. Elements of *Idiognathodus*, *Adetognathus,* and *Hindeodus* were the most commonly recovered forms. Although a few conodonts were obtained from most samples, none of the sections yielded a good series of successive faunas. The better faunas come from the lower to middle portions of the Red House. Conodonts from the Red House Formation have been described and illustrated previously from the type Derryan section (e.g., Lane et al. 1972; Kaiser and Manger, 1991; Johnson et al. 1997), but no systematic study of the conodont faunas of the entire unit has been completed.

We recovered a variety of morphotypes of *Neognathodus* from the Red House Formation, few of which occur in any abundance (Fig. 15). Although the potential of using species of *Neognathodus* to subdivide Lower and Middle Pennsylvanian strata has been recognized (e.g., Lambert, 1992; Barrick et al., 2004), insufficient taxonomic and stratigraphic study has been completed to provide a basis for a refined correlation. Preliminary data from the Red House Formation suggest that three successive *Neognathodus* intervals may be present, which permit a tentative subdivision of the Red House Formation into lower, middle, and upper parts (Fig. 15).

In the lower part of the Red House, conodont faunas contain *Neognathodus* P_1 elements with a restricted dorsal tip and reduced rostral lobe. Many of these specimens fall within the broad range of variation assigned to *Neognathodus atokaensis* Grayson. Others forms have a shorter, broader outer lobe with pronounced transverse ridges and appear to be closer to *N.* sp. A of Lambert (1992). A few examples of *N. bassleri* (Lane) occur in the lower Red House.

In the middle part of the Red House Formation, nearly symmetrical *Neognathodus* P_1 elements appear, in which the carina extends to near the dorsal tip of the platform, but does not reach it. The dorsal extension of the carina may comprise a series of nodes or a narrow, fused ridge or a combination of both. The margins of the platform lie near the same elevation as the carina. This appears to be *Neognathodus* sp. B of Lambert (1992), which was described from upper Atokan beds in Iowa. The few asymmetrical *Neognathodus* P_1 elements from the middle Red House have a strongly reduced outer lobe on which the transverse ornamentation is reduced, but the lobe is not as reduced in length or as smooth as those illustrated for *N. kanumai* Koike or *N. nataliae* Alekseev and Gerelzezeg.

In the upper part of the Red House Formation at some sections (Nakaye Mountain, Yellowjacket Mine), *Neognathodus* sp.

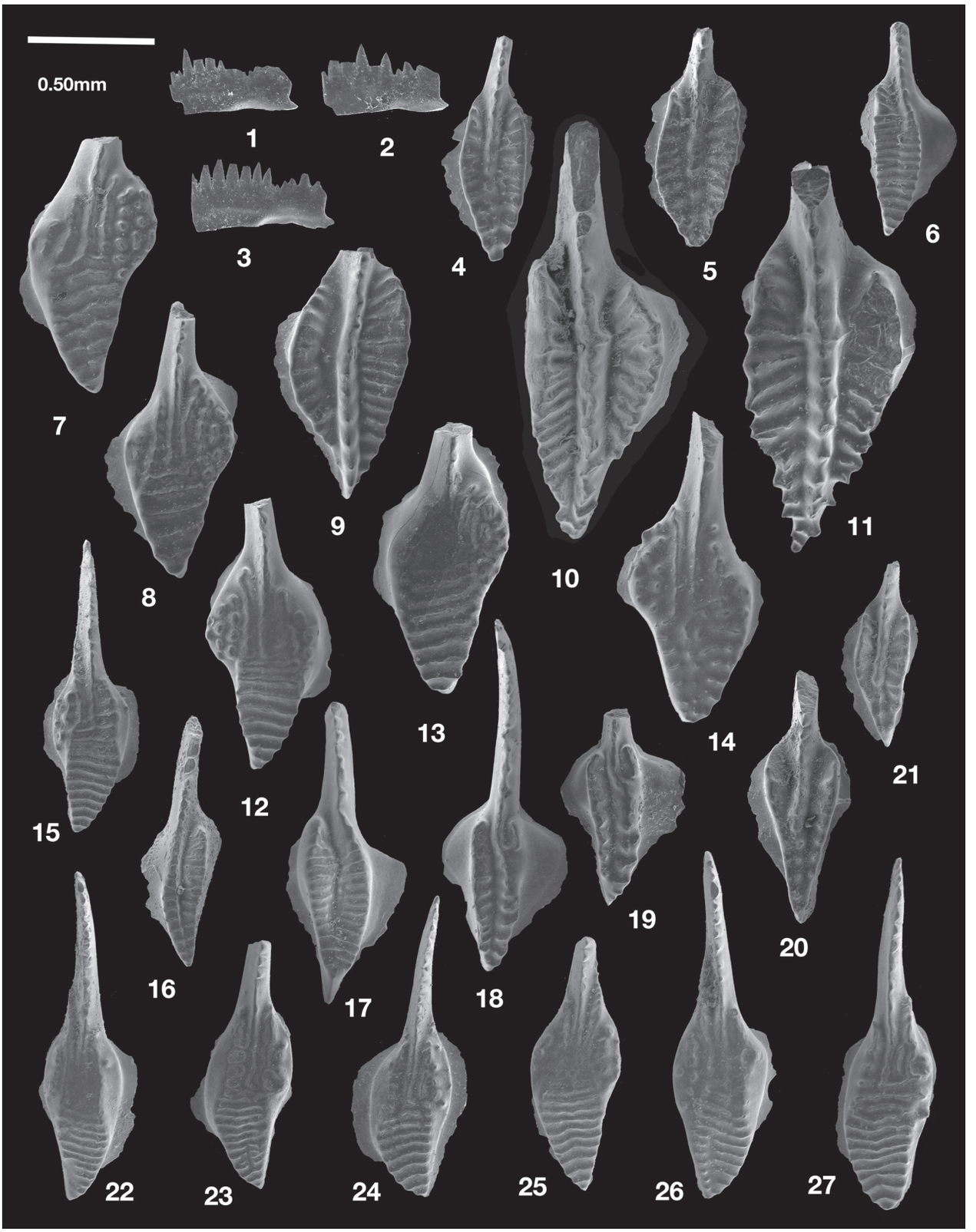


FIGURE 15. Selected conodonts from the Red House Formation. Specimens are in the collections of Texas Tech University. **1-3**, *Diplognathodus* cf. *D. coloradoensis* (Murray and Chronic) of von Bitter and Merrill (1980) (NAK3-42); **4-5**, *Neognathodus* sp. B of Lambert (1992) (NAK3-42); **6**, **16-17**, *Idiognathoides sinuatus* (Harris and Hollingsworth), **6** (NAK3-42), **16-17** (DH-15); **7-8**, **12-14**, **24**, *Idiognathodus klapperi* Lane and Straka, **7-8**, **12-14** (NAK3-4), **24** (DH-15); **9-11**, **20-21**, *Neognathodus atokaensis* Grayson group, **9-11** (NAK3-4), **20-21** (DH-15); **15**, **25-26**, *Idiognathodus incurvus* Dunn(DH-15); **18-19**, *Declinognathodus marginodosus* Grayson (DH-15); **22-23**, **27** *Idiognathodus sinuosus* Ellison and Graves (DH-15).

B remains common, but is joined by *N. colombiensis* (Stibane), in which the carina merges with the platform margins and forms the posterior tip of the platform. As in *N.* sp. B, the carina and platform margins lie at about the same elevation on P_1 elements of *N. colombiensis*.

Relatively few specimens of *Declinognathodus marginodosus* Grayson and *Idiognathoides sinuatus* (Harris and Hollingsworth) were recovered from the Red House Formation. Elements of these two species occur in many samples from the lower Red House, and they are less common in the middle Red House. None were obtained from the upper Red House. Most of the few P_1 elements of *Diplognathodus* recovered from the Red House Formation possess a relatively long, partially denticulate spatula. Merrill (1973, 1975) and von Bitter and Merrill (1980) distinguished these Atokan forms (*D.* cf. *D. coloradoensis*) from elements with a short, fused spatula that is more typical of the Desmoinesian *D. coloradoensis* (Murray and Chronic). Examples of *D. coloradoensis* reported from the Red House at the type Derryan section (Clopine et al., 1991; Kaiser and Manger, 1991) are likely *D.* cf. *D. coloradoensis*. Only a couple of Red House specimens appear to have a fully denticulated margin like *D. orphanus* (Merrill, 1973, 1975).

The Red House conodont faunas are dominated by *Idiognathodus* elements (Fig. 15), but the species composition within individual samples and through the formation is difficult to resolve. The lower Red House *Idiognathodus* collections include a combination of P_1 elements of *I. sinuosus* Ellison and Graves, *I. klapperi* Lane and Straka, and possibly *I. incurvus* Dunn. Examples of *I. sinuosus* retain some asymmetry of the P_1 element pairs, but the elements possess the additional nodes and greater lobe development transitional to the younger species *I. incurvus*. Proctor (1992) suggested that a series of morphotypes connected *I. sinuosus* with curved, but more symmetrically paired P_1 elements of *I. incurvus* in the Dimple Limestone in the Marathon basin, West Texas. Both taxa have dorsally extended adcarinal ridges (Grayson et al., 1990). The shorter, straighter, more symmetrically paired P_1 elements of *I. klapperi* have short adcarinal ridges that are restricted to the platform surface, but they also appear to be derived from *I. sinuosus* (Proctor, 1992). Grayson et al. (1990) and Rexroad et al. (1998) applied these species names based on the modal morphology observed in a collection compared with what they perceived to be a gradual unilinear phylogeny. We prefer to treat these taxa as distinct morphotypic species. Most samples from the lower to middle Red House Formation are dominated by *I. klapperi* P_1 elements, some of which display slight elongation of the adcarinal ridges. In the middle to upper Red House Formation, *Idiognathodus incurvus* becomes more common, and new P_1 elements with shorter, broader platforms and larger lobes appear. These later Red House forms are better represented in the Whiskey Canyon section in the Mud Springs Mountains where three morphotypes may be present.

The conodont faunas suggest that the Red House Formation represents most of the time commonly assigned to the Atokan Stage. Although a precise definition of the base of the Atokan does not exist, the presence of *Neognathodus atokaenis*-like forms, *Idiognathodus incurvus, Declinognathodus marginodosus,* and the "Atokan" forms of *Diplognathodus* in the lower and middle Red House, each indicate an Atokan age. The occurrence of *N. colombiensis* in the upper Red House indicates a later Atokan age (Barrick et. al., 2004). No conodont taxa used to characterize lower Desmoinesian strata (Lambert, 1992; Barrick et. al. 2004; Boardman et al. 2004) were recovered from the Red House Formation. The small conodont fauna obtained from the middle of the Sandia Formation at Cerros de Amado (Socorro County, NM: Lucas et al., 2009b) is similar to those from the lower and middle Red House Formation.

Brachiopod Biostratigraphy

A variety of macroinvertebrate fossils are present in limestone and shale beds of the Red House Formation, primarily crinoids (mostly columnals), brachiopods and bryozoans and lesser numbers of mollusks--bivalves and gastropods. Other than the articles by Gehrig (1958) and Sutherland (1991), we know of no published studies of these fossils.

Based on Gehrig (1958) and Sutherland (1991), there are two age-distinctive brachiopod assemblages in the Red House Formation (Fig. 14). At the type Derryan section, at the base of the Red House Formation, in a thin (~0.7 m thick) black shale and nodular limestone, Morrowan brachiopods are present (Sutherland and Manger, 1984; Manger et al., 1987; Sutherland, 1991). These are 12 brachiopod species, including nine species restricted to the Morrowan: *Composita* cf. *C. gibbosa* Mather, *Linoproductus nodosus* (Newberry), *Neochonetes*? *platynotus* (White), *Pliochonetes*? *arkansanus* (Mather), *Sandia welleri* (Mather), *Punctospirifer morrowensis* Sutherland and Harlow, *Rhynchopora magnicosta* Mather, *Spirifer goreii* Mather and *Zia novamexicana* Sutherland and Harlow (see Sutherland, 1991). It is important to note that these brachiopods indicate a Morrowan age, but not a precise age within the Morrowan. Furthermore, Manger et al. (1987) presented evidence of an unconformity between the brachiopod-bearing horizon and overlying Atokan limestone at the type Derryan section. Therefore, it seems likely that there is a Morrowan-Atokan hiatus of relatively short duration within the lowermost Red House Formation at the type Derryan section.

Gehrig (1958) documented brachiopods from the Red House and overlying Gray Mesa formations at Whiskey Canyon in the Mud Springs Mountains. He concluded that the Red House (his Derry) yields a brachiopod fauna distinct from that of the overlying Gray Mesa Formation (his "Des Moines"). Thus, he identified four brachiopod species as restricted to the Red House Formation – *Chonetes striatus* Gehrig, *Marginifera* cf. *M. haydenensis* Girty, *Reticulariina* cf. *R. spinosa* (Norwood and Pratten) and *Rhipidomella carbonaria* (Swallow). According to Gehrig (1958), at least 15 species of 11 genera first appear in the Gray Mesa Formation.

THE ARM OROGENY AND THE RED HOUSE AND SANDIA FORMATIONS

Strata of the Red House Formation are the first sedimentary record of the ARM orogeny in Sierra County, New Mexico (Fig.

16). To the north, in Socorro County, and northward in New Mexico, the stratigraphic unit at the base of the Pennsylvanian section is almost everywhere the Sandia Formation (e.g., Lucas et al., 2009b; Krainer et al., 2011b). The Sandia Formation is of Atokan age and clearly homotaxial to and essentially correlative to the Red House Formation. The two formations differ primarily in the greater thickness of the Sandia Formation and the presence of substantial beds of quartzose sandstone in the Sandia Formation (e.g., Krainer et al., 2011b).

Sediments of the Red House Formation mainly represent deposits of a deep shelf environment with coarse siliciclastic sediments of a tidal-fluvial environment locally developed at the base and approximately in the middle of the succession. Fusulinids, conodonts and brachiopods indicate a Morrowan to mainly Atokan age. In central New Mexico, ARM deformation started during the latest Morrowan/Atokan (Kues and Giles, 2004). At that time, uplift and erosion of the Pedernal uplift occurred (Ye et al., 1996). This event, which marks the beginning of the ARM deformation (basin development), caused the first extensive Pennsylvanian transgression in New Mexico (Kluth and Coney, 1981; Kluth, 1986; Ye et al., 1996; Dickinson and Lawton, 2003; Nelson and Lucas, 2011) and deposition of siliciclastic and carbonate sediments of the Sandia Formation in central New Mexico (Krainer et al., 2011b). The southernmost outcrops of the Sandia Formation are east of Socorro and in the southern Oscura Mountains. Farther south the Sandia Formation grades into the Red House Formation, in which coarse siliciclastic rocks are locally developed at the base and occur as a widespread thin horizon approximately in the middle of the succession.

Deposition of Red House carbonate sediments was on a deeper marine shelf than those of the Sandia carbonates to the north. Siliciclastic sediments of the Sandia Formation are nonmarine and shallow marine. Kottlowski (1965, p. 142) apparently first used the term Cristobal-Caballo arch to refer to an ARM positive in Sierra County. Based on isopach maps of the Red House Formation, Kalesky (1988) reconstructed two arches separated by a paleo-low he called the Caballo trough (Fig. 16). Here, we term these "arches" the Cristobal and Caballo uplifts (Fig. 16). Petrography of the coarse siliciclastic sedimentary rocks of the Red House Formation indicates dominantly granitic and subordinate metamorphic source rocks. Given that the coarse siliciclastic intervals in the Red House Formation thin towards the south and southwest, the material was probably derived from easterly source areas in the Pedernal and more proximal Caballo and Cristobal uplifts (Fig. 16). We infer that the siliciclastic intervals of the Red House Formation reflect tectonic movements related to the ARM deformation (uplift of the ARM highlands, increased erosion and deposition of coarse siliciclastic sediment in the adjacent basin).

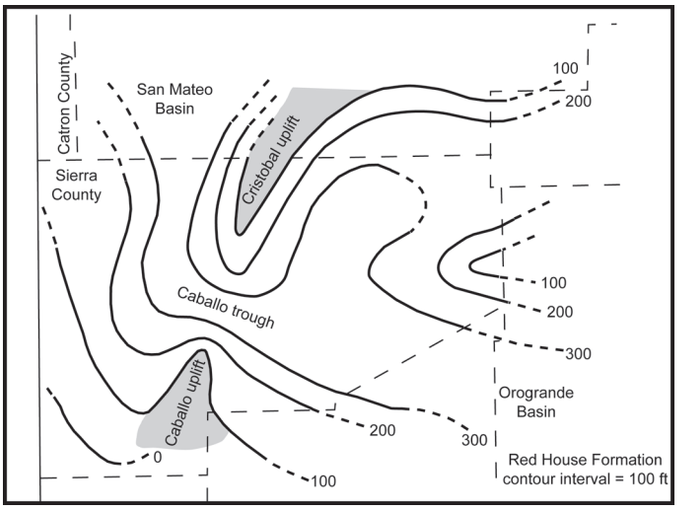


FIGURE 16. Schematic diagram of ARM uplifts in Sierra County that affected Red House Formation deposition (after Kalesky, 1988). Isopach map from Kalesky (1988) is of Red House Formation thickness.

ACKNOWLEDGMENTS

Our work in the Fra Cristobal Mountains was made possible by Ted Turner and Tom Waddell of the Armendaris Ranch. John Nelson assisted us in some of the field work, as did Ed Simpson. Bruce Allen, Bob Colpitts and John Nelson provided helpful reviews that improved the quality of the manuscript.

REFERENCES

Barrick, J.E., Lambert, L.L., Heckel, P.H. and Boardman, D.R., 2004, Pennsylvanian conodont zonation for Midcontinent North America: Revista Espanola de Micropaleontologia, v. 36, p. 231-250.

Barrick, J.E., Lucas, S.G. and Krainer, K., 2012, Conodonts from the Pennsylvanian section at Green Canyon, Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, 63rd Field Conference Guidebook 63, this guidebook.

Boardman, D.R., Heckel. P.H. and Marshall, T.R., 2004, Preliminary report on lower Desmoinesian (mid-Moscovian) conodonts from lower and middle Cherokee Group of southern Midcontinent North America: Newsletter on Carboniferous Stratigraphy, v. 22, p. 41-47.

Clopine, W.W., 1990, Middle Pennsylvanian fusulinid biostratigraphy of the type Derryan area in southern New Mexico and westernmost Texas: Ph.D. dissertation, Norman, University of Oklahoma, 271 p.

Clopine, W.W., 1991a, Lower and Middle Pennsylvanian measured sections, type Derryan region, southern New Mexico and westernmost Texas: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 373, 125 p.

Clopine, W.W., 1991b, Lower and Middle Pennsylvanian fusulinid biostratigraphy in south-central New Mexico and West Texas: A brief review: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 181-186.

Clopine, W.W., 1992, Lower and Middle Pennsylvanian fusulinid biostratigraphy of southern New Mexico and westernmost Texas: New Mexico Bureau of Mines and Mineral Resources, Bulletin 143, 68 p.

Clopine, W.W., Manger, W.L., Sutherland, P.K. and Kaiser, D.A., 1991, Lower and Middle Pennsylvanian stratigraphic relations, type Derryan region, southern New Mexico and westernmost Texas: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 173-181.

Cserna, E.G., 1956, Structural geology and stratigraphy of the Fra Cristobal quadrangle, Sierra County, New Mexico: Ph.D. dissertation, New York, Columbia University, 104 p.

Darton, N.H., 1928, "Red beds" and associated formations in New Mexico with an outline of the geology of the state: U.S. Geological Survey, Bulletin 794, 356 p.

Dickinson, W.R. and Lawton, T.F., 2003, Sequential intercontinental suturing as the ultimate control for Pennsylvanian ancestral Rocky Mountains deformation: Geology, v. 31, p. 609-612.

Douglass, R.C., 1977, The development of fusulinid biostratigraphy; *in* Kauffman, E.G. and Hazel, J.E., eds., Concepts and methods of biostratigraphy: Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, p. 463-481.

Eardley, A.J., 1951, Structural geology of North America: New York, Harper and Brothers, 624 p.

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

Gehrig, J.L., 1958, Middle Pennsylvanian brachiopods from the Mud Springs Mountains and Derry Hills, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 3, 22 p.

Gordon, C.H., 1907, Notes on the Pennsylvanian formations in the Rio Grande valley, New Mexico: Journal of Geology, v. 15, p. 805-816.

Grayson, R.C., Jr., Merrill, G.K. and Lambert, L.L., 1990, Carboniferous conodont apparatuses: Evidence of a dual origin for Pennsylvanian taxa; *in* Ziegler, W., ed., 1st International Senckenberg Conference and 5th European conodont symposium (ECOS V) Contributions IV, Papers on conodonts and Ordovician to Triassic conodont stratigraphy: Courier Forschungsinstitut Senckenberg, v. 118, p. 353-396.

Harley, G.T., 1934, The geology and ore deposits of Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 10, 220 p.

Herrick, C. L., 1900, The geology of the White Sands of New Mexico: Journal of Geology, v. 8, p. 112–128.

Hill, J.D., 1956, Paleozoic stratigraphy of the Mud Springs Mountains, Sierra County, New Mexico: M.S. thesis, Albuquerque, University of New Mexico, 72 p.

Johnson, K.W., Merrill, G.K. and Brown, L.M., 1997, Conodont biostratigraphy of the Derryan type section (Morrowan-Desmoinesian), Sierra County, New Mexico (abstr.): Geological Society of America, Abstracts with Programs, v. 29, p. 17.

Kaiser, D.A., 1990, Conodont biofacies analysis of the Lower to Middle Pennsylvanian (Morrowan and Atokan), south-central New Mexico and westernmost Texas: M.S.thesis, Norman, University of Oklahoma, 115 p.

Kaiser, D.A. and Manger, W.L., 1991, Morrowan-Atokan (Pennsylvanian) conodont biofacies, south-central New Mexico and westernmost Texas: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 188-192.

Kalesky, J.F., 1987, Tectonics and depositional environments in the Early Pennsylvanian of south-central New Mexico: American Association of Petroleum Geologists Bulletin, v. 71, 240 p.

Kalesky, J.F., 1988, Lithofacies, stratigraphy and cyclic sedimentation in a mixed carbonate and siliciclastic system, Red House Formation (Atokan), Sierra County, New Mexico: M.S. thesis, Las Cruces, New Mexico State University, 202 p.

Kelley, V.C. and Silver, C., 1952, Geology of the Caballo Mountains: University of New Mexico, Publications in Geology 4, 286 p.

Keyes, C.R., 1904, Unconformity of the Cretaceous on older rocks in central New Mexico: American Journal of Science, 4th series, v. 18, p. 360-362.

King, W.E., 1973, Fusulinids *Millerella* and *Eostaffela* from the Pennsylvanian of New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources, Memoir 26, 34 p.

Kluth, C., 1986, Plate tectonics of the ancestral Rocky Mountains; *in* Peterson, J. A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United states: American Association of Petroleum Geologists, Memoir 41, p. 353-369.

Kluth, C.F. and Coney, P.J., 1981, Plate tectonics of the ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

Kottlowski, F.E., 1960, Summary of Pennsylvanian sections in southwestern New Mexico and southeastern Arizona: New Mexico Bureau of Mines and Mineral Resources, Bulletin 66, 187 p.

Kottlowski, F.E., 1965, Facets of the late Paleozoic strata in southwestern New Mexico: New Mexico Geological Society, 16th Field Conference Guidebook, p. 141-147.

Krainer, K. and Lucas, S.G., 2004, Type sections of the Pennsylvanian Gray Mesa and Atrasado formations, Lucero uplift, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 7-30.

Krainer, K., Lucas, S.G. and Spielmann, J. A., 2011a, Stratigraphy and sedimentation of the Middle Pennsylvanian Red House Formation, Caballo Mountains, Sierra County, New Mexico: New Mexico Geology, v. 33, p. 56-57.

Krainer, K., Lucas, S. G. and Vachard, D., 2011b, Lectostratotype section of the Pennsylvanian Sandia Formation, Bernalillo County, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 53, p. 71-85.

Kues, B.S., 2001, The Pennsylvanian System in New Mexico – overview with suggestions for revision of stratigraphic nomenclature: New Mexico Geology, v. 23, p. 103-122.

Kues, B. S. and Giles, K. A. , 2004, The late Paleozoic ancestral Rocky Mountains system in New Mexico; *in* Mack, G. H. and Giles, K. A., eds., The geology of New Mexico: A geologic history: New Mexico Geological Society, Special Publication 11 p. 95-136.

Lambert, L.L., 1992, Atokan and basal Desmoinesian conodonts from central Iowa, reference region for the Desmoinesian Stage: Oklahoma Geological Survey, Circular 94, p. 111-123.

Lane, H.R. and West, R.R., 1984, The inadequacies of Carboniferous serial nomenclature: North American examples: Oklahoma Geological Survey, Bulletin 136, p. 91-100.

Lane, H.R., Sanderson, G.A. and Verville, G.J., 1972, Uppermost Mississippian – basal Pennsylvanian conodonts and fusulinids from several exposures in the south-central and southwestern United States: 24th International Geological Congress, Montreal, sec. 7, p. 549-555.

Lee, W. T., 1909, The Manzano group of the Rio Grande valley, New Mexico. Stratigraphy of the Manzano Group: U. S. Geologic Survey, Bulletin 389, p. 5-40.

Lucas, S. G., Krainer, K. and Spielmann, J. A., 2009a, The Pennsylvanian section at Whiskey Canyon, Mud Springs Mountains, Sierra County, New Mexico: New Mexico Geology, v. 31, p. 46-47.

Lucas, S.G., Krainer, K. and Barrick, J.E., 2009b, Pennsylvanian stratigraphy and conodont biostratigraphy in the Cerros de Amado, Socorro County, New Mexico: New Mexico Geological Society, 60th Field Conference Guidebook, p. 183-212.

Lucas, S. G., Krainer, K. and Spielmann, J. A., 2012, Pennsylvanian stratigraphy in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, 63rd Field Conference Guidebook, this guidebook.

Manger, W.L., Sutherland, P.K. and Clopine, W.W., 1987, Morrowan-Atokan relations, type "Derryan" section, New Mexico (abstr.): Geological Society of America, Abstracts with Programs, v. 19, p. 173.ed

Maxwell, C.H. and Oakman, M.R., 1986, A Pennsylvanian unconformity in the Mud Springs Mountains: New Mexico Geological Society, 37th Field Conference Guidebook, p. 4-5.

Maxwell, C.H. and Oakman, M.R., 1990, Geologic map of the Cuchillo quadrangle, Sierra County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ-1686, scale 1:24,000.

McCleary, J.T., 1960, Geology of the northern part of the Fra Cristobal range, Sierra and Socorro counties, New Mexico: M.S. thesis, University of New Mexico, Albuquerque, 59 p.

Merrill, G.K., 1973, Pennsylvanian nonplatform conodont genera, I: *Spathognathodus*: Journal of Paleontology, v. 47, p. 289-314.

Merrill, G.K., 1975, Pennsylvanian conodont biostratigraphy and paleoecology of northwestern Illinois: Geological Society of America, Microform Publication, 3, 130 p.

Moore, R. C. and Thompson, M. L., 1949, Main divisions of Pennsylvanian Period and System: American Association of Petroleum Geologists Bulletin, v. 33, p. 275-302.

Nelson, E.P., 1986, Geology of the Fra Cristobal range, south-central New Mexico: New Mexico Geological Society, 37th Field Conference Guidebook, p. 83-91.

Nelson, W. J. and Lucas, S. G., 2011, Carboniferous geologic history of the Rocky Mountain region: New Mexico Museum of Natural History and Science, Bulletin 53, p. 115-142.

Proctor, D.D., 1992, Conodont fauna of the Dimple Limestone (Late Morrowan-Early Atokan, Early Pennsylvanian) in the Marathon Basin, Texas: Ph.D. dissertation, Lubbock, Texas Tech University, 101 p.

Rexroad, C.B., Brown, L.B., Devera, J. and Suman, R.J., 1998, Conodont biostratigraphy and paleoecology of the Perth Limestone Member, Staunton Formation (Pennsylvanian) of the Illinois Basin, U.S.A., *in* Szaniawski, H., ed., Proceedings of the Sixth European Conodont Symposium (ECOS VI): Palaeontologica Polonica, v. 58, p. 247-259.

Seager, W.R., 1986, Third-day road log, from Truth or Consequences to southeastern Caballo Mountains and San Diego Mountain via I-25 and the Jornada del Muerto: New Mexico Geological Society, 37th Field Conference Guidebook, p. 35-52.

Seager, W.R. and Hawley, J.W., 1973, Geology of Rincon quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 101, 42 p.

Seager, W.R. and Mack, G.H., 1991, Geology of Garfield quadrangle, Sierra and

Dona Ana counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 128, 24 p.

Seager, W.R. and Mack, G.H., 1998, Geology of the McLeod Tank quadrangle, Sierra and Dona Ana counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 77, scale 1:24,000.

Seager, W.R. and Mack, G.H., 2003. Geology of the Caballo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 49, 136 p.

Seager, W.R. and Mack, G.H., 2005, Geology of Caballo and Apache gap quadrangles, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 74, scale 1:24,000.

Spivey, R.C. and Roberts, T.G., 1946, Lower Pennsylvanian terminology in central Texas: American Association of Petroleum Geologists, Bulletin 30, p. 181-186.

Sutherland, P.K., 1991, Morrowan brachiopods from the type "Derryan" Series (Pennsylvanian), southern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 132, p. 186-188.

Sutherland, P.K. and Manger W.L., eds., 1984, The Atokan Series (Pennsylvanian) and its boundaries: Oklahoma Geological Survey, Bulletin 136, 198 p.

Thompson, M.L., 1942, Pennsylvanian System in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 17, 92 p.

Thompson, M. L., 1945, Pennsylvanian rocks and fusulinids of east Utah and northwest Colorado correlated with Kansas section: State Geological Survey of Kansas, Bulletin 60, p. 19-84.

Thompson, M.L., 1948, Early Pennsylvanian fusulinids of New Mexico and western Texas: University of Kansas, Paleontology Contributions 4, Article 1, part 3, p. 68-97.

Verville, G. J., Sanderson, G. A. and Madsen, M. E., 1986, Pennsylvanian fusulinids from the Fra Cristobal Range, Sierra County, New Mexico: New Mexico Geological Society, 37th Field Conference Guidebook, p. 215-223.

Von Bitter, P.H. and Merrill, G.K., 1980, Effects of variation on the speciation and phylogeny of *Diplognathodus*; *in* Ziegler, W., ed., 1st International Senckenberg Conference and 5th European conodont symposium (ECOS V) Contributions IV, Papers on conodonts and Ordovician to Triassic conodont stratigraphy: Courier Forschungsinstitut Senckenberg, v. 118, p. 105-129.

Wilde, G.L., 1990, Practical fusulinid zonation: The species concept; with Permian Basin examples: West Texas Geological Society Bulletin, v. 29, p. 5-34.

Wilde, G.L., 2006, Pennsylvanian-Permian fusulinaceans of the Big Hatchet Mountains, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 38, 331 p.

Wilson, J.L., 1975, Carbonate facies in geologic history: Berlin, Springer-Verlag, 471 p.

Ye, H., Royden. L., Burchfield, C. and Schuperbach, M., 1996, Late Paleozoic deformation of interior North America: The greater ancestral Rocky Mountain deformation: American Association of Petroleum Geologists Bulletin, v. 80, p. 1397-1432.

Zeigler, P. A., 1988, Evolution of the Arctic-North Atlantic and the western Tethys: American Association of Petroleum Geologists, Memoir 43, 198 p.