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Stratigraphy of the Bisbee Group (Jurassic-Cretaceous), Little Hatchet Mountains, New Mexico

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STRATIGRAPHY OF THE BISBEE GROUP (JURASSIC–CRETACEOUS), LITTLE HATCHET MOUNTAINS, NEW MEXICO

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Abstract—Upper Jurassic–Lower Cretaceous strata of the Bisbee Group exposed in the Little Hatchet Mountains of Grant and Hidalgo Counties, New Mexico, are assigned to four formations: Broken Jug, Hell-to-Finish, U-Bar, and Mojado. The Broken Jug Formation is 1228 m thick and consists of marine strata and volcanic rocks assigned to the (ascending) dolostone, lower conglomerate, fine-grained upper conglomerate, and basalt members. The Hell-to-Finish Formation is 525 m thick and consists of two members named here: (1) Stone Cabin Gulch Member, a lower, 200-m-thick interval of interbedded bioturbated siltstone and marine limestone; (2) Winkler Ranch Member, an upper, 325-m-thick interval of conglomerate, enterolithic dolostone and red siltstone with pedogenic calcite nodules deposited in fan-delta and fluvial channels, sabkha and subaerial coast-plain environments, respectively. The U-Bar Formation is 237 m thick in the central part of the range at Howells Ridge, where it consists of the Carbonate Hill, Old Hachita, and Howells Ridge members. In the southern part of the range at Winkler Ranch, it is 972 m thick and consists of the Carbonate Hill, Old Hachita(?) and Still Ridge members. The Still Ridge Member is mostly skeletal sandstones deposited in shallow-water carbonate-ramp settings coeval with rudistid reefs that make up the Howells Ridge Member. The U-Bar Formation thus differs substantially in thickness and facies from north to south. The Mojado Formation is 1245 m thick and consists of the Fryingpan Spring, Sarten, and Rattlesnake Ridge members. Biostratigraphic data support the following age assignments: Late Jurassic-upper conglomerate member of Broken Jug Formation; late Aptian-Carbonate Hill Member of U-Bar Formation; early Albian-Old Hachita Member of U-Bar Formation; middle Albian-Howells Ridge Member of U-Bar Formation; late Albian–middle? Cenomanian-Mojado Formation. There are substantial unconformities at the Stone Cabin-Winkler Ranch, Carbonate Hill-Old Hachita, and the U-Bar-Mojado contacts. The unusually thick, complete Bisbee Group section in the southern part of the Little Hatchet Mountains was deposited near the thick keel of a rift basin that formed in Late Jurassic time. This section provides an important link between marine Jurassic rocks in the Chiricahua Mountains of southeastern Arizona and the Chihuahua trough in northern Mexico. Thickness changes in the U-Bar Formation record differential subsidence in the Bisbee rift basin.

INTRODUCTION

The Little Hatchet Mountains contain the thickest and most complete section of the Bisbee Group (Late Jurassic–early Late Cretaceous) exposed in southwestern New Mexico (Fig. 1). Although the section is thermally metamorphosed, it is possible to establish an essentially continuous section between subjacent Paleozoic rocks and suprajacent Laramide deposits. Darton (1922) first identified Lower Cretaceous strata in the Little Hatchet Mountains of southwestern New Mexico. In the ensuing 75 yrs, intermittent studies gradually defined the stratigraphy and age of these strata, and divided a section more than 3 km thick into the Broken Jug, Hell-to-Finish, U-Bar and Mojado formations of the Bisbee Group of Late Jurassic–early Late Cretaceous age. Here, we synthesize various aspects of these studies, and our own previously unpublished work, to present a comprehensive account of Bisbee Group lithostratigraphy, biostratigraphy, and correlation in the Little Hatchet Mountains.

PREVIOUS STUDIES

As Lasky (1947, p. 3-4) noted, early workers before Darton (e.g., Lindgren et al., 1910) suspected that some of the sedimentary rocks exposed in the Little Hatchet Mountains are of Cretaceous age. Darton

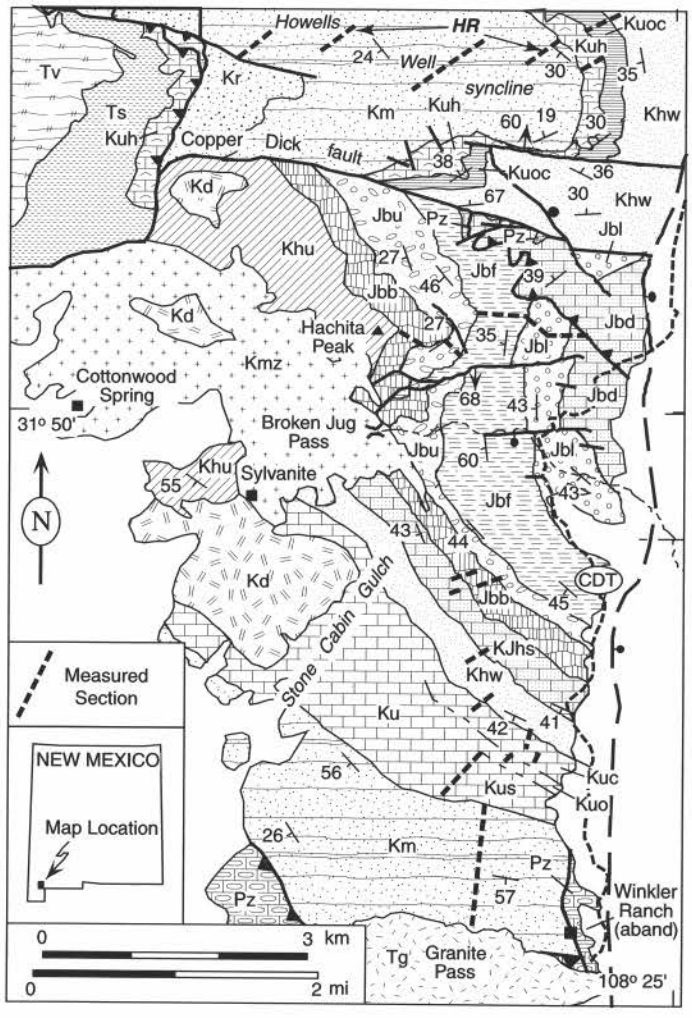


FIGURE 1. Geologic map of central and southern Little Hatchet Mountains showing locations of measured sections (thick dashed line segments) described in this article. **Pz**, undifferentiated Paleozoic strata. Bisbee Group: Broken Jug Formation-**Jbd**, dolostone member; **Jbl**, lower conglomerate member; **Jbf**, fine-grained member; **Jbu**, upper conglomerate member; **Jbb**, basalt member; Hell-to-Finish Formation-**Khu**, undifferentiated Hell-to-Finish Formation; **KJhs**, Stone Cabin Gulch Member; **Khw**, Winkler Ranch Member; U-Bar Formation-**Ku**, undifferentiated U-Bar Formation; **Kuc**, Carbonate Hill Member; **Kuo**, Old Hachita Member; **Kuoc**, Carbonate Hill and Old Hachita members, undifferentiated; **Kuh**, Howells Ridge Member; **Km**, Mojado Formation. **Kr**, Ringbone Formation; **Kmz** and **Kd**, cogenetic monzonite and diorite plutons generalized from Zeller (1970) and Channell et al. (this volume); **Ts**, Skunk Ranch Formation; **Tg**, Tertiary granite; **Tv**, Tertiary volcanic rocks. Adapted from Zeller (1970) and Lawton and Harrigan (1998). Short dashed line on east side of range is Continental Divide Trail (CDT).

AGE	Darton (1928a, b)	Lasky (1938, 1947)	Zeller (1970)	Lucas & Estep (1998b)	This paper
LATE CRETACEOUS		Skunk Ranch Conglomerate	Ringbone Formation	Ringbone Formation	Ringbone Formation
		Playas Peak Formation			
EARLY CRETACEOUS	Sarten Sandstone	Corbett Sandstone	Mojado Formation	Mojado Formation: Rattlesnake Ridge Member / Sarten Member / Fryingpan Spring Member	Mojado Formation: Rattlesnake Ridge Member / Sarten Member / Fryingpan Spring Member
	Comanche limestone	Howells Ridge Formation	U-Bar Formation	U-Bar Formation: Howells Ridge Member / Old Hachita Member / Carbonate Hill Member	U-Bar Formation: Howells Ridge Mbr/ Still Ridge Mbr / Old Hachita Member / Carbonate Hill Member
		Hidalgo Volcanics			
		Ringbone Shale	Hell-to-Finish Formation	Hell-to-Finish Formation	Hell-to-Finish Formation: Winkler Ranch Member / Stone Cabin Gulch Member
LATE JURASSIC		Broken Jug Limestone	unnamed Cretaceous? beds		Broken Jug Formation

FIGURE 2. Nomenclature of Bisbee Group strata in the Little Hatchet Mountains used by previous workers compared to the nomenclature advocated here.

(1922, 1928a, b) first collected Lower Cretaceous fossils in the Little Hatchet Mountains, and he observed that "the limestones in the Hatchet Mountain region closely resemble the Mural limestone of the Bisbee and Douglas region, Arizona, to which doubtless they are equivalent" (Darton, 1928b, p. 38). Darton (1928a, b) assigned sandstone-dominated strata above these limestones to the Sarten Sandstone, a Cretaceous unit he had earlier (Darton, 1916) named in the Cookes Range of Luna County (Fig. 2).

Lasky (1938) recognized that most of the sedimentary rocks exposed in the Little Hatchet Mountains are of Early Cretaceous (his "Trinity") age. Lasky (1938, 1947) assigned a total thickness of "17,000–21,000 ft" (5181–6400 m) to this section, and divided it into the (ascending) Broken Jug Limestone, Ringbone Shale, Hidalgo Volcanics, Howells Ridge Formation, Corbett Sandstone, Playas Peak Formation, and Skunk Ranch Conglomerate (Fig. 2). Fossils collected by Lasky (Scott, 1940) indicated age equivalence of part of this section to the Arizona Bisbee Group and to part of the Trinity Group of Texas, especially the Glen Rose Formation. Lasky's (1947) comprehensive publication on the geology of the Little Hatchet Mountains provided detailed descriptions of the Cretaceous rock units, listed their fossils and mapped their outcrop distribution.

Douglass (1960, p. 5, 11–12, fig. 13, pl. 17) described the large foraminiferan *Orbitolina* in the Little Hatchet Mountains from strata he termed Playas Peak Formation, Broken Jug Limestone, and Howells Ridge Formation. He noted (p. 5) that these units are "more or less contemporaneous" and might be one stratigraphic interval exposed on three different fault blocks. Significantly, Douglass' (1960, pl. 17) section 17 at Howells Ridge is the same as most of our section of the U-Bar Formation at Howells Ridge. Here, Douglass depicted a single, homoclinal section from the top of the Hell-to-Finish Formation (conglomerate at the base of his section) through the Carbonate Hill Member (shown by Douglass as ~70 m of limestone with abundant large mollusks), Old Hachita Member (~33 m of shale followed by ~30 m of *Orbitolina*-bearing limestone according to Douglass), and the Howells Ridge Member (~37 m of massive limestone in Douglass' section).

Zeller (1970), in a posthumously published report, re-evaluated the Lower Cretaceous stratigraphy in the Little Hatchet Mountains. Zeller's (1970) mapping differed substantially from that of Lasky, largely because Zeller concluded that Lasky had been misled by structural complexity and had thus failed to establish the proper succession of Cretaceous strata. Zeller (1970) assigned these strata to: (1) "unnamed Cretaceous? beds," about 457 m of marine limestone, dolomite, gypsum, and shale; (2) Hell-to-Finish Formation, approximately 1828 m of red shale, gray shale, red siltstone, limestone-cobble conglomerate, arkose and sandy (arkosic) limestone; (3) U-Bar Formation, about 1219 m of mostly marine limestone; and (4) Mojado Formation, mainly gray and tan quartz sandstone with shale interbeds with an estimated maximum thickness of 1524 m (Fig. 2). Zeller (1970) also concluded that the Ringbone Shale, Hidalgo Volcanics, Playas Peak Formation and Skunk Ranch Conglomerate of Lasky are post-Lower Cretaceous rocks. He assigned them to the Ringbone Formation (includes the Playas Peak and Skunk Ranch units) and the Hidalgo Volcanics of Late Cretaceous–Paleogene(?) age. Zeller (1970) noted that the five informal members of the U-Bar Formation that he recognized in the Big Hatchet Mountains (Zeller, 1965) are present in the Little Hatchet Mountains. Zeller also reported some "late Washita" (late Albian) molluscan taxa from the upper part of the Mojado Formation.

Hayes (1970, p. 30–32, figs. 5–6) also reinterpreted Lasky's (1938, 1947) stratigraphy, although somewhat differently than did Zeller. Hayes concluded that Lasky's Broken Jug Limestone, Playas Peak Formation and Howells Ridge Formation are the same stratigraphic unit, equivalent to the Hell-to-Finish and U-Bar formations of Zeller.

Hayes equated Lasky's Corbett Sandstone to Zeller's Mojado Formation. Hayes also concluded (as had Epis, 1956; and Richard and Courtright, 1960) that the Skunk Ranch Conglomerate-Ringbone Shale-Hidalgo Volcanics are Upper Cretaceous rocks.

Until recently, subsequent workers generally employed Zeller's (1970) stratigraphy of the Cretaceous strata in the Little Hatchet Mountains. Thus, in a regional review of Lower Cretaceous strata in southwestern New Mexico, Mack et al. (1986) employed the stratigraphy advocated by Zeller in the Little Hatchet Mountains (also see Clemons and Mack, 1988a, b; Mack, 1987a, b; Mack et al., 1988). Galemore (1986) presented detailed stratigraphic data and an analysis of sedimentation of the Mojado Formation. Campbell (1988) undertook a detailed study of the rudistid reef in the U-Bar Formation that forms the crest of Howells Ridge. Besides providing a comprehensive description of that reef, Campbell proposed (but did not publish) the following nomenclature for the members of the U-Bar Formation: Broken Jug Member (= brown limestone member of Zeller, 1965), Playas Peak Member (= oyster-limestone member of Zeller), Skunk Ranch Member (= limestone-shale member of Zeller) and Howells Ridge Member (= reef and suprareef members of Zeller). Campbell also suggested that the name Hatchita (sic) Formation be applied to the strata Zeller (1970) had termed "unnamed Cretaceous? beds."

Fieldwork during the late 1980s and early 1990s clarified the stratigraphy and age of strata in the Little Hatchet Mountains that Zeller (1970) had assigned to the Ringbone Formation and Hidalgo Volcanics. This work supported Zeller's conclusion that the Ringbone and Playas Peak formations of Lasky are one lithostratigraphic unit; dinosaur fossils and radioisotopic ages indicate this unit is of Late Cretaceous (Campanian) age (Lucas et al., 1990; Basabilvazo, 1991; Lawton et al., 1993; Anderson et al., 1998). Lawton et al. (1993) concluded that the Skunk Ranch Formation is a separate unit, of probable Paleogene age.

Harrigan (1995) restudied the rocks around Hachita Peak that Zeller (1970) had termed "unnamed Cretaceous? beds." Lawton and Harrigan (1998) published the results of this work, assigning these strata to a redefined Broken Jug Formation that consists of five informal members. Lucas et al. (1996) proposed a different interpretation, suggesting that part of this section is Permian and that part of it be assigned to the Hell-to-Finish Formation as a new member. As is clear below, the interpretation of Lucas et al. (1996) is rejected here in favor of that of Lawton and Harrigan (1998).

Lucas and Estep (1998b) revised the nomenclature and correlation of Bisbee Group strata in southwestern New Mexico (Fig. 2). In the Little Hatchet Mountains, they named the Old Hachita Member of the U-Bar Formation for strata Zeller (1965, 1970) had termed the limestone-shale member. Most recently, Lucas (2000a) re-evaluated the ammonites from the Old Hachita Member collected by Lasky and described by Scott (1940).

LITHOSTRATIGRAPHY

Introduction

Upper Jurassic and Lower Cretaceous strata exposed in the Little Hatchet Mountains are assigned to the Bisbee Group, a term originally applied to equivalent rocks in southeastern Arizona (Ransome, 1904) and also used widely in northern Mexico (Lucas and Estep, 1998b). In the Little Hatchet Mountains, the Bisbee Group consists of the (ascending) Broken Jug, Hell-to-Finish, U-Bar and Mojado formations (Fig. 2). Here, we describe the lithostratigraphy of these units based on measured sections in the Little Hatchet Mountains (Fig. 1).

Broken Jug Formation

The Broken Jug Formation is exposed only within the Hachita Peak quadrangle, where an essentially complete section is present on the eastern and southeastern flanks of Hachita Peak (Figs. 1, 3). An incomplete section is also exposed east of the range crest south of Broken Jug Pass, where the strata are stratigraphically contiguous with Lower Cretaceous rocks of our Winkler Ranch section. It is absent in the subsurface north of the Little Hatchet Mountains (Lawton and Clemons, 1992). Although the location of the pinch-out is unknown, we speculate that the present Copper Dick fault may coincide with the northern edge of the Broken Jug Formation. The informal members described here are those of Lawton and Harrigan (1998). In ascending order, they are the dolostone; lower conglomerate; fine-grained, upper conglomerate; and basalt members.

Dolostone member

The dolostone member consists of tan-weathering, fine-grained, sandy dolostone and dolomitic quartzarenite. It is tan on fresh surfaces. Beds are thin, ranging from 1 to 60 cm thick, and are laterally continuous on a scale of tens to hundreds of meters. Thin beds contain horizontal lamination, ripple cross-lamination and oscillation ripples with uncommon burrows (Fig. 4A). Thicker beds contain hummocky cross stratification, commonly with angular granules and pebbles of white and gray chert. Convolute lamination is locally present. The uppermost bed of the dolostone member is a tan–white-weathering bed, 0.5–2 m thick, of fine-grained carbonate litharenite. The sandstone consists of about 80% carbonate grains and 20% monocrystalline quartz grains.

On the eastern flank of Hachita Peak, the dolostone member is 140 m thick (Harrigan, 1995), but the base of the member is not exposed there. Map estimates indicate that it may be as much as 360 m thick (Lawton and Harrigan, 1998). It overlies Paleozoic strata on a sharp, unconformable contact overlain by a thin chert-clast breccia. Beds above the contact consist of white-weathering carbonate litharenite with 10–20% angular pebbles and granules of chert. The litharenite overlies thick-bedded crinoidal grainstone with large oblate, light-gray chert nodules interpreted as Escabrosa Limestone (Mississippian) or Horquilla Limestone (Pennsylvanian). The upper contact of the dolostone member is sharp and concordant. The dolostone member was deposited in a shallow-marine shelfal setting. Abundant evidence for wave deposition exists, and although unfossiliferous, the member contains uncommon burrows.

Lower conglomerate member

The lower conglomerate member consists of medium-gray, fine–medium-grained carbonate litharenite interbedded with brownish-gray calcareous mudstone and limestone- pebble-to-cobble conglomerate. Sandstone dominates the lower 55 m of the member and consists of 20–30-cm tabular beds with sharp bases and tops gradational into overlying mudstone beds. Sandstone beds locally contain Bouma sequences (Harrigan, 1995); they are commonly graded and contain horizontal lamination overlain by small current ripples that indicate sediment transport to the southeast. Flame structures are present at the bases of beds, and rounded pebbles of micrite as much as 5 cm in diameter are uncommon in the lower parts of beds. The sandstone consists of 60–70% rounded detrital carbonate grains, including micrite and sparry calcite, and 20–40% monocrystalline quartz grains. Argillaceous limestone–calcareous mudstone interbedded with the sandstone beds contains recumbent, isoclinally folded laminae, convolute laminae, rolled up laminae and scattered chert clasts (Fig. 4B).

Conglomerate is a conspicuous lithic type beginning 55 m above the base of the member. Conglomerate beds are 0.5–1 m thick, with matrix- to clast-supported textures Figs. 4C, D). Matrix consists of sandy calcareous mudstone and carbonate litharenite. Inverse grading is locally present in the lower few cm of the beds. Conglomerate grades upward through beds of carbonate litharenite as much as 20 cm thick into rippled calcareous siltstone that is very dark gray–black but weathers olive gray. Clasts in the conglomerate are rounded and generally less than 20 cm in maximum diameter, but range up to 40 cm in diameter. The clast population consists of 70–80% limestone and dolostone, 0–8% siltstone, 15–20% chert, and a trace of quartzarenite (Harrigan, 1995). Limestone clasts contain abundant fossils that indicate derivation from Paleozoic formations as young as Early Permian. Also present are irregular intraclasts of carbonate litharenite and calcareous siltstone as much as 25 cm long, with plastic-deformation features such as isoclinal folds and convolute laminae (Fig. 4E).

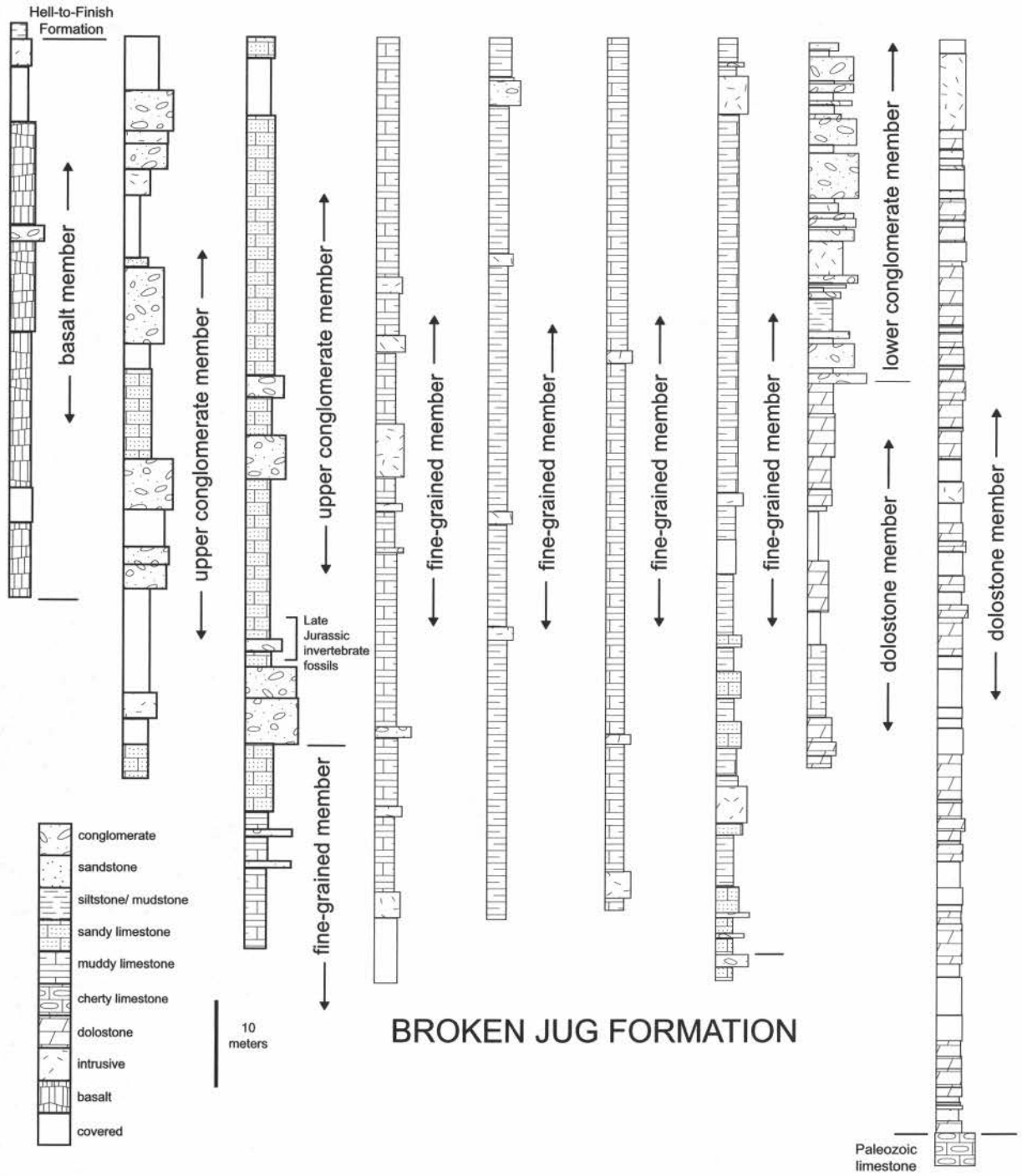


FIGURE 3. Measured stratigraphic section of the Broken Jug Formation in secs. 25–26, T28S, R16W (after Harrigan, 1995).

The lower conglomerate member is as much as 200 m thick. Its sharp basal contact lies at a conspicuous color change from tan to medium gray coincident with a thickening of individual beds. The upper contact is gradational with the overlying fine-grained member and is picked at the first point in the section where dark gray, almost graphitic, calcareous siltstone is an important component of the section. The base of the member is about 55 m down-section of the base of Zellers' (1970) Hell-to-Finish Formation, which he picked at the base of the first conspicuous conglomerate in the section. Adjacent to the Copper Dick fault, in the SW¼ sec. 23, T28S, R16W, conglomerate of this member is depositional on limestone with large silicified fusulinids interbedded with limestone-clast conglomerate interpreted as Virgilian and lower Wolfcampian beds of the Horquilla Limestone (Lawton and Harrigan, 1998). This observation indicates that locally the lower conglomerate member forms the base of the Broken Jug Formation. The lower conglomerate member was deposited by subaqueous sediment-gravity flows, including debris flows and turbidity currents, indicated by the matrix-supported textures, local inverse clast grading, and slump structures. The lower conglomerate member therefore represents abrupt deepening relative to the underlying dolostone member.

Fine-grained member

The fine-grained member consists of gray- and tan-weathering carbonate litharenite, siltstone and mudstone. The lower half of the member is dominantly dark gray calcareous mudstone and siltstone in massive to thinly laminated beds. Laminated beds contain common recum-

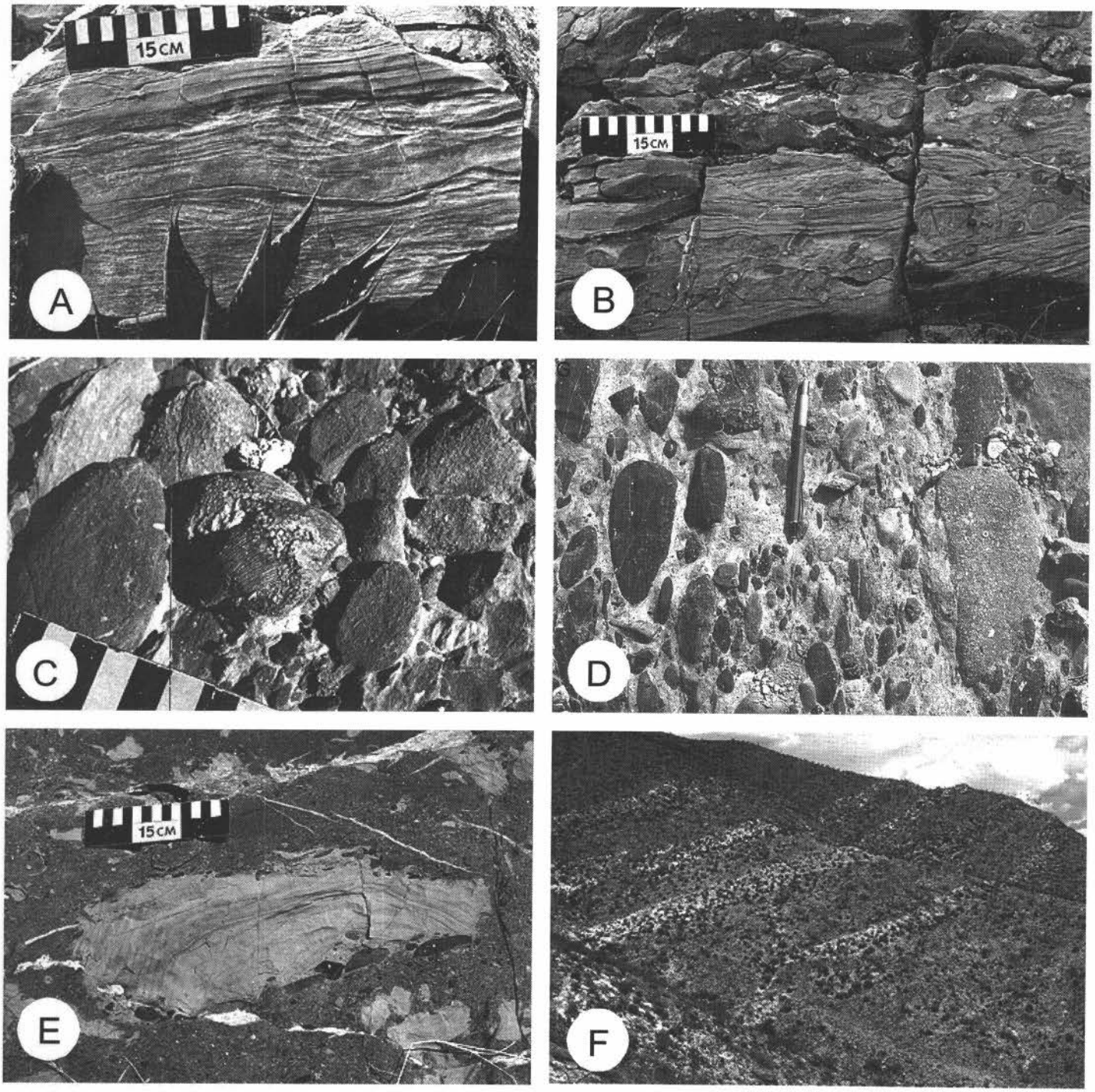


FIGURE 4. Photographs of selected outcrops of the Broken Jug Formation. **A**, Wave ripple cross-lamination and hummocky cross-stratification in fine-grained sandstone, dolostone member of Broken Jug Formation. **B**, Matrix-supported conglomerate and rolled-up laminated mudstone bed, upper part of lower conglomerate member of Broken Jug Formation. **C**, Clast-supported conglomerate, including silicified Productid brachiopod clast, lower conglomerate member of Broken Jug Formation. **D**, Matrix-supported conglomerate, lower conglomerate member of Broken Jug Formation. Clast alignment may have resulted from ductile deformation of rock. Pencil is 15 cm long. **E**, Armored intraclast of calcareous siltstone with deformed laminae in matrix-supported granule-pebble conglomerate, lower conglomerate member of Broken Jug Formation. **F**, Upper conglomerate member of Broken Jug formation, east flank of Hachita Peak (view north). White beds are conglomerate, gray beds are sandstone and siltstone. Basalt member forms uppermost dark gray slope in upper left of photograph.

bent isoclinal, intrastratal folds. Locally siltstone beds are rolled and compacted to form elliptical roll-up structures that are several centimeters to as much as a meter in thickness. Uncommon, thin beds of matrix-supported, chert- and limestone-clast conglomerate are present in the siltstone. The upper half of the member consists of tabular beds of tan-weathering, fine–medium-grained carbonate litharenite with siltstone- and mudstone-filled burrows. Oscillation ripples in beds with abundant quartz sand grains are present but uncommon in the upper part. Beds are 20–40 cm thick and alternate with gray weathering calcareous siltstone.

The fine-grained member is 367 m thick on the east flank of Hachita Peak (Lawton and Harrigan, 1998). It rests gradationally upon the lower conglomerate member. The upper contact is sharp and overlain by a 6-m-thick bed of white-weathering, limestone- and chert-clast conglomerate. The member was deposited in a delta-front setting characterized by

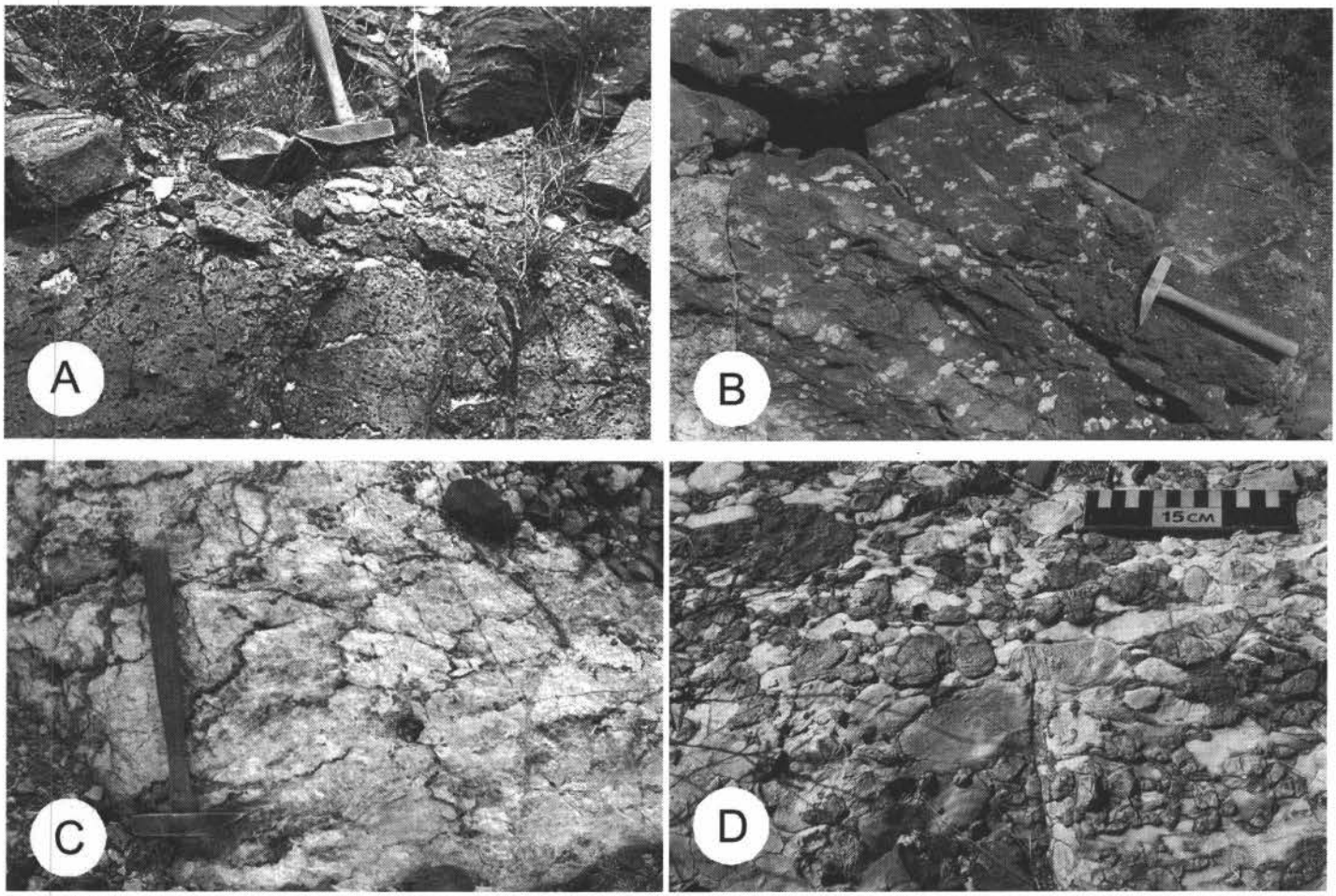


FIGURE 5. Photographs of selected outcrops of Broken Jug and Hell-to-Finish formations. **A**, Vesicular basalt flow top overlain by calcareous siltstone with ripple cross-lamination (at hammer head) basalt member of Broken Jug Formation. **B**, Pedogenic calcite nodules in brown siltstone, lower part of Winkler Ranch Member of Hell-to-Finish Formation. **C**, "Enterolithic' marble, upper part of Winkler Ranch Member of Hell-to-Finish Formation. Thin dark selvages are mud-rich carbonate. Hammer handle is 35 cm long. **D**, Clast-supported pebble conglomerate of chert (medium-gray high relief) and limestone (light gray and medium-gray low relief) clasts, of Winkler Ranch Member of Hell-to-Finish Formation.

slumping and intermittent sediment-gravity flows.

Upper conglomerate member

The upper conglomerate member consists of thick, medium-gray to white-weathering beds of clast-supported conglomerate. Beds are tabular, 3–24 m thick, with sharp planar tops and bases, and laterally continuous (Fig. 4F). The conglomerate locally lacks visible internal stratification, elsewhere consists of tabular to upward-convex beds 1–1.5 m thick. Pebbles are rounded, range in size from 1–25 cm, with a dominant size of about 6–10 cm. The overall clast population consists of about 80% fossiliferous limestone with fusulinids and crinoids, 10–20% gray and white chert, commonly with replaced crinoids, and a few percent of tan quartzarenite to quartzite. The matrix of the conglomerate is typically medium–coarse-grained carbonate litharenite with abundant chert grains. Conglomerate composes 40% of the member.

Conglomerate is interbedded with intervals of very fine–medium-grained, tan-weathering quartzarenite and gray carbonate litharenite. The sandstone beds are 6–20 cm thick; bedding is defined by alternating intervals of mottled, bioturbated sandstone and beds that preserve wispy horizontal laminae, oscillation ripples, trough cross-beds, and hummocky cross-stratification. Fragments of black pelecypods are present in the sandstone. Sandstone and conglomerate beds form upward-coarsening successions 10–36 m thick.

The upper conglomerate member is 200 m thick. It is sharp but conformable upon the fine-grained member and is sharply overlain by the lowermost lava flow of the basalt member. It was deposited by braid deltas or alluvial-fan deltas in which both gravel and sand beds were locally reworked by waves. Sparse marine fossils in the interbedded sandstone intervals indicate proximity of gravel deposition to a marine setting.

Basalt member

The basalt member consists of two intervals of gray-weathering vesicular basalt flows separated by an interval of sedimentary rocks. Flows are 1–30 m thick. Flow tops are vesicular and overlain by either a succeeding flow or sedimentary rocks (Fig. 5A). Chemical analysis of the flows indicates that they are alkali basalts with high TiO_2, high MgO, and trace-element chemistry similar to that of ocean-island basalt (Harrigan, 1995).

Olive-gray–tan-weathering quartzose sandstone and white carbonate litharenite, siltstone and conglomerate are interbedded with the basalt flows to form non-volcanic intervals ranging from less than a meter thick to a middle interval 65 m thick in which basalt is absent. The conglomerate contains uncommon clasts of vesicular basalt

The basalt member is 234 m thick on the southeastern flank of Hachita Peak (Lawton and Harrigan, 1998) and 288 m thick on the ridge south of Broken Jug Pass. Basalt flows are thin in the upper 50 m of the member and are difficult to recognize as a result of pervasive contact metamorphism. These observations may explain the disparity in thickness at two localities only 4 km apart. The base of the member is the base of the lowermost basalt flow, which rests abruptly on fine–medium-grained sandstone with trough cross-beds. The top of the member is defined as the top of the uppermost basalt flow, which is overlain by light brown, mottled calcareous siltstone of the Hell-to-Finish Formation. The map

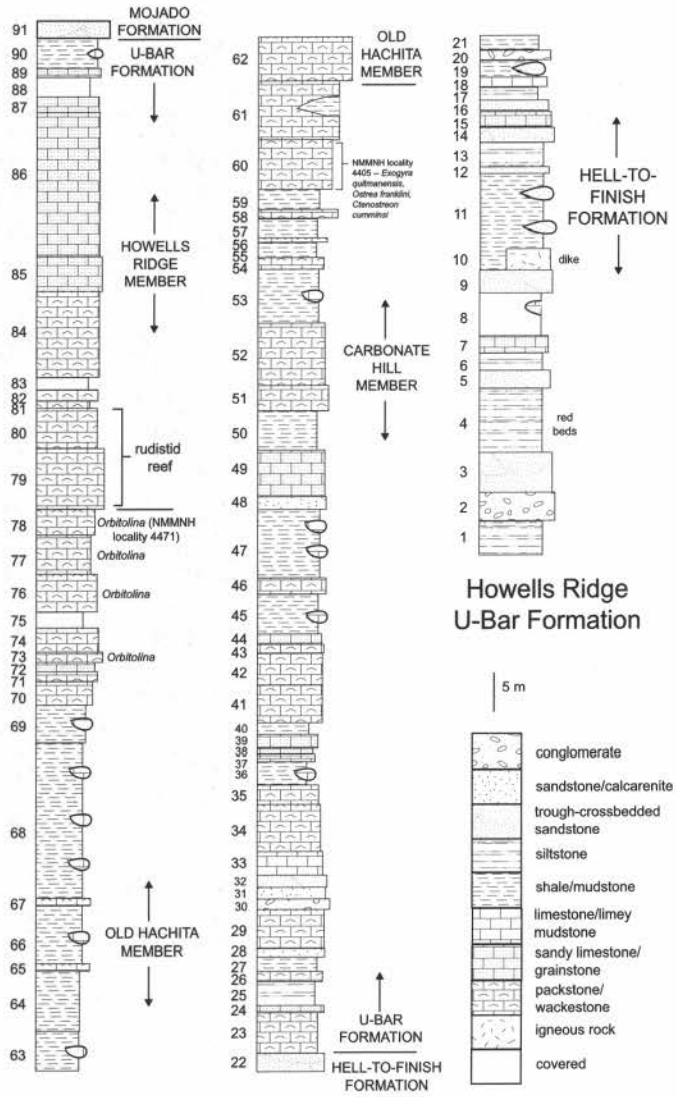


FIGURE 6. Measured stratigraphic section of the Hell-to-Finsh and U-Bar formations at Howells Ridge. Section measured in the S½ sec. 13, T28S, R16W.

distribution of this member corresponds reasonably well to that of a diorite sill mapped by Zeller (1970). The basalt member was deposited as sub-aerial lava flows, represented by the basalt, and as braided-fluvial deposits, represented by graded conglomerate-sandstone intervals.

Hell-to-Finish Formation

We divide the Hell-to-Finish into two newly named members where it is exposed in the southern part of the Little Hatchet Mountains. In ascending order, these are the Stone Cabin Gulch and Winkler Ranch members. The Hell-to-Finish Formation also crops out at Howells Ridge beneath the U-Bar Formation, but the base of the formation is not exposed (Zeller, 1970; Mack et al., 1986). At Howells Ridge, only the upper part of the Winkler Ranch Member is exposed (Fig. 6). The Hell-to-Finish Formation is 525 m thick at our measured section at Winkler Ranch (Fig. 7).

Stone Cabin Gulch Member

We name the lower member of the Hell-to-Finish Formation in the Little Hatchet Mountains the Stone Cabin Gulch Member after the arroyo of that name near the type section (Figs. 1, 7). The Stone Cabin Gulch Member consists of brown-weathering, fine–medium-grained sandstone in tabular bedsets 2.5–5 m thick interbedded with gray-weathering, mottled limestone as much as 10 m thick. The limestone contains small, cuspate, black calcite inclusions that are probably shell fragments. Thin beds of chert-pebble conglomerate are locally present at the bases or tops of sandstone intervals. Sandstone beds locally have planar foresets 5–20 cm thick that alternate with mottled horizons interpreted to be bioturbated. Sandstone bedsets commonly coarsen upward, but fining-upward sandstone intervals are also present. The upper part of the member contains two thick, conspicuous beds of white–tan marble 9–12 m thick. They are nodular, consisting of irregular tracts of pure marble separated by thin, gray, mud-rich selvages; the texture is similar to enterolithic anhydrite textures found in sabkha evaporites (Kendall, 1984). X-ray diffraction analysis indicates that the rock is composed of dolomite with a trace of barite (Nancy McMillan, personal commun., 2000), which probably represents replacement of former evaporites. The upper interval of marble, which forms the upper bed of the member, contains a platy bed of light-green air-fall tuff.

The Stone Cabin Gulch Member is 200 m thick at its type locality in the NE¼ sec. 2, T29S, R16W. It is best exposed on the nearby ridge crest in the SW¼ and the SE¼ of section 2. Its basal contact is gradational with the basalt member and lies above the uppermost basalt flow. Its upper contact is sharp, probably unconformable, and underlies a conspicuous, white-weathering chert- and limestone-clast conglomerate at the base of the Winkler Ranch Member of the Hell-to-Finish Formation. The Stone Cabin Gulch Member was deposited in shallow-marine to marginal-marine environments, the latter a supratidal sabkha represented by the dolomitic marble beds, which are interpreted as replaced evaporite horizons.

Winkler Ranch Member

We name the upper member of the Hell-to-Finish Formation in the Little Hatchet Mountains the Winkler Ranch Member after the abandoned homestead of that ranch near the type section (Figs. 1, 7). The lower 200 m of the Winkler Ranch Member consists of dominant reddish-brown siltstone with discrete, cm-scale calcite nodules (Fig. 5B). The nodules locally coalesce to form calcite-rich intervals as much as 10 m thick. Thin walls of very fine-grained sandstone and siltstone are conspicuous between the coalesced nodules. Interbedded with the siltstone are beds of conglomerate 2–3 m thick that grade up-section into fine–medium-grained sandstone with trough cross-beds, horizontal lamination and current ripple cross-lamination. These upward-fining intervals are 2–4 m thick and are broadly lenticular in outcrop. The lower part of the member was deposited in a braided-river environment, with the lenticular conglomerate-sandstone beds representing broad channels and the nodular siltstones representing subaerial overbank deposits with pedogenic nodules (Mack et al., 1986).

The upper 125 m of the Winkler Ranch Member consists of striking, white-weathering enterolithic marble (Fig. 5C), similar to that at the top of the Stone Cabin Gulch Member, in beds 4–8 m thick that are interbedded with conglomerate and fine–coarse-grained quartzose sandstone. The conglomerate beds are 2–3 m thick, clast-supported and contain well-rounded, well-sorted clasts of chert and limestone as much as 30 cm in diameter (Fig. 5D). Sandstone beds contain current ripple cross-lamination, possible symmetrical ripple cross-lamination and hummocky cross-stratification. Possible shell fragments are locally present. This upper interval was deposited in sabkha and coarse-grained marginal marine environments, possibly wave-reworked braid deltas.

The Winkler Ranch Member is 325 m thick in our measured section at Winkler Ranch. The basal contact with the Stone Cabin Gulch Member is sharp and likely unconformable. The type section is in the SW¼ sec. 2, T29S, R16W. Only the lower interval of the Winkler Ranch Member resembles the Hell-to-Finish Formation described elsewhere in southwestern New Mexico (e.g., Zeller, 1965). The strong marine influence observed in the Stone Cabin Gulch Member and the upper interval of the Winkler Ranch Member is apparently unique to the rapidly subsiding keel of the Bisbee basin recorded in the southern part of the Little Hatchet Mountains.

U-Bar Formation

Two complete sections of the U-Bar Formation are exposed in the

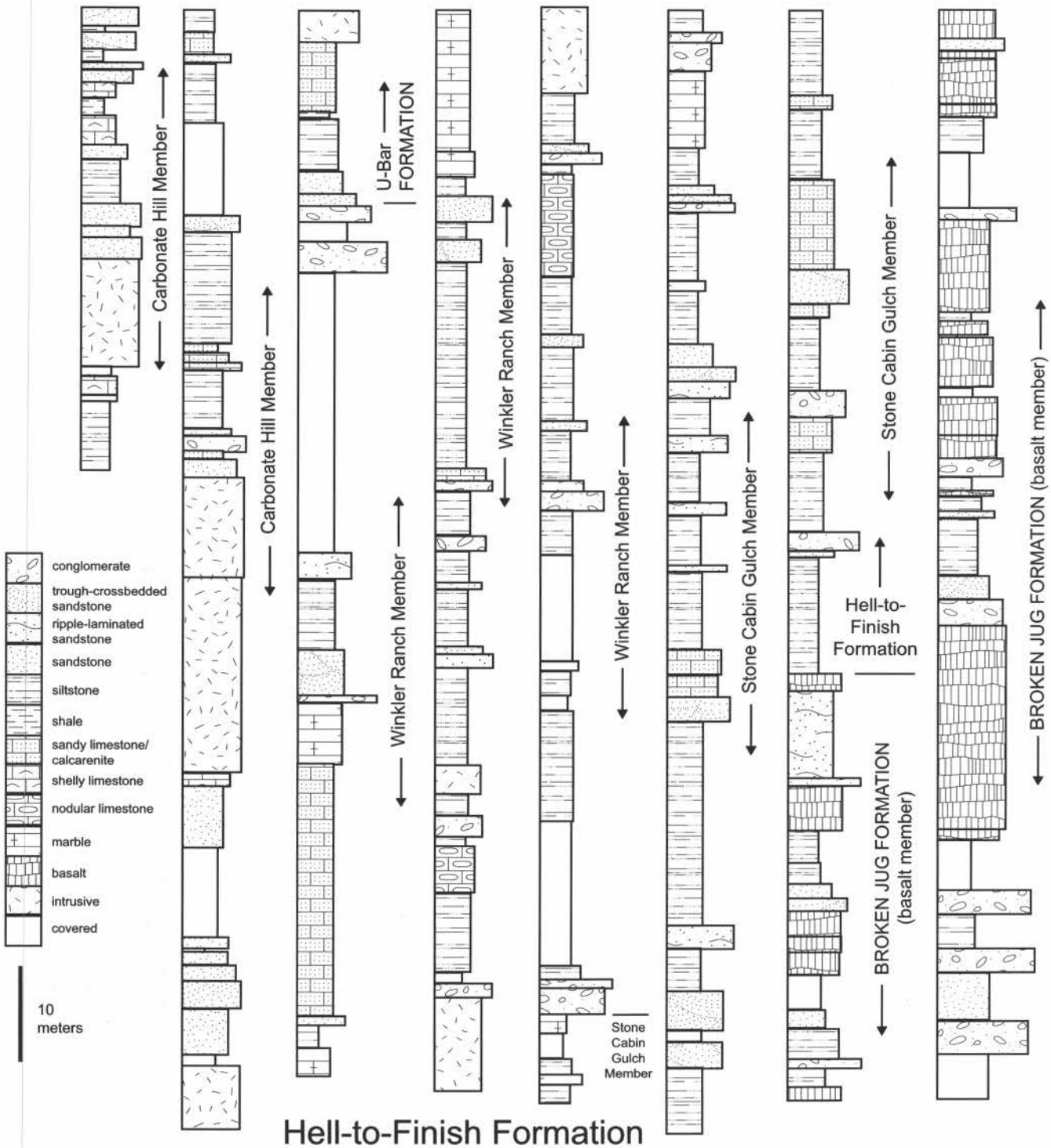


FIGURE 7. Measured stratigraphic section of the Hell-to-Finish Formation in sec. 2, T29S, R16W.

Little Hatchet Mountains: (1) near the southeastern edge of Howells Ridge (sec. 13, T28S, R16W), where the formation is 237 m thick and consists of the Carbonate Hill, Old Hachita, and Howells Ridge members (Fig. 6); (2) north of the abandoned Winkler Ranch homestead (sec. 11, T29S, R16W), where the U-Bar is 972 m thick and consists of the Carbonate Hill, Old Hachita and Still Ridge members (Fig. 8). At both locations, the U-Bar Formation conformably overlies the Hell-to-Finish Formation and is overlain by the Mojado Formation with evident disconformity. At other locations in the Little Hatchet Mountains, U-Bar Formation strata are either structurally disrupted and/or too metamorphosed to allow an accurate appraisal of their thickness, lithology and/or stratigraphic succession. However, in some places, important sections of all or part of one member are available and provide useful stratigraphic and/or biostratigraphic data. An example is the type section of the Old Hachita Member described by Lucas and Estep (1998b).

Along Howells Ridge there is some structural disruption of U-Bar Formation strata beneath the rudistid reef at the base of the Howells Ridge Member. Zeller (1970) mapped a thrust fault here, a concept endorsed by most subsequent workers (e.g., Campbell, 1988; Clemons and Mack, 1988b; Lucas and Estep, 1998b). However, Karlstrom et al. (1994) argued for a low-angle detachment fault to explain the disruption. Nevertheless, no thrust or detachment fault is present at the south-

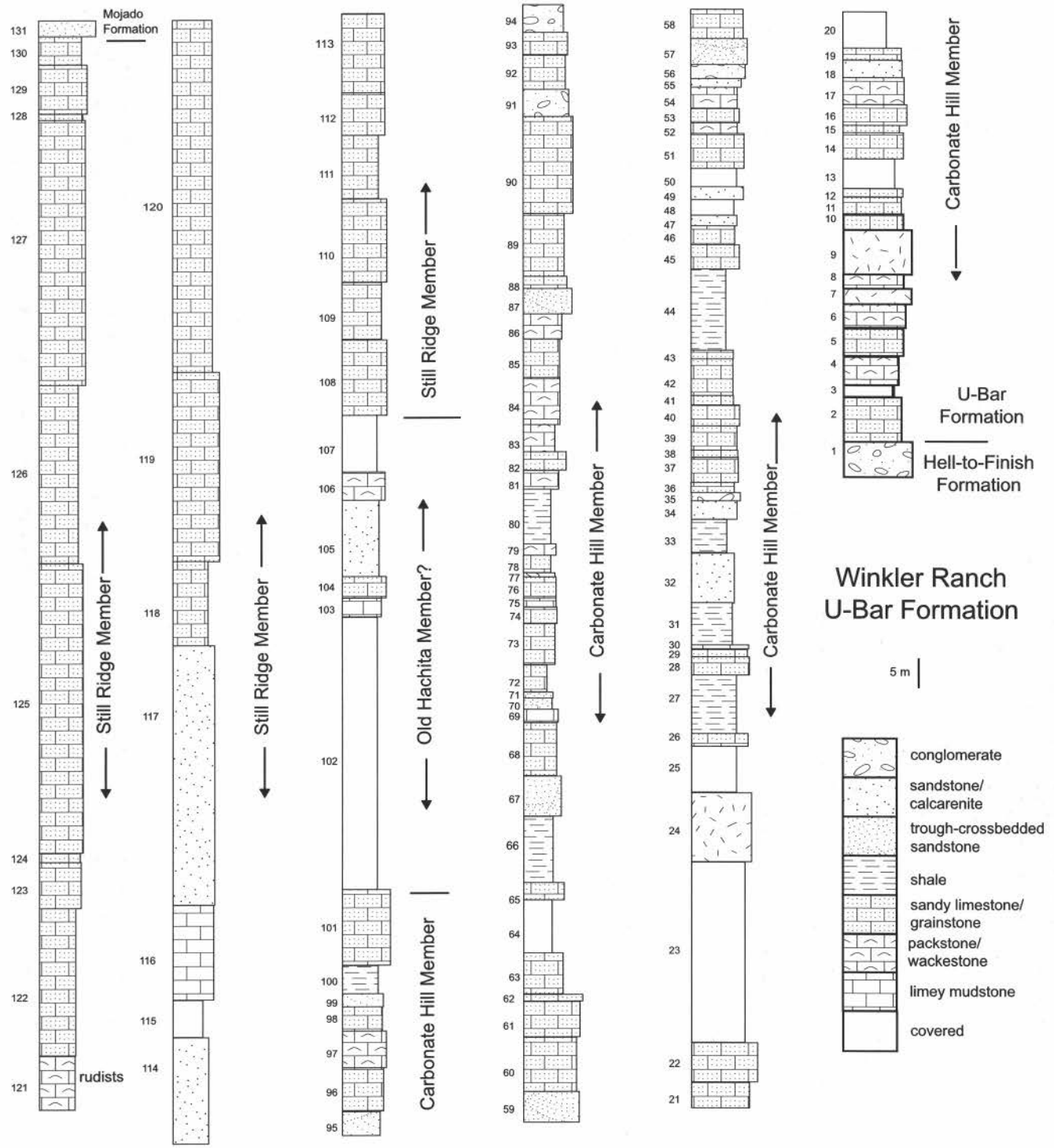


FIGURE 8. Measured stratigraphic section of the U-Bar Formation at Winkler Ranch. Section measured in sec. 11, T29S, R16W

eastern end of Howells Ridge (note especially that U-Bar strata are in correct stratigraphic order), where we measured a complete section of the U-Bar Formation (Figs. 6, 9A).

Carbonate Hill Member

The unit Zeller (1965, 1970) termed the oyster-limestone member of the U-Bar Formation in the Big Hatchet and Little Hatchet Mountains is the same unit Gillerman (1958) named the Carbonate Hill Limestone in the central Peloncillo Mountains. Therefore, Lucas and Estep (1998b) identified the Carbonate Hill Member as the basal interval of the U-Bar Formation across much of southwestern New Mexico.

In the Little Hatchet Mountains, the Carbonate Hill Member is 474 m thick at the Winkler Ranch section but only 112 m thick at the Howells Ridge section (Figs. 6, 8). At both sections, the contact of the Hell-to-Finish with the overlying U-Bar Formation (Carbonate Hill Member) is placed by us at the base of the first obviously marine (fossiliferous) limestone in a transitional interval between the two formations where limestone characteristic of the Carbonate Hill Member is interbedded with sandstone and shale characteristic of the Hell-to-Finish. This transitional interval is about 20 m thick. Limestone beds low in this interval are either nodular and unfossiliferous (probably of pedogenic origin) or

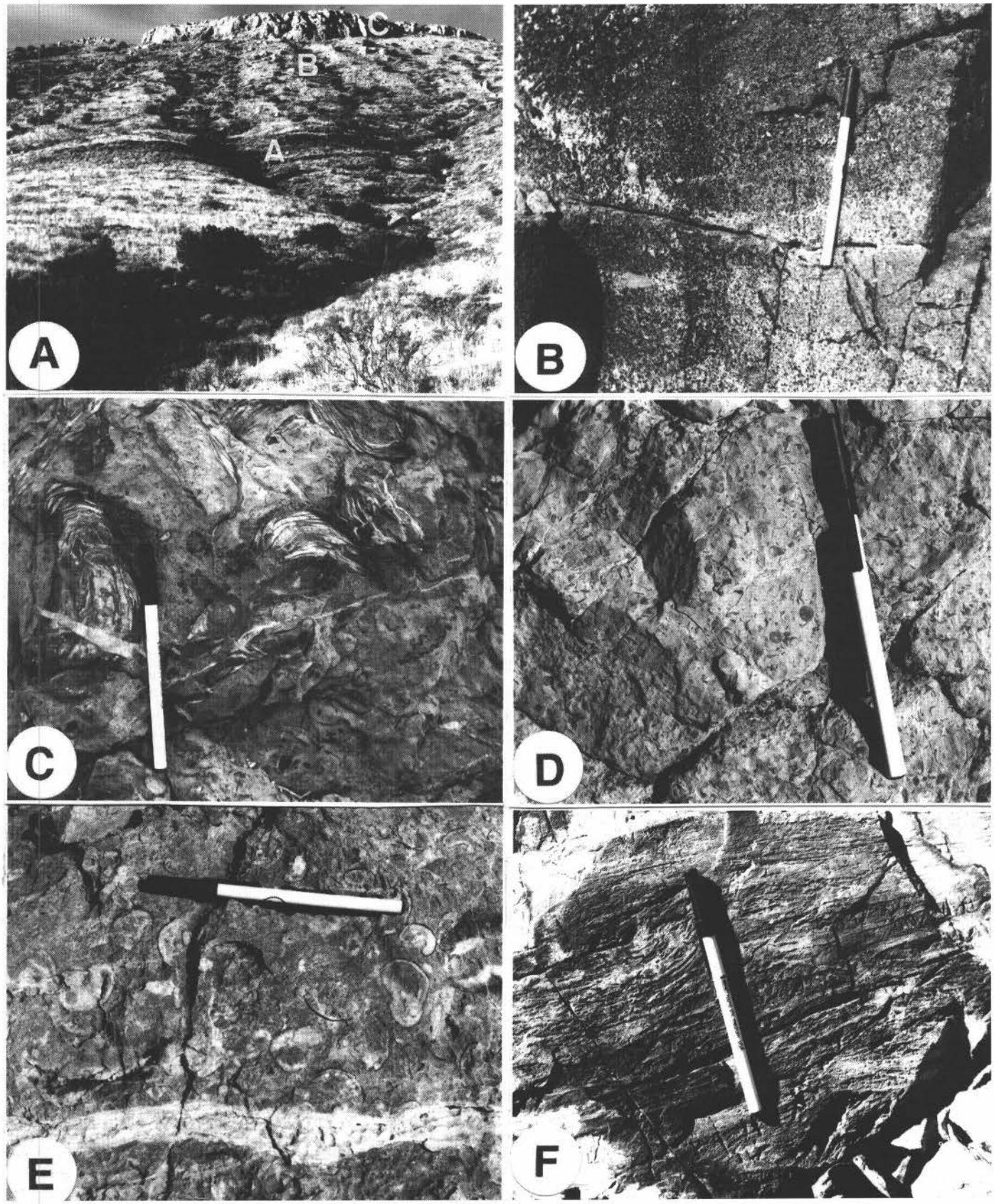


FIGURE 9. Photographs of selected outcrops of the U-Bar Formation. **A**, Overview of most of Howells Ridge section of the U-Bar Formation showing ledgy Carbonate Hill Member (A) overlain by slope-forming Old Hachita Member (B) capped by rudistid reef of Howells Ridge Member (C). **B**, Coarse sandstone in Carbonate Hill Member at Howells Ridge (unit 48 of measured section). **C**, *Ostrea* packstone in Carbonate Hill Member at Howells Ridge (unit 60 of measured section). **D**, *Orbitolina* packstone near top of Old Hachita Member at Howells Ridge (unit 78 of measured section). **E**, Caprinid rudists in limestone of the Howells Ridge Member at Howells Ridge (unit 80 of measured section). **F**, Typical grainstone of Still Ridge Member at Winkler Ranch (unit 110 of measured section).

have evident algal structures. We include these limestones in the Hell-to-Finish Formation. The lowest limestone bed we include in the Carbonate Hill Member has bivalve shells or bivalve shell debris.

Zeller (1970) stated that the lowest member of the U-Bar Formation in the Little Hatchet Mountains is the "brown limestone member." Lucas and Estep (1998b) formally named this unit the Big Tank Member of the U-Bar Formation and only recognized it in the Big Hatchet Mountains, where it is 118 m thick and dominantly interbedded micritic and oolitic, unfossiliferous limestone and siltstone. No stratigraphic interval at or near the base of the U-Bar Formation in the Little Hatchet Mountains closely resembles the Big Tank Member. Probably, strata of the lower part of the Carbonate Hill Member are correlative. Therefore, we do not recognize the Big Tank Member in the Little Hatchet Mountains, but instead assign the lower interval of the U-Bar Formation to the Carbonate Hill Member.

The Carbonate Hill Member is the most widely distributed member of the U-Bar Formation in southwestern New Mexico. It crops out in the Peloncillo, Animas, Big Hatchet, Little Hatchet, Sierra Rica, Victorio, and East Potrillo Mountains (Gillerman, 1958; Zeller, 1965, 1970; Zeller and Alper, 1965; Lucas and Estep, 1998b, 2000b; Lucas et al., 2000a, b). In the Little Hatchet Mountains, as at all of its outcrops, the most characteristic lithotype is thickly bedded of packstone dominated by shells of *Exogyra*, *Ostrea* and *Ceratostreon*, turritellid gastropods and lesser numbers of trigoniid and other bivalves, serpulid worm tubes and rare ammonites (Fig. 9C). At the Howells Ridge section, such packstones are 25% of the measured section, and at Winkler Ranch they are about 9% of the section.

Most other limestone beds in the Carbonate Hill Member are grainstones. They are about 20% of the Howells Ridge section, and they are 44% of the Winkler Ranch section. The other prominent lithotype is shale—37% of the Howells Ridge section and 21% of the Winkler Ranch section. Sandstone (Fig. 9B), including calcarenite, is about 13–14% of both sections, and conglomerate is only a minor lithotype (1–3%). Typically, beds are medium gray or olive gray in color.

The Carbonate Hill Member thus is a ledgy, slope former of coarse limestone beds characterized by abundant fossils of large bivalves. Its base is the base of the U-Bar Formation, as discussed above. The base of the overlying Old Hachita Member of the U-Bar Formation is a thin bed of coarse limestone full of shell debris followed by an olive-gray shale slope.

Old Hachita Member

Lucas and Estep (1998b) named Zeller's limestone-shale member of the U-Bar Formation the Old Hachita Member, with its type section near Old Hachita in the Little Hatchet Mountains (NE¼ SE¼ sec. 12, T28S, R16W). The Old Hachita Member of the U-Bar Formation is exposed only in the Big Hatchet and Little Hatchet Mountains.

At the Howells Ridge section, the Old Hachita Member is 69 m thick and mostly shale (65% of the section) and lesser amounts of limestone (35% of the section). Here, the Old Hachita Member can be divided into two intervals: (1) lower 44 m of light olive-gray shale with some thin ledges of bioclastic limestone and some limestone concretions; and (2) upper 25 m dominated by medium-gray *Orbitolina* packstones (Fig. 9D). The type section of the Old Hachita Member, about 2 km northeast of the Howells Ridge section, is at least 113 m thick (its top is not exposed) and also can be divided into a lower shaly interval and an upper interval dominated by *Orbitolina* packstones (Lucas and Estep, 1998b, fig. 7). The Old Hachita Member is thus a slope forming unit dominated by shale above the highest bivalve packstone of the Carbonate Hill Member and below the lowest rudistid limestone of the Howells Ridge Member.

Identification of the Old Hachita Member in the Winkler Ranch section (Fig. 8) is not completely certain. At this section, a mostly covered slope forms a persistent interval about 83 m thick between strata of the Carbonate Hill and Still Ridge members. We assign this interval to the Old Hachita Member, but in the absence of extensive outcrop, the assignment is not a definite one.

Howells Ridge Member

Lucas and Estep (1998) used the name Howells Ridge Member (following the suggestion of Campbell, 1988) to refer to Zeller's (1965) reef and suprareef members of the U-Bar Formation. The Howells Ridge Member crops out in the Animas, Big Hatchet, Little Hatchet and Sierra Rica Mountains.

The Howells Ridge Member is the rudistid reef and related reef margin facies that defind the crest of Howells Ridge in the Little Hatchet Mountains. Here, the member is about 57 m thick, but the reef core of light gray coral/rudistid boundstones, packstones and bafflestones is only about 10–15 m of this thickness (Figs. 6, 9A, E). The remainder of the unit is mostly interbedded ledges of gray oolitic packstones, wackestones and grainstones and slopes of shale.

Campbell (1988) provided a detailed description of the Howells Ridge Member in the Little Hatchet Mountains. The reef is a massive, cliff-forming limestone with no discernable bedding that is locally highly recrystallized. The associated strata are backreef lagoonal lithofacies that either directly overlie or are laterally equivalent to the reef.

Still Ridge Member

Gillerman's (1958) Still Ridge Formation, named in the central Peloncillo Mountains, was redefined by Lucas and Estep (1998b) as the Still Ridge Member of the U-Bar Formation. The Still Ridge Member crops out in the Peloncillo, Victorio, Little Hatchet, and East Potrillo Mountains, where it consists mostly of unfossiliferous sandy limestone, grainstone, calcarenite, and sandstone. Its maximum thickness is in the Little Hatchet Mountains, where the Still Ridge Member is 441 m thick at the Winkler Ranch section. Significantly, the Still Ridge and Howells Ridge members of the U-Bar Formation are mutually exclusive—only one member makes up the uppermost U-Bar Formation at a given locality except in the Little Hatchet Mountains where both members are present.

At the Winkler Ranch section in the southern portion of the range, the Still Ridge Member is the upper interval of the U-Bar Formation. At the Howells Ridge section in the northern part of the range, indeed all along Howells Ridge, the Howells Ridge Member is the upper interval of the U-Bar Formation. At the Winkler Ranch section, the dominant lithotype of the Still Ridge Member is medium-gray sandy limestone (74% of the section) (Fig. 9F). Subordinate lithotypes are calcarenite (14% of the section) and grainstone (9%). One fossiliferous bed is present in the Still Ridge Member (Fig. 8, bed 121) and contains rudists. It probably represents a local biostrome, as are found in the Still Ridge Member in the East Potrillo Mountains (Seager and Mack, 1994).

The Still Ridge Member thus is a cliff- and cuesta-former dominated by coarse-grained limestones. Its base is the first such limestone bed above slope forming shale and *Orbitolina* packstones of the Old Hachita Member. The contact of the Mojado Formation on the Still Ridge Member is a sharp surface where trough cross-bedded, quartzose sandstone rests directly on sandy limestone. We interpret this contact as a disconformity, (biostratigraphic data support this, see below).

Mojado Formation

Only one essentially complete section of the Mojado Formation is exposed in the Little Hatchet Mountains—the section in the Howells Well syncline that can be pieced together in the S½ secs. 13–15, T28S, R16W and that Galemore (1986) first described (Fig. 10). Here, the Mojado Formation is 1245 m thick. North and west of the abandoned Winkler Ranch homestead, in the SW¼ sec. 11 and W½ sec. 14, T29S, R16W, a much metamorphosed but intact section of most of the Mojado Formation is exposed, and it is 1145 m thick (Fig. 11). Our description of the Mojado Formation in the Little Hatchet Mountains is thus based on these two sections.

Galemore's (1986) section of the Mojado at Howells Well is essentially the same as our Howells Well section, but it includes about 200 m more of the upper Mojado. It thus seems that 1245 m is a reasonable estimate of the maximum thickness of the Mojado Formation in the Little Hatchet Mountains.

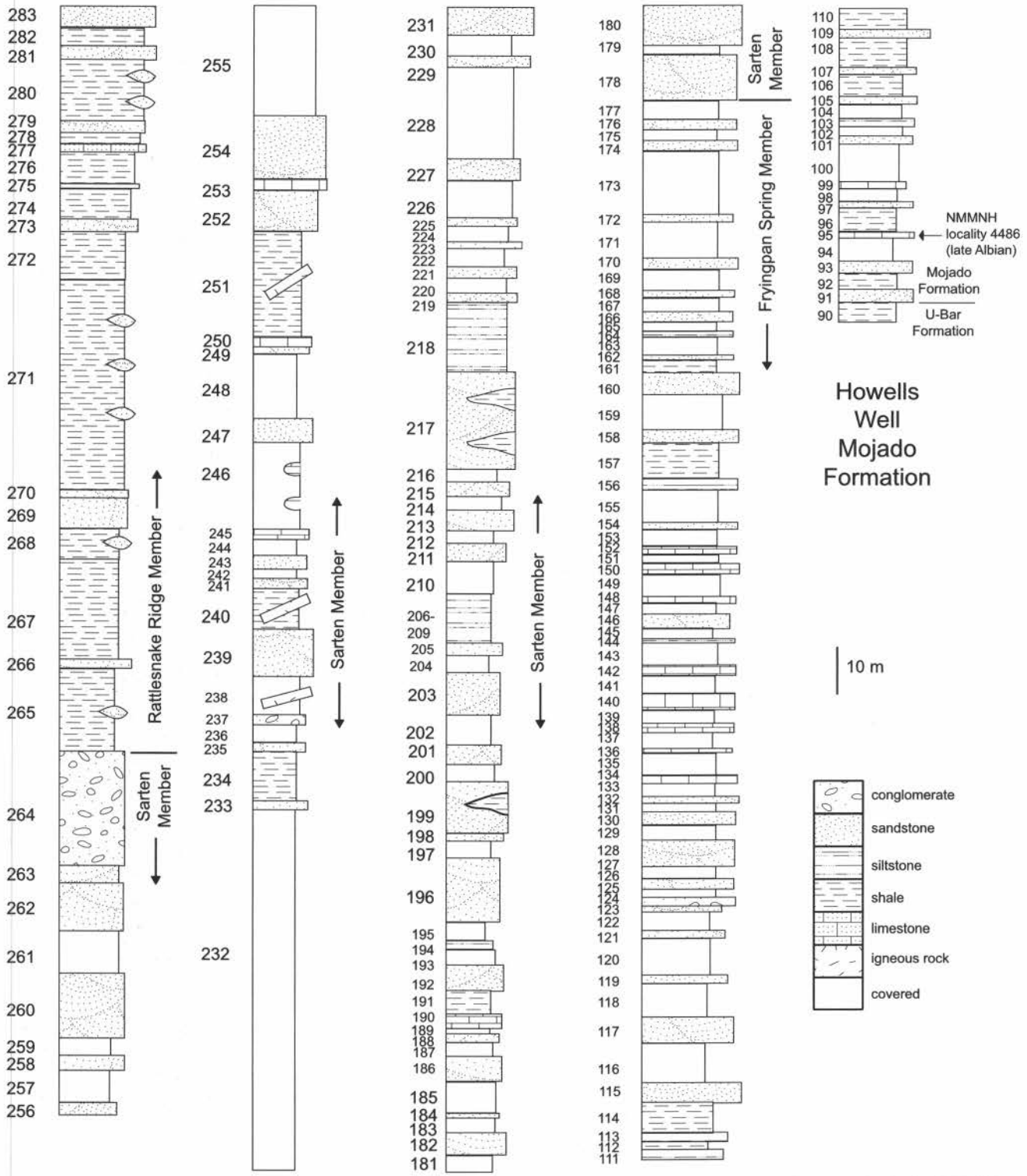


FIGURE 10. Measured stratigraphic section of the Mojado Formation at Howells Well. Section measured in the S½ secs. 13–15, T28S, R16W

Throughout the range, the Mojado Formation can be divided into three members (Galemore, 1986). Here, we follow the formal terminology of Lucas and Estep (1998b) and identify these members as the (ascending) Fryingpan Spring, Sarten, and Rattlesnake Ridge members.

Fryingpan Spring Member

Lucas and Estep (1998b) named the lower member of the Mojado Formation in the Cookes Range of Luna County the Fryingpan Spring Member. At its type section, the Fryingpan Spring Member is 22 m thick, and the unit is mostly sandstone and sandy siltstone with characteristic interbeds of limestone and shale that contain a marine invertebrate fauna of late Albian (*Mortoniceras equidistans* ammonite zone) age. In the Little Hatchet Mountains, the Fryingpan Spring Member is much thicker (165–248 m). Galemore's (1986) "lower member" of the Mojado Formation in his Howells Well section is the same unit we term Fryingpan Spring Member.

At the Winkler Ranch section, the Fryingpan Spring Member is 165

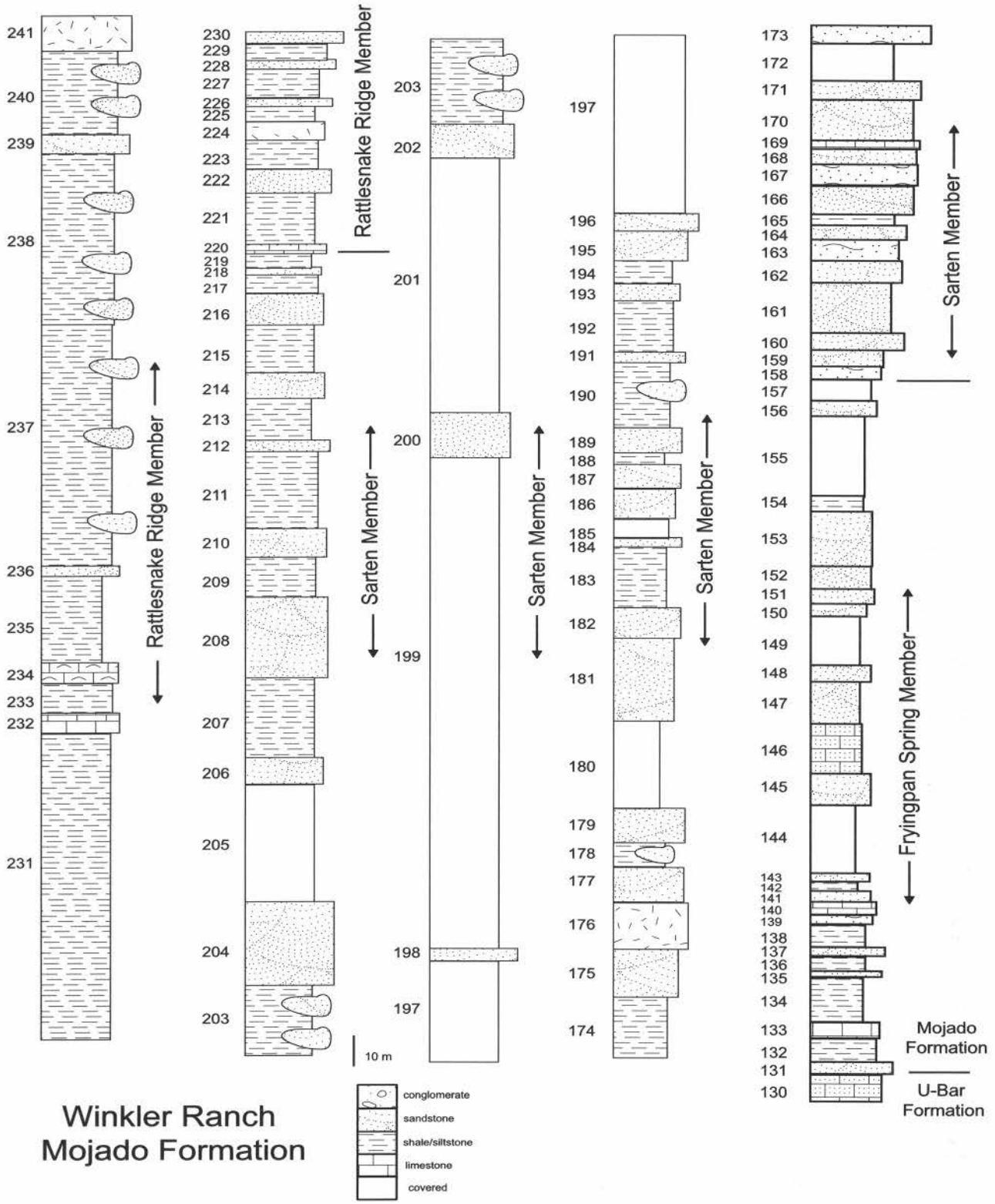


FIGURE 11. Measured stratigraphic section of the Mojado Formation at Winkler Ranch. Section measured in secs. 11 and 14, T29S, R16W.

m thick, but about 40% of the section is covered, though most of the covered intervals probably are beds of shale. Sandstone is the dominant exposed lithotype (37% of the section), shale is less well exposed (18% of the section), and limestone is a minor component (4% of the section). At the Howells Well section, the Fryingpan Spring Member is 248 m thick, but 56% of the section is covered, though most of the covered beds probably are shale. Sandstone and shale are both equally well exposed (each is about 19% of the section), and limestone is a minor (5%) but conspicuous lithotype. Sandstones of the Fryingpan Spring Member are mostly gray or yellowish brown, trough cross-bedded and quartzose. Some are bioturbated. Shales are mostly olive gray, and limestones are a striking bluish gray and contain marine molluscan fossils.

Thus, in the Little Hatchet Mountains, the Fryingpan Spring Member is a slope forming unit, mostly shale, that contains a few thin, conspic-

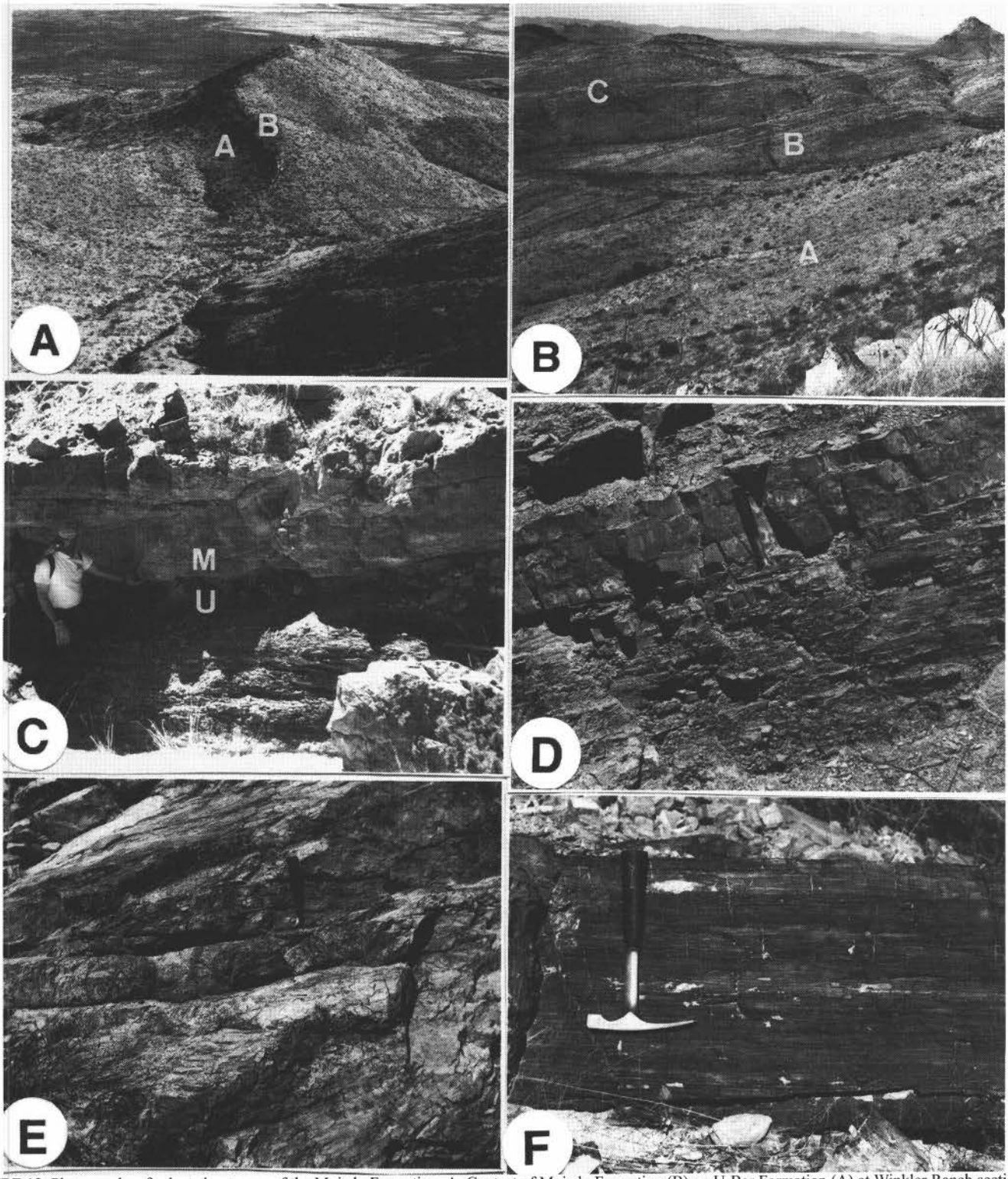


FIGURE 12. Photographs of selected outcrops of the Mojado Formation. **A**, Contact of Mojado Formation (B) on U-Bar Formation (A) at Winkler Ranch section. **B**, Overview of lower part of Howells Well section showing uppermost U-Bar Formation (A) overlain by slope-forming Fryingpan Spring Member (B) and cuesta-forming Sarten Member (C) of Mojado Formation. **C**, Sharp, disconformable contact of base of Mojado Formation (M) on uppermost U-Bar Formation (U) at Howells Well section. **D**, Thinly-bedded shale and limestone of Fryingpan Spring Member at Howells Well section. **E**, Cross-bedded sandstone characteristic of Sarten Member at Howells Well section. **F**, Thinly laminated shale characteristic of Rattlesnake Ridge Member at Howells Well section.

uous beds of limestone that yield marine invertebrate fossils, mostly bivalves and gastropods (Fig. 12B, D). The base of the Fryingpan Spring Member is the base of the Mojado Formation discussed earlier (Fig. 12C), and its top is the first thick succession of nonmarine sandstone beds at the base of the Sarten Member.

Sarten Member

Lucas and Estep (1998b) restricted the term Sarten Sandstone of Darton (1916) to refer to the middle member of the Mojado Formation, which is dominated by nonmarine (fluvial) sandstone. At its type sec-

tion in the Cookes Range, the Sarten Member is 58 m thick and is mostly sandstone. Locally, the unit contains a few thin beds of limestone with marine fossils. In the Little Hatchet Mountains, the Sarten Member is much thicker (541–762 m). Galemore's (1986) "middle member" of the Mojado is the same unit we term the Sarten Member.

At the Winkler Ranch section, the Sarten Member is 762 m thick, and much of the section (44%) is covered. The dominant exposed lithotype is relatively thick bedded, trough cross-bedded sandstone (31% of the section) and slope-forming mudstone/shale (24% of the section). Only a single, thin (0.6-m-thick) bed of limestone with marine fossils is present near the base of the member.

At Howells Well, the Sarten Member is 541 m thick, but about half (54%) of the unit is covered. The dominant exposed lithotype is sandstone (34% of the section), with minor exposure of shale (7%), a few thin siltstone beds and a few thin (<1 m) beds of marine limestone and one thick (23 m) bed of conglomerate/conglomeratic sandstone. Sandstone beds of the Sarten Member are generally gray or yellowish brown, medium–coarse-grained, quartzose and ferruginous and trough cross-bedded. Some contain petrified wood, and very few beds in the Sarten Member have marine fossils or bioturbation. Mudstone/shale beds are generally olive gray, and there are a few beds of conglomerate/conglomeratic sandstone.

Thus, in the Little Hatchet Mountains, the Sarten Member of the Mojado Formation is characterized by thick (3–20 m) beds of relatively coarse-grained, trough cross-bedded sandstone that form cuestas and a generally lack marine indicators (Fig. 12E). The base of the Sarten Member is the base of the first thick succession of fluvial sandstones above shale-dominated strata of the Fryingpan Spring Member. The top of the Sarten Member is the highest such succession of sandstones below shale-dominated slopes of the Rattlesnake Ridge Member.

Rattlesnake Ridge Member

The Rattlesnake Ridge Member of the Mojado Formation (Lucas and Estep, 1998b) has its type section in the Cookes Range, where it is about 6 m thick and consists of silty sandstone and siltstone that yield a marine invertebrate fauna from limestone nodules. In the Little Hatchet Mountains, the unit is much thicker (up to 410 m). Galemore (1986) used the term "upper member" for what we term the Rattlesnake Ridge Member.

At Winkler Ranch, the Rattlesnake Ridge Member is at least 218 m thick, and almost all of it is shale (89% of the section). A few thin beds of sandstone (7%) and marine limestone (4%) are components of the section. At the Howells Well section, the Rattlesnake Ridge Member is at least 182 m thick and, similarly, it is mostly shale (87% of the section). Thin beds of sandstone make up the rest (13%) of the section. Shale beds of the Rattlesnake Ridge Member are generally olive gray and sandy. Sandstone beds are of similar color and are generally fine grained, quartzose and trough cross-bedded. Some marine bioturbation is present, and some beds (especially limestones) yield marine molluscan fossils.

In the Little Hatchet Mountains, the Rattlesnake Ridge Member can thus be characterized as a predominantly shale unit with a few sandstone and limestone beds that indicate marine influence (Fig. 12F). Its base is the first shale or limestone bed above the stratigraphically highest, thick sandstone interval at the top of the Sarten Member. The Upper Cretaceous (Campanian) Ringbone Formation unconformably overlies the Rattlesnake Ridge Member.

BIOSTRATIGRAPHY AND CORRELATION

Broken Jug Formation

Fossils thus far collected from the Broken Jug Formation are bivalves, gastropods and corals. Studies of these specimens have not been completed, but suggest a Late Jurassic age. Thus, a colonial coral from a sandstone bed in the lower part of the upper conglomerate member (Harrigan, 1995) was recently identified as *Thamnasteria* cf. *T. imlayi* Wells (Harry Filkhorn, personal commun., 2000). Similar species are known from the Smackover Formation (Oxfordian) in the subsurface of Arkansas (Wells, 1942) and from the Upper Jurassic of northern Chihuahua (Reyeros de Castillo, 1974), about 90 km east-southeast of the Little Hatchet Mountains. A few meters stratigraphically higher in the upper conglomerate member, NMMNH locality 4487 yields a bivalve assemblage dominated by *Gryphaea mexicana* Felix, a characteristic Late Jurassic taxon (Imlay, 1940). These fossils and their biostratigraphic significance will be detailed in a later paper.

Hell-to-Finish Formation

No age diagnostic fossils are known from the Hell-to-Finish Formation throughout southwestern New Mexico. Therefore, its age has generally been inferred to be Aptian because of its gradational contact with the overlying, upper Aptian base of the U-Bar Formation.

U-Bar Formation

The U-Bar Formation is the most fossiliferous unit of the Bisbee Group in southwestern New Mexico, so it has relatively precise age control based on biostratigraphy. The Carbonate Hill Member contains a prolific bivalve fauna dominated by *Exogyra quitmanensis* Cragin, *Ostrea franklini* Coquand, and *Ceratostreon cumminsi* Stanton (Fig. 13A–E). Locally, the unit yields ammonites of the latest Aptian *Kazanskyella spathi* Zone (Sandidge, 1985; Lucas, 2000b; Lucas and Estep, 2000a, b).

At its type section, the Old Hachita Member yields ammonites that indicate an early Albian age in the zone of *Douvilleiceras* cf. *D. mammillatum* (Schlotheim) (Fig. 13G–J) (Lucas, 2000a, b). As Lucas (2000a, b) noted, one ammonite zone at the base of the Albian—the *Hypacanthoplites cragini* Zone of Young (1974)—has not been identified in the Carbonate Hill Member-Old Hachita Member interval. This suggests a possible unconformity equivalent to one ammonite zone at the Aptian-Albian boundary in southwestern New Mexico. It is also important to note that the large foraminiferan *Orbitolina texana* Roemer, common in the Old Hachita Member in the Little Hatchet Mountains (Fig. 13F), has a long temporal range from latest Aptian through middle Albian and thus is not a precise age indicator (Schroeder, 1975; Scott, 1987).

All workers agree that the Howells Ridge Member is of middle Albian age (e.g., Zeller, 1965; Weise, 1982; Campbell, 1988), but a more precise reading of the biostratigraphic evidence suggests it spans a relatively short interval close to the early–middle Albian transition. The Howells Ridge Member yields the caprinid rudists *Coalcomana ramosa* (Boehm), *Caprinuloidea perfecta* (Palmer), *Caprinuloidea lenki* (Boehm) and *Eoradiolites* spp. (Zeller, 1965; Weise, 1982; Campbell, 1988). The large foraminiferans from this unit are *Paracoskinolina sunnilandensis* (Maync), *Dictyoconus walnutensis* (Carsey), and *Orbitolina texana* Roemer. The co-occurrence of these rudists and foraminiferans defines a short time interval that encompasses the latest early Albian and the early middle Albian; at its maximum, this is the time interval from the *Hypacanthoplites comalensis* through the *Metengenoceras hilli* ammonite zones (Schroeder, 1975; Coogan, 1977; Schroeder et al., 1978; Young, 1982; Scott, 1987). The following conclusions thus can be made:

1. The Howells Ridge Member, i.e., the rudistid reef and its associated reef-margin facies, is the same age biostratigraphically as the upper Mural Limestone reefs of southeastern Arizona. Hayes (1970) suggested this correlation long ago, but it has subsequently been rejected, without justification, by Warzeski (1987), among others. Thus, there was a widespread episode of rudistid reef formation at about the beginning of the middle Albian in the New Mexico-Arizona portion of the Bisbee basin.

2. Lucas and Estep (1998a, fig. 4, 1998b, fig. 4) indicated that the lowest stratigraphic record of the late Albian index foraminiferan *Cribratina texana* is in the upper part of the Howells Ridge Member. This is an error based on a misreading of Zeller (1965). There is no evidence that any part of the Howells Ridge Member is of late Albian age.

3. Weise (1982, p. 134) suggested that the upper part of the Howells Ridge Member ("suprareef member") could be as young as late middle Albian, even though the same rudistids and foraminiferans that indicate

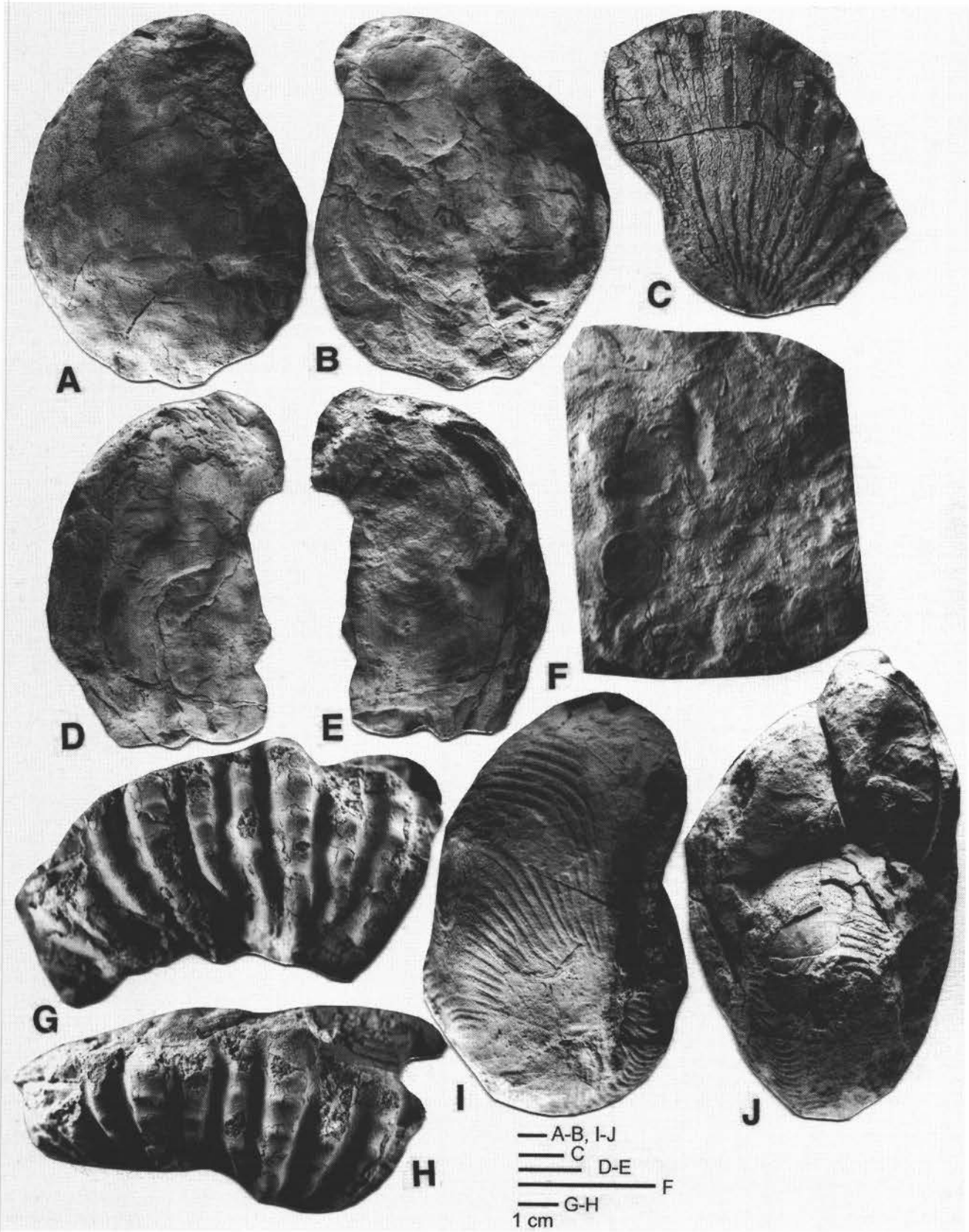


FIGURE 13. Selected biostratigraphically important fossils from the U-Bar Formation in the Little Hatchet Mountains. **A**–**B**, *Exogyra quitmanensis* Cragin, NMMNH P-31559 from NMMNH locality 4405 (compare to Stanton, 1947, pl. 26). **C**, *Ctenostreon cumminsi* Stanton, NMMNH P-31558 from NMMNH locality 4405 (compare to Stanton, 1947, pl. 35, figs. 1-6). **D**–**E**, *Ostrea franklini* Coquand, NMMNH P-31557 from locality 4405 (compare to Lucas and Estep, 2000, fig. 5C–D). **F**, *Orbitolina texana* Roemer, NMMNH P-31560 from NMMNH locality 4471 (comapre to Douglass, 1960, pl.4). **G**–**H**, *Douvilleiceras* aff. *D. mammillatum* (Schlotheim). NMMNH P-31421 from NMMRH locality 1365, **I**–**J**, *Cymatoceras* cf. *C. neohispanicum* (Burckhardt), NMMH P-31556 from NMMNH locality 1356 (compare Burckhardt, 1925, pl. 1, figs. 1–4 and Miller and Harris, 1945, p. 8).

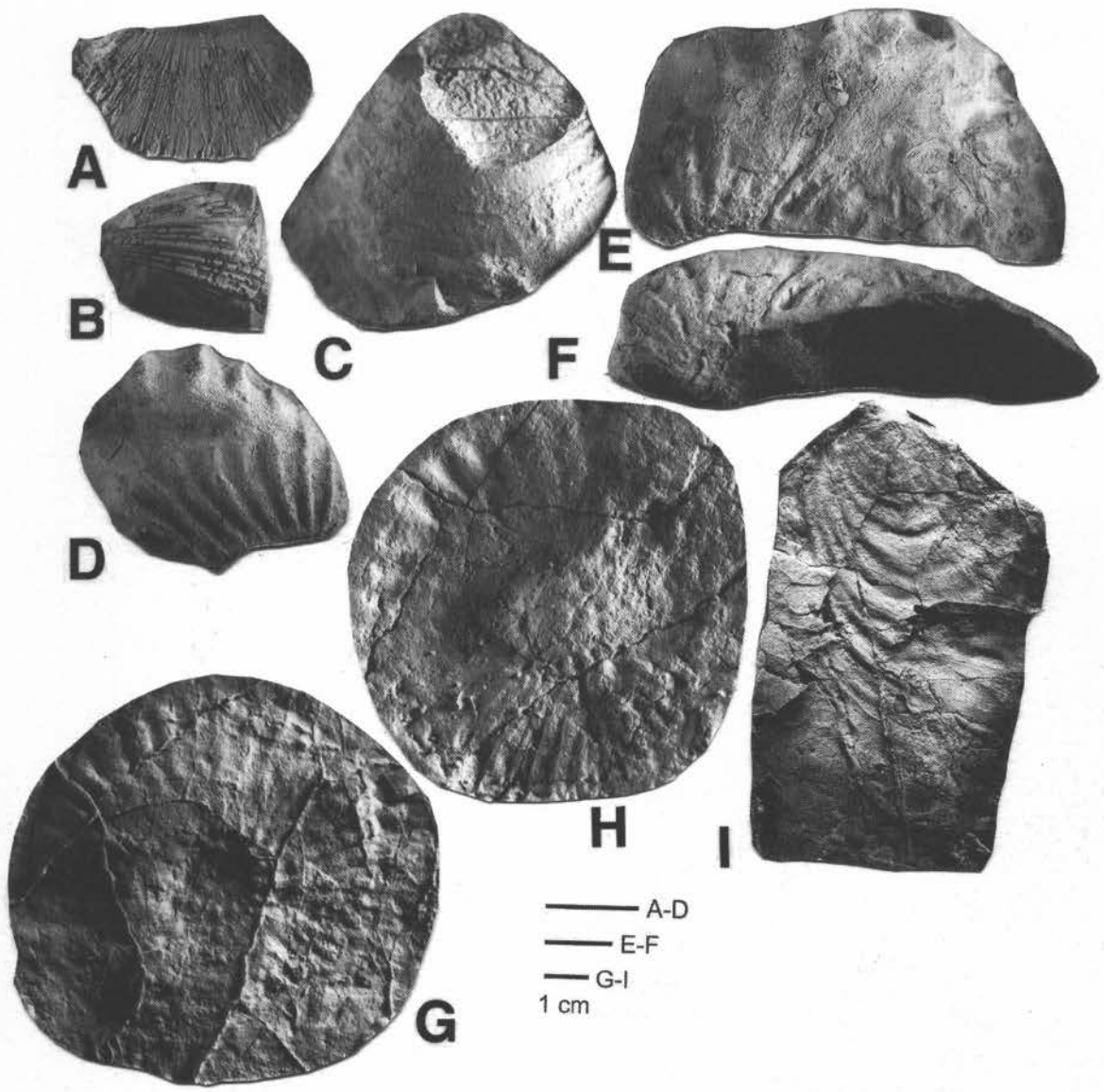


FIGURE 14. Selected fossils from the Mojado Formation in the Little Hatchet Mountains. **A**, *Neithea texana* (Roemer), NMMNH P-31786, part of left valve. **B**, *N. texana*, NMMNH P-31785, part of right valve. **C**, *Protocardia* sp., NMMNH P-31791. **D**, *Scabrotrigonia emoryi* (Conrad), NMMNH P-31784, incomplete left valve. **E**–**F**, *S. emoryi*, NMMNH P-31782, incomplete right valve. **G**–**H**, *Tarrantoceras* sp., NMMNH P-31793, rubber peel (G) and impression (H) of lateral surface. **I**, *Inoceramus* sp., NMMNH P-31792. A–F, from NMMNH locality 4486; G–I, from NMMNH locality 4488.

an older age for the reef are present throughout the unit. Furthermore, the so-called "suprareef" consists of reef-margin facies largely coeval with the reef itself (Campbell, 1988). Therefore, there is no evidence that any part of the Howell's Ridge Member is younger than early middle Albian.

4. Therefore, there is a substantial hiatus at the base of the Mojado Formation that represent much of middle Albian time and part of the late Albian. About six ammonite zones appear to be missing at this hiatus.

Campbell (1988) concluded that a precondition for establishment of the U-Bar rudistid reefs was stabilization of the substrate by extensive blue-green algal mats and large foraminiferans (*Orbitolina*) as well as submarine cementation and firm-ground formation associated with drowning and low sedimentation rates. The reefs then formed as part of a ramp-ooid-pellet barrier complex (Read, 1985) during the T5 transgression of Kauffman (1977a), or, more precisely, during the transgression that immediately followed the major regression at the early-middle Albian boundary (Kauffman and Caldwell, 1993, fig. 4). This was the time of peak rudistid reef development in the Caribbean portion of Tethys (Kauffman and Johnson, 1988). The U-Bar rudistid reefs were thus isolated bodies surrounded by a high-energy inner-ramp blanket of skeletal sandstones such as are characteristic of the Still Ridge Member. This suggests that the Howells Ridge Member and Still Ridge Member are, at least in part, laterally equivalent.

Mojado Formation

Both Zeller (1970) and Campbell (1988) mentioned late Albian molluscs from the Mojado Formation in the Little Hatchet Mountains, but no documentation was provided. Ammonites from the basal interval (Fryingpan Spring Member) of the Mojado Formation in the Cookes Range (Cobban, 1987; Lucas et al., 1988) indicate it is of late Albian age, in the ammonite zone of *Mortoniceras equidistans*.

At NMMNH locality 4486 near the base of the Mojado Formation we collected a fossil assemblage of bivalves that indicates a late Albian age. Numerous specimens of *Scabrotrigonia emoryi* (Conrad) (e.g., Fig 14D–F) show characteristic features of this taxon, including a prominent beak, a concave dorsal margin, strongly convex ventral margin,

elongate shell posteriorly and ornamentation by numerous narrow, equally-spaced nodose ribs that are deflected back from the dorsal midline then forward so that they form a backward-directed "v" on the escutcheon (cf. Böse, 1910, p. 121, pl. 24, figs. 1–3, pl. 25, figs. 1, 3, 5, pl. 26, fig. 1; Adkins, 1928, p. 121; Kues et al., 1985, fig. 8J–K). *S. emoryi* has its oldest occurrence in late Albian strata.

Poorly preserved cardiid bivalves from locality 4486 appear to belong to *Protocardia* (Fig. 14C) but are too incomplete to be assigned to a species (cf. Scott, 1975, pl. 1). The third common bivalve is *Neithea texana* (Roemer) (Fig. 14A–B), characterized by small, triangular to circular inequivalve shells with flat ribs with narrow interspaces and primary ribs that project beyond the shell margin (Böse, 1910, p. 93, pl. 15, figs. 2–4, 6; Adkins, 1932, p. 127, pl. 17, figs. 2–4; Kues et al., 1985, fig. 8M–N). This bivalve, too, has its oldest record in late Albian strata. Indeed, this bivalve assemblage is diagnostic of late Albian time, being found, for example, in the Tucumcari Shale of east-central New Mexico (Kues et al., 1985) and the Mesilla Valley Shale at Cerro de Cristo Rey near El Paso (Böse, 1910), both units of late Albian age (Lucas et al., 1988; Kues, 1997). These bivalves do not provide correlation to the ammonite zone, but they are consistent with the upper Albian *Mortoniceras equidistans* Zone. The base of the Mojado Formation in the Little Hatchet Mountains thus is definitely of late Albian age.

No direct age constraints are known for the middle Mojado Formation, which is largely nonmarine. Ammonites from the upper part of the Mojado Formation in the Animas Mountains and Big Hatchet Mountains indicate it is latest Albian, in the *Drakeoceras drakei* Zone (Lucas and Estep, 1998a). In the Cookes Range, however, the youngest Mojado strata are earliest Cenomanian in age.

NMMNH locality 4488 in the Little Hatchet Mountains is in dark marine shale of the uppermost Mojado Formation, about 30 m below its unconformable contact with the overlying Ringbone Formation. We have only begun to collect and study this locality, but its fauna clearly is of Cenomanian age. Significant in this regard is the impression of an ammonite (Fig. 14G–H) that we tentatively identify as *Tarrantoceras* sp. This ammonite shows numerous features characteristic of *Tarrantoceras*: moderately evolute, flattened flanks, whorls higher than wide, ornamentation of numerous, mostly rectiradiate narrow primary and secondary ribs that bear inner and outer ventrolateral tubercles, and primary ribs arise from umbilical bullae (Stephenson, 1955; Cobban, 1988). It compares well to specimens of *Tarrantoceras sellardsi* (Adkins) illustrated by Cobban (1988, pl. 1, figs. 9, 11) and Cobban et al. (1989, fig. 68A–E, 72S), but our specimen is too poorly preserved to allow a species-level identification. *Tarrantoceras* is a widely distributed middle-upper Cenomanian ammonite, and its nearest occurrence is in the middle Cenomanian Boquillas Formation at Cerro de Cristo Rey near El Paso (Kennedy et al., 1988).

An inoceramid bivalve (Fig. 14I) from NMMNH locality 4488 further reinforces a Cenomanian age assignment. This specimen also is not well enough preserved to allow a species-level identification. It is characterized by a broadly subquadrate shell with a subterminal umbo, small convexity, and ornamentation of narrow ribs with unsymmetrical curvature and wide, concave interspaces. It thus shows strong similarity to early-middle Cenomanian inoceramids such as "*Inoceramus bellvuensis*" Reeside (Reeside, 1922, pl. 46; Kauffman, 1977b, pl. 4, fig. 3). Thus, the uppermost Mojado Formation in the Little Hatchet Mountains is of Cenomanian age, but more fossils will be needed to make a more precise age assignment.

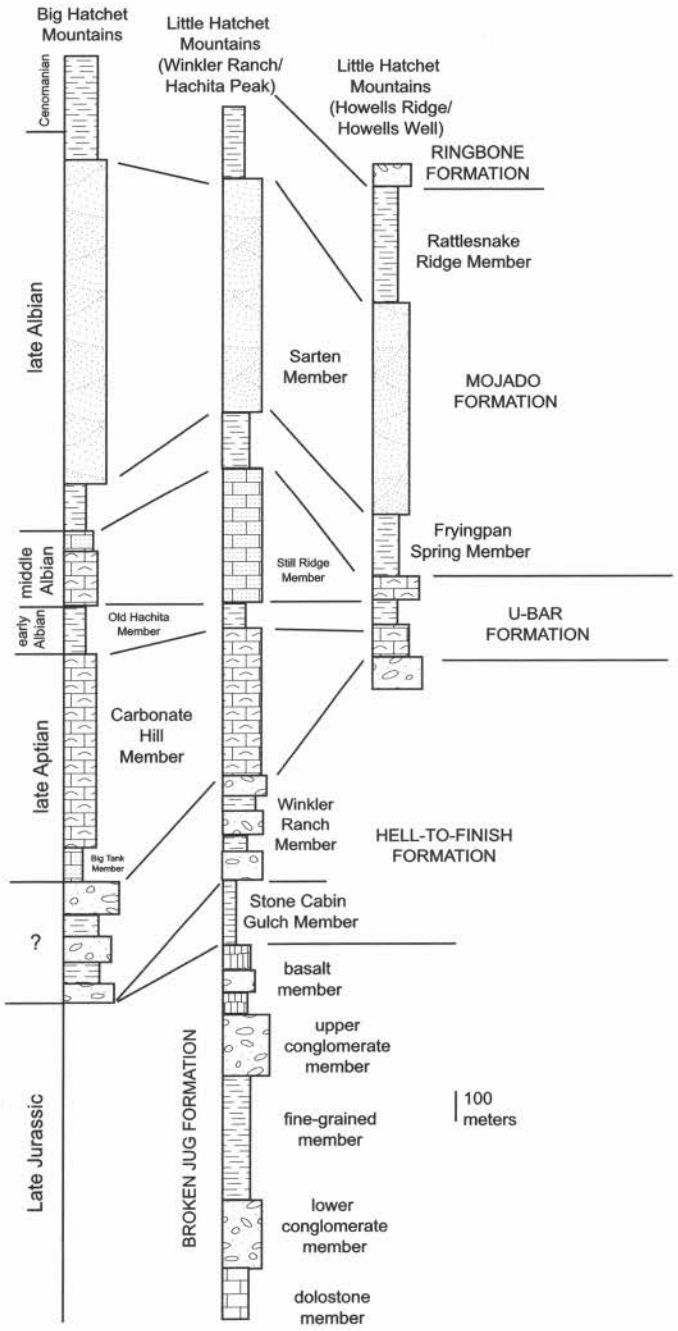


FIGURE 15. Correlation of Bisbee Group strata from the Big Hatchet Mountains (after Zeller, 1965) to the Winkler Ranch and Howells Ridge-Howells Well sections in the Little Hatchet Mountains.

DISCUSSION

The thick Bisbee Group section in the Little Hatchet Mountains forms an important stratigraphic link between similar stratigraphic sections in the Chihuahua trough to the east and southeast and the Chiricahua Mountains in southeastern Arizona. Marine rocks of Late Jurassic age (La Casita Formation) form the basal part of the section in the Chihuahua trough. These are overlain by evaporites and marginal marine rocks of the Navarrete Formation and non-marine red beds of the Las Vigas Formation. A similar stratigraphic section that consists of marine Upper Jurassic strata and mafic volcanics inferred to be overlain by the Lower Cretaceous Morita Formation is likewise present in the Chiricahua Mountains (Lawton and Olmstead, 1995). The recognition of at least one, and perhaps two, marine intervals that predate the classic Hell-to-Finish red beds (our Winkler Ranch Member) yields a Bisbee Group section that is consonant with that in nearby regions and provides a paleogeographic link with Late Jurassic marine conditions in northeastern Mexico.

Like the Upper Jurassic–Lower Cretaceous section in the Chihuahua trough, the thick Bisbee section of the southern part of the Little Hatchet Mountains lacks a conspicuous basal conglomerate, such as the Glance Conglomerate of southeastern Arizona (Ransome, 1904; Bilodeau, 1982) or basal conglomerate of the Hell-to-Finish described elsewhere

in southwestern New Mexico (Mack et al., 1986). Thin conglomerates are present at the base of the Jurassic section in the Chiricahua Mountains, but do not exceed a few meters in thickness (Lawton and Olmstead, 1995). Indeed, the basal conglomerate does not appear to be characteristic of the thick rift keel, but rather is present adjacent to and on fault blocks nearer the rift margin and thus signals the presence of local uplifted sources (e.g., Bilodeau, 1982; Bayona and Lawton, this volume).

Improved understanding of the dramatic thickness and facies changes of the Bisbee Group (Fig. 15) will necessarily improve understanding of rift-basin structure and subsequent deformation patterns. We have already addressed the improbability of a large-displacement bedding-plane fault at Howells Ridge, whose existence was postulated primarily on the basis of sharp member contacts and an unusually thin stratigraphic section (Zeller, 1970). Depositional thinning across rift structures and recognition of the proper order of stratigraphic members combine to obviate the need for structural omission or repetition at Howells Ridge. We anticipate that careful studies of Bisbee stratigraphy will help unravel apparently complex structural relations elsewhere in southwestern New Mexico.

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