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## ***Paleoceanographic events and faunal crises recorded in the Upper Cambrian and Lower Ordovician of west Texas and southern New Mexico***

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### ABSTRACT

**A revised lithostratigraphy for Lower Paleozoic strata in New Mexico and west Texas was developed through detailed sedimentological study of the Bliss and Hitt Canyon Formations within a refined temporal framework assembled from precise biostratigraphic (trilobite and conodont) and chemostratigraphic (carbon isotope) data. Member boundaries within the Hitt Canyon now correspond with mappable and essentially isochronous horizons that represent major depositional events that affected sedimentation in basins throughout Laurentian North America. This trip is designed to examine these and other important intervals, such as the extinction horizons at the base and top of the Skullrockian Stage, and to demonstrate the utility of associated faunas and isotopic excursions for correlation within and beyond the region.**

**Keywords:** Cambrian, Ordovician, stratigraphy, New Mexico, Texas.

### INTRODUCTION

The lowermost Paleozoic rocks in southern New Mexico and west Texas were deposited when a rugged Precambrian topography was inundated by the Sauk Transgression. They comprise a basal mixed clastic-carbonate package of highly vari-

able thickness and lithology, the Bliss Formation, overlain by a thick succession of carbonates known collectively as the El Paso Group. Over the past 50 years, a bewildering number of names has been assigned to the numerous formations and members recognized within the El Paso Group, as shown in **Figure 1**. For a more complete and detailed summary of the nomenclatural

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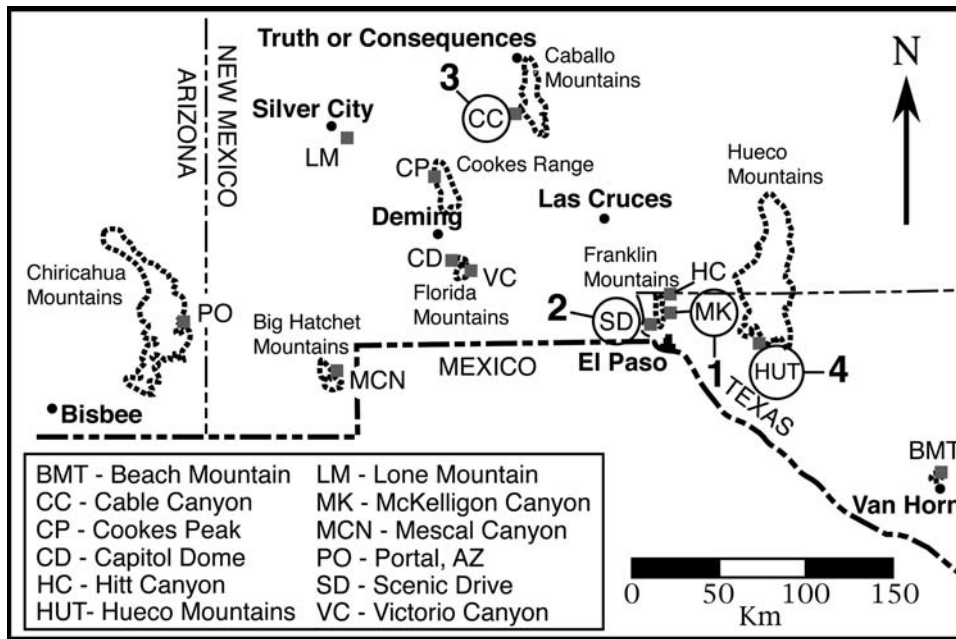


Figure 2. Location map showing sections included in the present study. Field trip stops are circled and labeled with stop number (1-4).

Formations & Members	System	Series	Stage	Trilobite Zones/Subzones	Conodont Zones	Conodont Subzones				
McKelligon	Ordovician	Ibexian	Stairsian	<i>R. superciliosa</i>	<i>Acodus deltatus</i>					
				Jose Mbr	<i>Tesselacauda</i>	<i>Macerodus diana</i>				
				Cooke's Member	<i>Leiostegium - Kainella</i>	Low Diversity Interval				
					<i>Paraplethopeltis</i>	<i>Rossodus manitouensis</i>				
				Sierrite Member	<i>Bellefontia - Xenostegium</i>	<i>Cordylodus angulatus</i>	<i>Clavohamulus hintzei</i>			
					<i>Symphysurina</i>	<i>lapetognathus</i>	<i>Hirsutodontus simplex</i>			
				Bliss	Cambrian	Sunwaptian (upper)	Saukia Zone	<i>Missisquoia</i>	<i>Cordylodus lindstromi</i>	<i>Clavohamulus elongatus</i>
								<i>E. apopsis</i>	<i>Cordylodus intermedius</i>	<i>Fryxellodontus inornatus</i>
								<i>Saukiella serotina</i> Subzone	<i>Cordylodus proavus</i>	<i>Hirsutodontus hirsutus</i>
								<i>Saukiella junia</i> Subzone	<i>Eoconodontus</i>	<i>Cambroistodus minutus</i>
<i>Rasettia magna</i> Subzone	<i>P. muelleri</i>	<i>Eoconodontus notchpeakensis</i>								
<i>Saratogia</i>	<i>Proconodontus posterocostatus</i>									
lower member			<i>Proconodontus tenuiserratus</i>							

Figure 3. Biostratigraphic and chronostratigraphic units represented in the study interval. Columns with bold lines on the left show position/age of member boundaries where best constrained by biostratigraphic data in New Mexico.

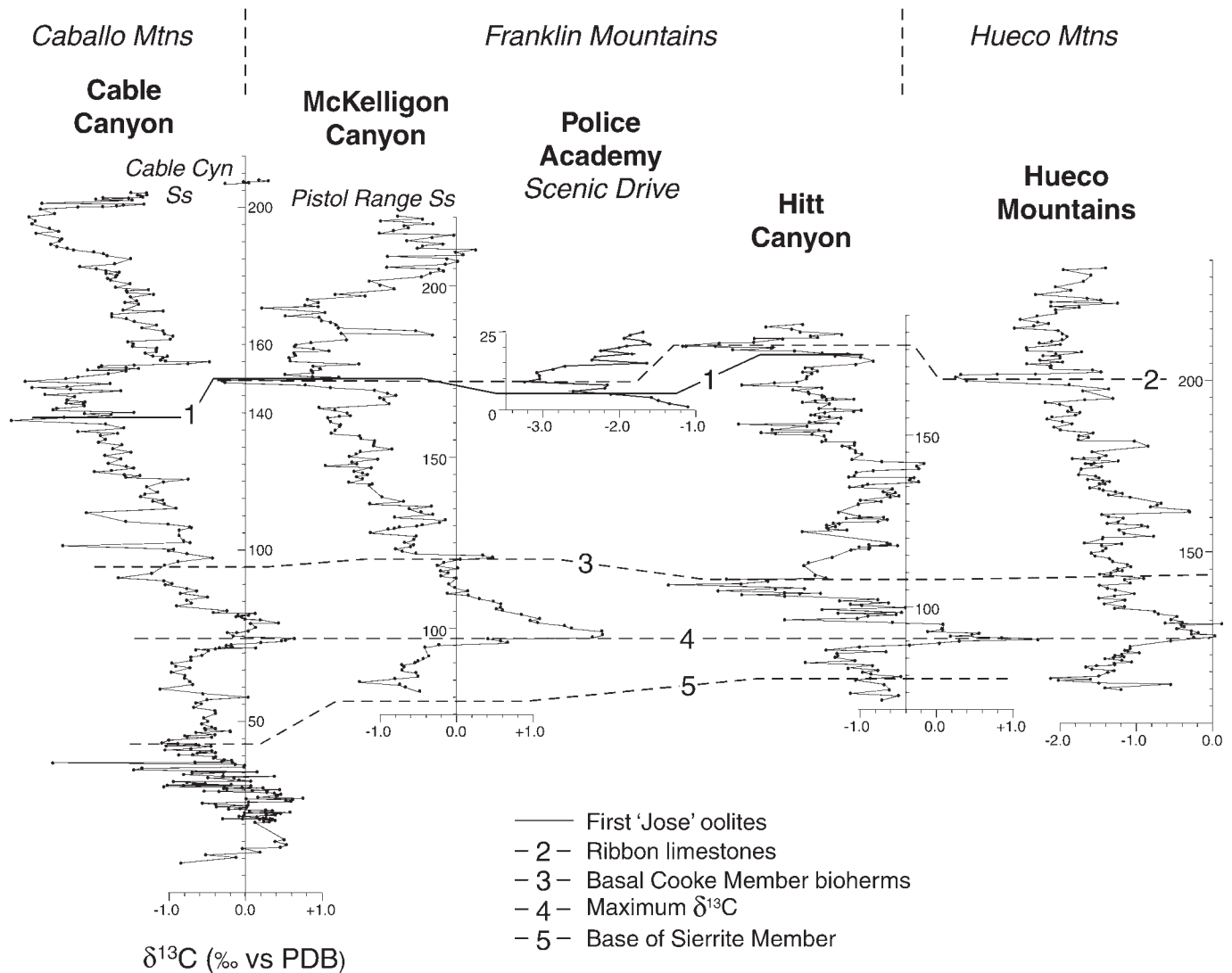


Figure 4. Fence diagram of carbonate  $\delta^{13}\text{C}$  profiles across southern New Mexico into west Texas. Datum is the basal Stairsian positive excursion.

Laurentian rocks. Profiles from the four major sections are bracketed by two prominent excursions of  $>2\%$ , with  $\sim 1\%$  variations occurring at several intervening levels. A thin  $2\%$  positive excursion spans the base of the Stairsian Stage. Smaller-scale variation below this prominent feature provides extremely precise chronostratigraphic correlation of the base of the Sierrite Member in all 4 sections. A second, strongly negative excursion coincides precisely with the base of the Jose Member at the top of the Hitt Canyon Formation—a horizon that we interpret as representing a submergence event. This event caps a long-term trend toward more negative values that is especially prominent in the Cable Canyon section.  $\delta^{13}\text{C}$  profiles from McKelligon Canyon, Texas, and Cable Canyon, New Mexico, indicate additional  $\delta^{13}\text{C}$  variation above the basal Jose event and suggest that high-resolution

geochemical correlation of the regressive Pistol Range Member of the McKelligon Formation to areas outside the Franklin Mountains might eventually be possible. These  $\delta^{13}\text{C}$  excursions already have proven extremely useful for determining the position of the base of the Stairsian Stage and the level representing the Jose submergence event in west Texas, where the scarcity of macrofossils and pervasive dolomitization of critical intervals makes precise correlation within that interval very difficult.

#### DAY 1—SOUTHERN FRANKLIN MOUNTAINS, TEXAS

Follow McKelligon Canyon Drive west from its intersection with Alabama Street into McKelligon Canyon, and park at the westernmost picnic tables at the head of the canyon. Hike a

short distance southwest to a gully where the contact between granitic basement and overlying sandstone is well exposed. This is the base of the section, which follows the gully to the left and ascends the spur at the head of the gully.

Note: Stops on day 1 are within Franklin Mountains State Park, and collecting without a Texas State Scientific Collecting Permit is prohibited.

### Stop 1. McKelligon Canyon

#### *Bliss Formation*

The pink granite, nonconformably overlain by quartzitic sandstone at the base of the Bliss, is the Red Bluff Granite, the youngest Proterozoic formation in the Franklin Mountains. For a thorough and useful summary of the units within the Precambrian in the Franklin Mountains, see LeMone (1988). In a few places, presumably the highest points on the inherited Precambrian topography, Lower Ordovician carbonates rest directly on basement, but in most sections, basal Bliss strata consist of sandstone and conglomerate. We divide the Bliss Formation into two informal members: a lower one dominated by quartz-rich sandstone and strongly hematitic lithologies and an upper member with abundant glauconite and significantly more carbonate. The hematitic portions of the lower member in some areas of New Mexico include ore-grade oolitic hematite. The boundary between the members is sharp and likely represents a significant transgression in each section, although perhaps not the same event in all sections. The age of the lower Bliss is poorly established in most sections, but the sparse biostratigraphic data available suggest that the base of the upper Bliss in New Mexico is significantly older than the base of the upper member in Texas.

Hayes (1975) designated this locality the type section for the Bliss Formation. A lithologic column is provided as [Figure 5](#). Here at McKelligon Canyon, the basal 4.67 m comprises a coarse-grained sandstone facies that formed in very shallow water during the initial transgression of the eroded Precambrian surface. It includes massive beds that formed by rapid deposition of coarse sediment from suspension and horizontally laminated beds that record deposition at velocities associated with upper plane bed conditions. The appearance slightly higher of glauconitic, bioturbated sandstone records deepening to where the reduced wave and flow energy allowed the infauna to more completely churn the sediment after deposition. At 42.31 m, a trough cross-bedded sandstone facies, created by deposition from ripples and small dunes that probably formed under unidirectional currents, appears and continues up to the contact with the overlying Sierrite Limestone at 77.64 m. A zone of red-stained (hematitic) beds representing all lithofacies of the lower Bliss occurs from 56.39 to 61.04 m. This interval might correlate with a hematite-rich interval from 84.7 to 92.35 m in the Hueco Mountain section. The top of the hematitic interval, marked by a pebble lag at McKelligon Canyon and by appearance of dense concentrations of glauconite in the Hueco Mountains, is used to define the base of the upper Bliss in both sections.

#### *El Paso Group*

***Hitt Canyon Formation—Sierrite Member.*** We will visit the type section of the Sierrite Limestone of Kelly and Silver (1952) at Cable Canyon in the Caballo Mountains, New Mexico (Stop 3). There the base of the unit is marked by the near disappearance of glauconite and other noncarbonate components whose abundance in the underlying Bliss Formation makes it less resistant to erosion than the cliff-forming purer limestone of the Sierrite. We retain the original definition of the Bliss-Sierrite contact as corresponding with the shift to pure carbonate (and the base of the cliffs in western sections) and place the Bliss-Hitt Canyon contact in McKelligon Canyon somewhat arbitrarily at a sharp contact between very sandy dolomite with prominent trough cross-bedding (below) and purer dolomite (above). This is probably the horizon used by LeMone (1969) as the top of his lower member of the Sierrite Formation. Although the base of the Sierrite in McKelligon Canyon lacks the physiographic expression that characterizes the base of the Sierrite in New Mexico, the contact is easily recognized by a shift to more pure carbonate.

The Sierrite Limestone was originally defined as a formation at the base of the El Paso Group. We amend its definition by considering the Sierrite a member of the Hitt Canyon Formation and by moving the top of the member upward to coincide with the appearance of meter-scale microbial biostromes, a horizon that appears to have greater correlation potential than the top of the cliff-forming limestone selected by Kelly and Silver (1952). Unlike the base of the Sierrite, which becomes younger to the east, this new upper contact displays no evidence of diachrony. To the contrary, conodont and  $\delta^{13}\text{C}$  data both suggest that the initiation of microbial reef growth recorded by that horizon was effectively synchronous across and perhaps even beyond the study area. The basal bed of our Sierrite Member in McKelligon Canyon yielded conodonts of the Lower Ordovician *Rossodus manitouensis* Zone. Repetski (1988) reported diagnostic elements of this same zone only 20 m above the base of the Bliss at Scenic Drive (Stop 2), where the formation is over 80 m thick, leaving little room for Cambrian or even lower Skullrockian strata.

***Hitt Canyon Formation—Cokes Member.*** This middle member of the Hitt Canyon Formation contains at least two intervals of microbial reefs and associated grainstone to rudstone. It is roughly equivalent to the Cooks and Victorio Mountains Formations of Flower (1964, 1969, 1968) and LeMone (1969, 1996), which have not been adopted by subsequent workers due to the largely biostratigraphic basis of their definition. The name was selected to acknowledge the considerable contributions of Rousseau Flower and David LeMone to the study of Lower Paleozoic strata in the southwest. It is changed slightly in spelling to avoid confusion with the more restricted interval identified by those authors as the Cooks Formation and to match the spelling used on most modern maps for the Cookes Range north of Deming. The base of the Cookes at McKelligon Canyon is slightly less than 120 m above the base of the section (Fig. 5). Many of the characteristic microbial reefs, particularly those low in the member, have been thoroughly dolomitized at this locality. Some better-

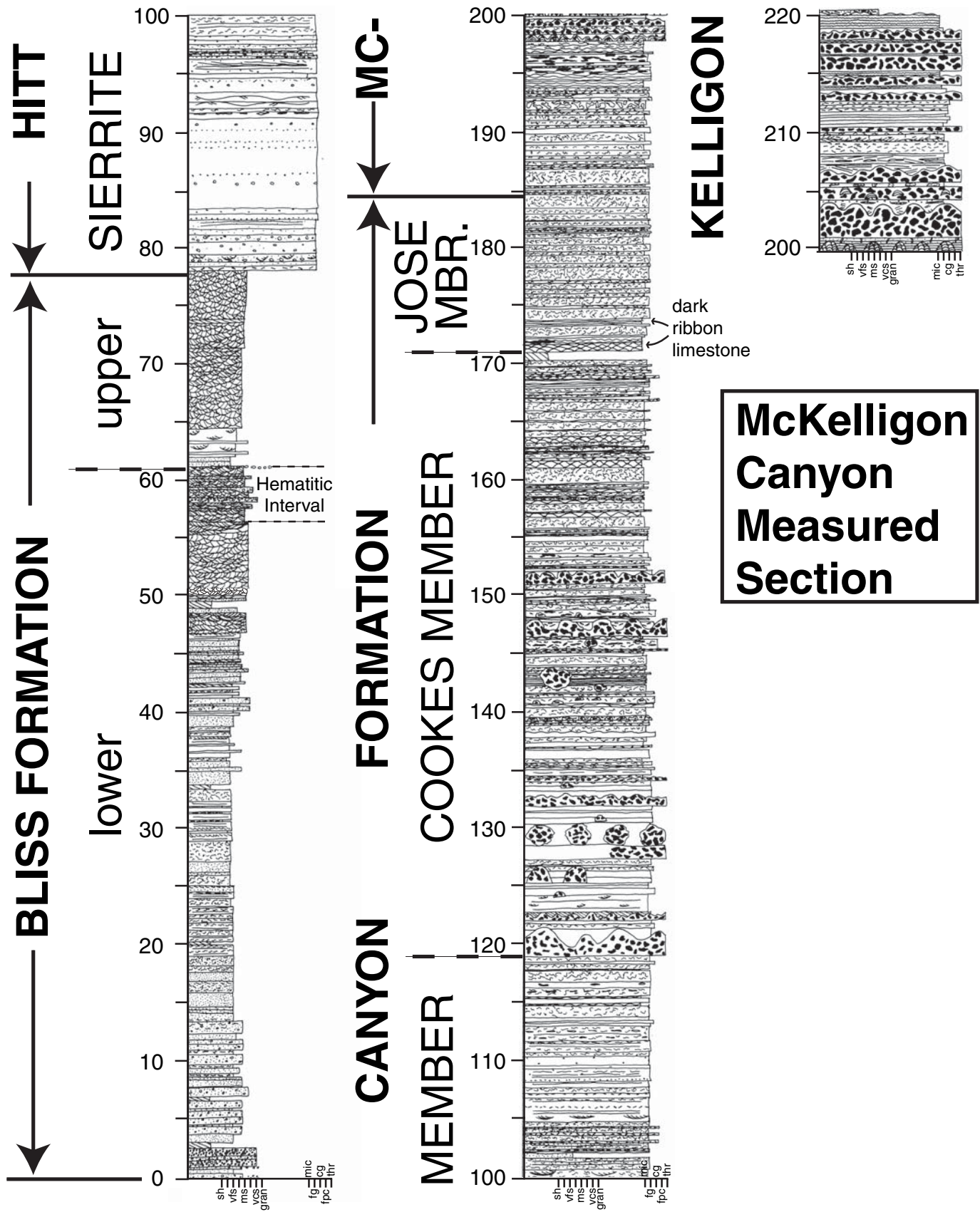


Figure 5. Lithologic column for McKelligon Canyon measured section (Stop 1). Siliciclastic lithologies (inset to left) include shale (sh); very fine, medium, and very coarse sandstone (vfs, ms, vcs); and granules (gr). Carbonate lithologies drawn to far right of column include micrite (mic); fine and coarse grainstone (fg, cg); flat pebble conglomerate (fpc), and thrombolitic boundstone (thr).

preserved reefs do occur higher in the member, but more impressive reefs will be seen in the Cookes Member in the Caballo and Hueco Mountains sections. The highest 15–20 m of the Cookes Member here in the Franklin Mountains consists largely of conspicuously burrowed lime mudstone to fine grainstone with some thin, nodular, lime mudstone intervals.

**Jose Member.** First described in the Cookes Range by Flower (1964), the Jose is an interval of dark (medium gray), oolitic packstone to grainstone with some beds containing small quantities of quartz sand that weathers in relief. Some of the thicker beds in the unit commonly also display fabric-selective dolomitization wherein only the ooid nuclei are dolomitized and stand out as small orange grains against the darker limestone around them. The Jose is the thinnest member of the formation, ranging in thickness from ~3 m to nearly 20 m in the sections that we have examined. Clemons (1991) reported greater thicknesses from some areas in his comprehensive analysis of the El Paso Group. These thicknesses probably are exaggerated by inclusion of strata that do not display the characteristics required for assignment to the Jose Member in the present study. This is definitely the case here in the Franklin Mountains, where previous authors (LeMone, 1996; Clemons, 1991; Hayes, 1975) equated the Jose with the Middle Sandy Zone of Harbour (1972) and the Chamizal Member of Lucia (1969). While the arenaceous interval identified as the Jose Formation by Flower and LeMone does indeed correspond almost precisely with the Middle Sandy Zone and the Chamizal, it is not equivalent to the oolitic package that has been traced across southern New Mexico as the Jose Member. The true Jose Member is present in the Franklin Mountains, but it is a characteristically thin (12–17 m) interval whose top lies ~18 m (or more) below the base of the sandy interval misidentified as the Jose in previous studies. The top of the highest dark grainstone bed is used in our lithostratigraphic scheme to define the base of the overlying McKelligon Formation. The interval between the top of the Jose Member and the top of the sandy interval, which is marked in the southern Franklin Mountains by a conspicuous orange-weathering sandstone bed 0.5–2 m thick, is reassigned to the base of McKelligon. That interval could be designated as a separate member of the formation below the Pistol Range Member of Flower (1964, 1969) and LeMone (1969, 1996), who used the aforementioned orange sandstone bed as the base of the McKelligon. A very strenuous climb is required to see the Pistol Range sandstone bed and the underlying dolomitic interval mistaken for the Jose Member here in McKelligon Canyon. The exposures along Scenic Drive (Stop 2) provide much easier access to these units and some remarkable reefs in the McKelligon Formation as well.

Influenced by the sandy and oolitic character of the unit, Clemons (1991) interpreted the Jose Member as the product of relative sea level fall that introduced shallower, higher energy conditions than those represented by the units above and below it. In contrast, we consider the Jose Member to be the result of submergence of the platform and the lithologies within the member to be the deepest water facies in the Hitt Canyon Formation (Taylor et

al., 2001). The oolite is dark, and well-developed cross-stratification is uncommon; most beds are either structureless or conspicuously burrowed. Additionally, thin intervals of ribbon limestone occur at or just above the base of the member in the Franklin and Hueco Mountains. These intervals of dark, very thin-bedded lime mudstone rhythmically interbedded with organic-rich shale might be the deepest water lithofacies in the El Paso Group, having formed in a deep shelf or upper slope environment seaward of the oolite. Alternatively, they might have accumulated as more proximal quiet water deposits that formed in the lee of a distal ramp oolitic shoal. The base of the Jose Member is defined by the lowest dark oolitic packstone to grainstone or the lowest dark ribbon limestone. Two ribbon limestone intervals are well exposed at the base of the Jose Member here at roughly 171–173 m into the section (Fig. 5). The same two recessive intervals are recognizable in the Police Academy section along Scenic Drive (Stop 2b; Fig. 6). The ribbon limestone is particularly important as a surrogate for the oolitic lithologies in the Hueco Mountains (Stop 4), where the overlying burrowed grainstone is not as dark as typical Jose, and oolitic fabrics have not yet been confirmed. The submergence event apparently also inhibited microbial reef growth. Although the Jose contains thrombolites in a few places, they are scarce, relatively small, and isolated in contrast to the large, laterally continuous buildups that characterize the bounding Cookes Member and McKelligon Formation. A thin (<15 m) interval of bioturbate lime mudstone to fine packstone separates the top of the Jose and the lowest McKelligon reef in many sections (including this one), making the contact less conspicuous than where reefs occur at the very base of the McKelligon.

The Jose Member is the most productive unit in the Hitt Canyon Formation for macrofossils in New Mexico, where it contains an abundant fauna dominated by asaphid trilobites (Loch et al., 2003). In contrast, it yields very few macrofossils in Texas, and most are mollusks of little biostratigraphic utility. A single collection of fewer than 20 trilobite specimens from the base of the Jose at Hitt Canyon in the northern Franklin Mountains consists entirely of hystricurid trilobites. Although the sample size is too small to allow rigorous statistical comparison, the contrast in generic composition is remarkably similar to that documented in Skullrockian faunas in the Tribes Hill Formation of New York by Westrop et al. (1993). As in the Tribes Hill, the trilobite faunas from the Jose suggest the existence of two biofacies: one dominated by mollusks and including hystricurid trilobites, and another dominated by asaphid trilobites with a much subordinate mollusk component.

Conodonts from the Jose assign it to the medial Stairsian *Macerodus diana* Zone, allowing correlation with successions outside of Texas and New Mexico. The Jose submergence event is recorded in the central Appalachians, where an entire platform-to-slope transect is preserved, including intact shelfbreak and upper slope facies (Taylor et al., 1996). In that area, the highest member of the Grove Formation, recently named the Woodsboro Member by Brezinski (2004), records onlap and the replacement of shelfbreak microbial reefs and shelf-edge sands with dark, shaly upper slope facies during deposition of the *M. diana* Zone

(Taylor et al., 1996). Farther west, in the Great Valley of Maryland, coeval strata of the “oolitic member” of the Rockdale Run Formation (Sando, 1957) record suppression of microbial reef growth and deposition of oolite, just as occurred in the deposition of the Jose Member in the Southwest.

The submergence event can also be tracked geographically using carbonate  $\delta^{13}\text{C}$  profiles. The carbonate  $\delta^{13}\text{C}$  stratigraphic profiles generated from multiple sections in the southwestern United States (Fig. 4) include a major ( $>2\%$ ) negative excursion that coincides precisely with the base of the Jose Member. This “Jose Event” has proven useful in confirming the age-equivalence of the oolitic interval and associated ribbon limestones in the Franklin and Hueco Mountains to the Jose Member in southern New Mexico. The same negative excursion is also present just above the base of the San Juan Formation in the Argentine Precordillera (Buggisch et al., 2003), in the Malyi Karatau Range, Kazakhstan, and probably in the Arbuckle Mountains, Oklahoma (Gao and Land, 1991). Associated conodonts indicate that the event was virtually coincident with the appearance of the conodont *Paraoistodus proteus*, a species used to recognize the base of the British “Arenig.” This linkage to the globally recognized Arenig transgression reinforces our interpretation of the base of the Jose as a product of sea level rise.

Drive out McKelligon Canyon Drive (east), turn right onto Alabama Street, then right onto Richmond Avenue, and continue to Scenic Drive. Turn right into the parking lot for the Police Academy (obtain permission in advance). Beware of traffic: Scenic Drive is narrow and heavily traveled.

## STOP 2. McKelligon Formation and Upper Hitt Canyon Formation along Scenic Drive

Exit vehicles and walk southwest from the Police Academy along Scenic Drive, ascending stratigraphically to the conspicuous, orange-weathering sandstone at the base of the Pistol Range Member.

### Stop 2a. McKelligon Formation—Pistol Range Member and Underlying Strata

The strata above the orange, dolomitic sandstone here at Scenic Drive constitute the type section of the McKelligon Formation (LeMone, 1969), which is well known for its prominent sedimentary cycles (Goldhammer et al., 1993) and biohermal complexes (Toomey and Ham, 1967; Toomey, 1970; Toomey and Nitecki, 1979; Rigby et al., 1999). The latter differ from the microbial buildups of the underlying Hitt Canyon Formation in the abundance of the demosponge *Archaeoscyphia* and the presence of the alga *Calathium*. The thin (1–1.5 m), orange-weathering, cross-bedded, dolomitic sandstone that occurs a short distance below the McKelligon reefal facies has played a prominent role in defining that formation boundary in all previous studies. Cloud and Barnes (1948) used this sandstone to define the base of their Unit B in dividing the El Paso Group into three parts, lettered from bottom to top. Flower (1964) and LeMone (1969, 1996)

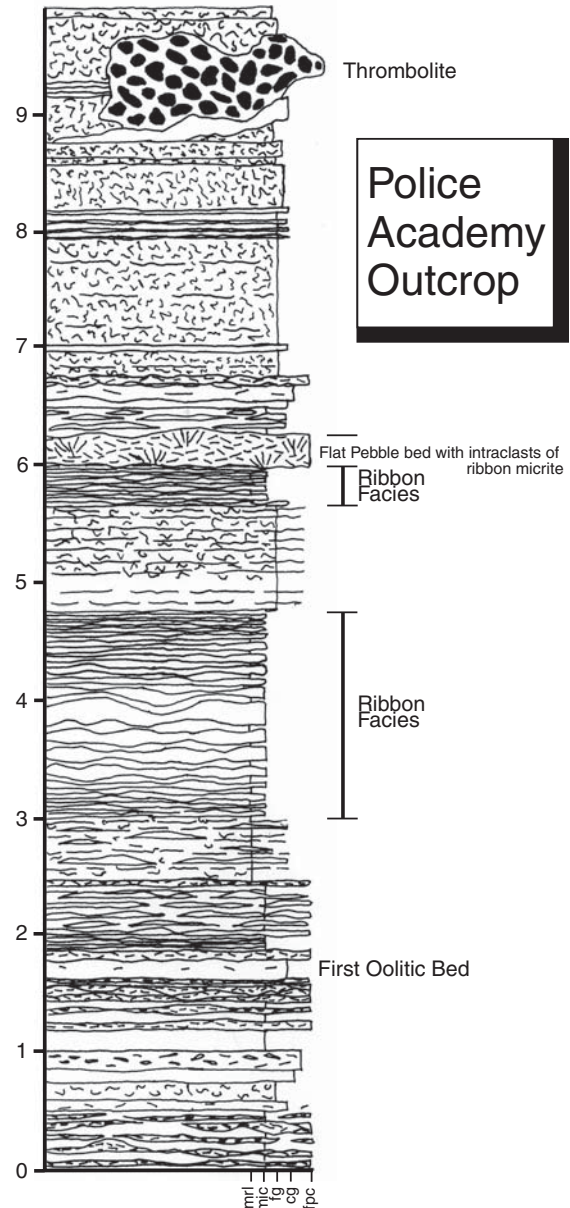


Figure 6. Detailed lithologic column of outcrop at the Police Academy (Stop 2b) showing the highest 1.7 m of the Cookes Member and the basal 8.3 m of the Jose Member of the Hitt Canyon Formation. Base of lowest oolitic bed defines base of Jose Member. See Figure 5 caption for lithologic abbreviations.

used the base of this sandstone to define the base of the McKelligon Formation, setting that bed and the overlying 21–24 m of dolomite apart as the basal Pistol Range Member of the McKelligon. Unfortunately, Flower and LeMone misidentified the 22 m of sandy dolomite directly below the Pistol Range Member as the Jose Formation, correlating it incorrectly with the dark oolitic limestone interval assigned that name in New Mexico, a misrelation perpetuated by Hayes (1975) and Clemons (1991).

One consequence of this miscorrelation is the interpretation of the base of the Pistol Range Member in the Franklin Mountains as an unconformity with a lacuna that includes the time represented by the Mud Springs Mountain Formation and Snake Hills Formation in New Mexico (Fig. 1, column 3). Flower (1964) erected those formations to accommodate 6–9 m of stromatolitic limestone with the gastropod *Bridgites* and as much as 18 m of overlying thinly bedded limestone (respectively) that occur directly above the (true) Jose in southern New Mexico (LeMone, 1983). Finding no evidence of these units or their faunas directly above what they believed to be the Jose in the Franklins, Flower (1969) and LeMone (1969) understandably concluded that an unconformity must exist to account for the absence of as much as 27 m of strata. Our discovery of a dark oolitic interval (the true Jose) some distance below the base of the Pistol Range reveals that the purportedly missing strata are present in the Franklin Mountains succession, but *below* the Pistol Range, rather than above it. The thickness of the interval between the base of the Pistol Range Member and the top of the true Jose Member along Scenic Drive could not be established with certainty owing to faulting that complicates that part of the Scenic Drive section. However, at Hitt Canyon, the top of our Jose Member is separated from the top of the sandy dolomitic interval mistaken for the Jose by 28 m of strata, including a 7 m stromatolitic reef interval. Similarly, the base of the Pistol Range Member lies at 220.5 m in the McKelligon Canyon section (Fig. 5), 35 m above the top of the true Jose Member, and stromatolitic reefs are common between those horizons. The reefs are all dolomitized, so it is not possible to say whether they originally contained *Bridgites* or any other diagnostic macrofossil. Nonetheless, the simplest interpretation is that the strata below the Pistol Range Member that we assign to the base of the McKelligon Formation (including the “Jose and Chamizal Formations of previous authors) are the dolomitized equivalents of the Mud Springs Mountain and Snake Hills Formations in New Mexico. That being the case, there remains no evidence of an unconformity at the level of the Pistol Range sandstone.

Continue walking down-section, and return to the parking area for the Police Academy.

#### **Stop 2b. Jose Member of the Hitt Canyon Formation at the Police Academy**

The outcrop at the Police Academy exposes the highest few meters of the Cookes Member and the basal 8 m of the Jose Member (Fig. 6). The two ribbon limestone intervals seen at the base of the Jose Member at McKelligon Canyon are well developed in this section as well, although the base of the member is placed slightly lower at a thin bed of oolitic grainstone. Features seen here, but not seen in the Jose at McKelligon Canyon, include a prominent flat pebble conglomerate bed and an isolated thrombolite just under 1 m in thickness. Otherwise, the consistency in lithologic character between the two locations is remarkable. The lateral persistence of the Jose Member, not only along the length of the Franklin Mountains but across all of southern New Mexico,

justifies placement of the base of the McKelligon Formation at the top of this unique interval rather than at the base of the Pistol Range Member as defined by the sandstone bed higher in the section. Although it is well developed and conspicuous at the south end of the Franklin Mountains, the sandstone at the base of the Pistol Range thins northward to less than a meter at McKelligon Canyon and is represented at Hitt Canyon only by an inconspicuous interval of quartz sandy carbonate ~6 m thick. It has not been recognized in any sections in southern New Mexico.

Leave the Police Academy; turn right (west) to continue along Scenic Drive, then left onto Rim Road. Bear right at the stop sign onto Kerbey Street, then left onto Mesa (State Route 20); travel six blocks to West Schuster Avenue. Follow West Schuster to I-10; take I-10 west to Las Cruces, New Mexico. Follow I-25 north from Las Cruces to Truth or Consequences and take the northern exit (Exit 79). Pull into the Best Western Motor Lodge on the right. Driven distance is ~120 mi (193 km).

### **DAY 2—CABALLO MOUNTAINS, NEW MEXICO**

Return to I-25 and travel south to Exit 29, Caballo Dam. Turn right at the end of exit the ramp, and go south for 2.9 miles on Route 187. Turn left (east) at a telecommunications tower; travel 1.2 mi, and turn left at three-way intersection, then travel 0.8 mi, and turn right (east) onto a dirt road. Go 0.3 mi to another three-way intersection, and turn left (north). Travel 1.0 mi, pass under I-25, then go 1.8 mi farther, with the river on your left, and bear right at the fork in the road; to the left is the east end of Caballo Dam. Travel 4.0 mi as the road winds, rises, and falls across the dissected bajada, and turn right onto a rocky two-track road (four-wheel drive required) that leads east toward the range. Driving distance: Motel to Exit 29, 21 mi (34 km); I-25 to the four-wheel drive road, 12 mi (19.3 km).

#### **STOP 3. Cable Canyon/Bat Cave Gulch Measured Section**

##### **Stop 3a. Overview of the Sections**

Compare the view to the east with [Figure 7](#), which shows the locations of formation boundaries and measured sections in the footwall of the thrust fault that repeats the McKelligon Formation just north of Cable Canyon. Note the immense Bat Cave (BC) in the El Paso Group, barely visible at the left (north) edge of the figure, and the location of the old Sierrite Mine (SM) at the base of the Bliss on the north flank of the closer hill, capped by Hitt Canyon carbonates. The extremely glauconitic upper member of the Bliss Formation forms the conspicuous dark band on the hillside. These sections have provided the most continuous and highly resolved sequence of trilobite and conodont faunas, and the most complete  $\delta^{13}\text{C}$  profile, yet recovered from the Upper Cambrian and Lower Ordovician of New Mexico. Collections from the Bliss and Hitt Canyon Formations reveal that these units span much or all of the Sunwaptan Stage, the entire Skullrockian Stage, and most or all of the Stairsian Stage (Fig. 3) in this area.

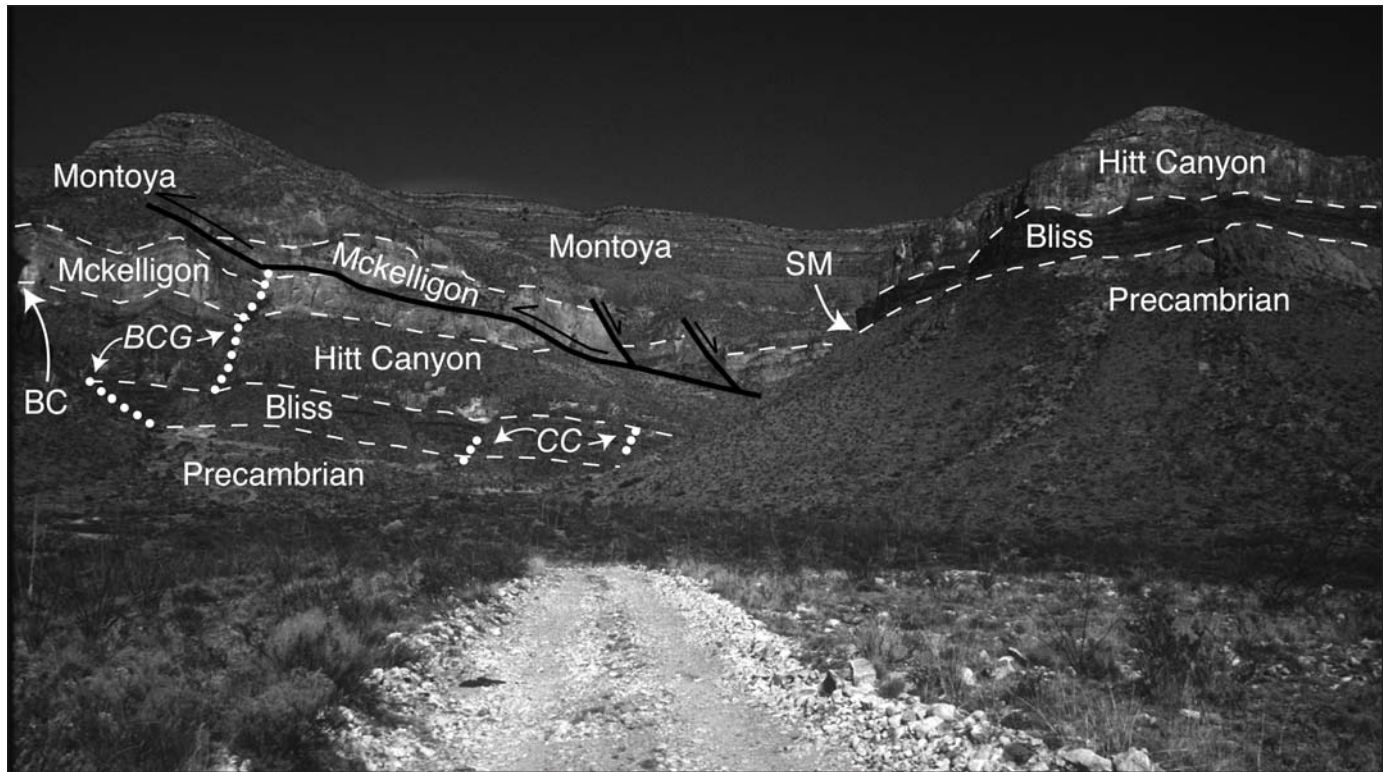


Figure 7. Distant view of Cable Canyon on the west side of the Caballo Mountains from the 4WD road in from the west (Stop 3a), showing the location of the Cable Canyon section (CC) of Taylor and Repetski (1995) just north of the Sierrite Mine (SM) and the Bat Cave Gulch section (BCG) of the present study in the gully below the Bat Cave (BC).

Drive east for 2.1 mi (3.38 km) into Cable Canyon. Drive all the way to the cliffs on the north side of the canyon before turning left onto an old mine road that runs along the base of the steep slope supported by the Bliss Formation (the Jeep at the bottom of Fig. 8A is parked at that turnoff). Park where the road ends just south of small, old quarry in Precambrian basement. Hike to the quarry and ascend the gully upslope (east) of it, toward the cliffs. This is the Bat Cave Gulch section.

### **Stop 3b. Lower Segment of Bat Cave Gulch Section—Bliss Formation**

**Millardan Series—Steptoean and Sunwaptan Stages.** The lower member of the Bliss is thin at this locality (Fig. 9), comprising a few meters of quartzitic sandstone at the base and 2 m of oolitic hematite at the top. This is the ore that was mined at the old Sierrite Mine on the south side of the canyon. The top of the oolite and its sharp contact with the lowest thin dolomite bed of the upper member are well exposed here. The upper member was measured and sampled in the cliffs and steep slopes on the south side of the gully, which ends at the base of the cliff supported by the Sierrite Member of the Hitt Canyon Formation, for which this locality is the designated type section.

The ages of the lower member and the basal strata of the upper member of the Bliss are poorly constrained. No diagnostic

trilobites of the medial Upper Cambrian Steptoean Stage were recovered here; however, Flower (1969) reported an *Elvinia* trilobite Zone fauna with the uppermost Steptoean genus *Camarraspis* from low in the Bliss at White Signal in southwestern New Mexico. The brachiopod *Eoorthis* was recovered in the present study from sandstone beds interstratified with oolitic hematite in the lower member at Lone Mountain and was reported from a few other locations in southern New Mexico by Flower (1969). This suggests a basal Sunwaptan age for the highest beds of the lower member. If that age is correct, the base of the Sunwaptan lies within the lower member, and the transgression recorded by the base of the upper member in New Mexico was a Sunwaptan event. The Sunwaptan strata in the upper member yield very few fossils, but conodont collections from dolomite beds at this locality verify the presence of faunas as old as the *Proconodontus tenuiserratus* Zone (or lowest part of the *P. posterocostatus* Zone) and as young as the uppermost Sunwaptan *Cambroistodus minutus* Subzone of the *Eoconodontus* Zone (Taylor and Repetski, 1995). Some of the trilobite species recovered from the Bat Cave Gulch section are shown in Figure 10. A small collection from the highest meter of Sunwaptan strata includes *Euptychaspis kirki* (Fig. 10P), a species restricted to the *Saukiella serotina* Subzone of *Saukia* Zone, corroborating the age indicated for these strata by the conodonts.

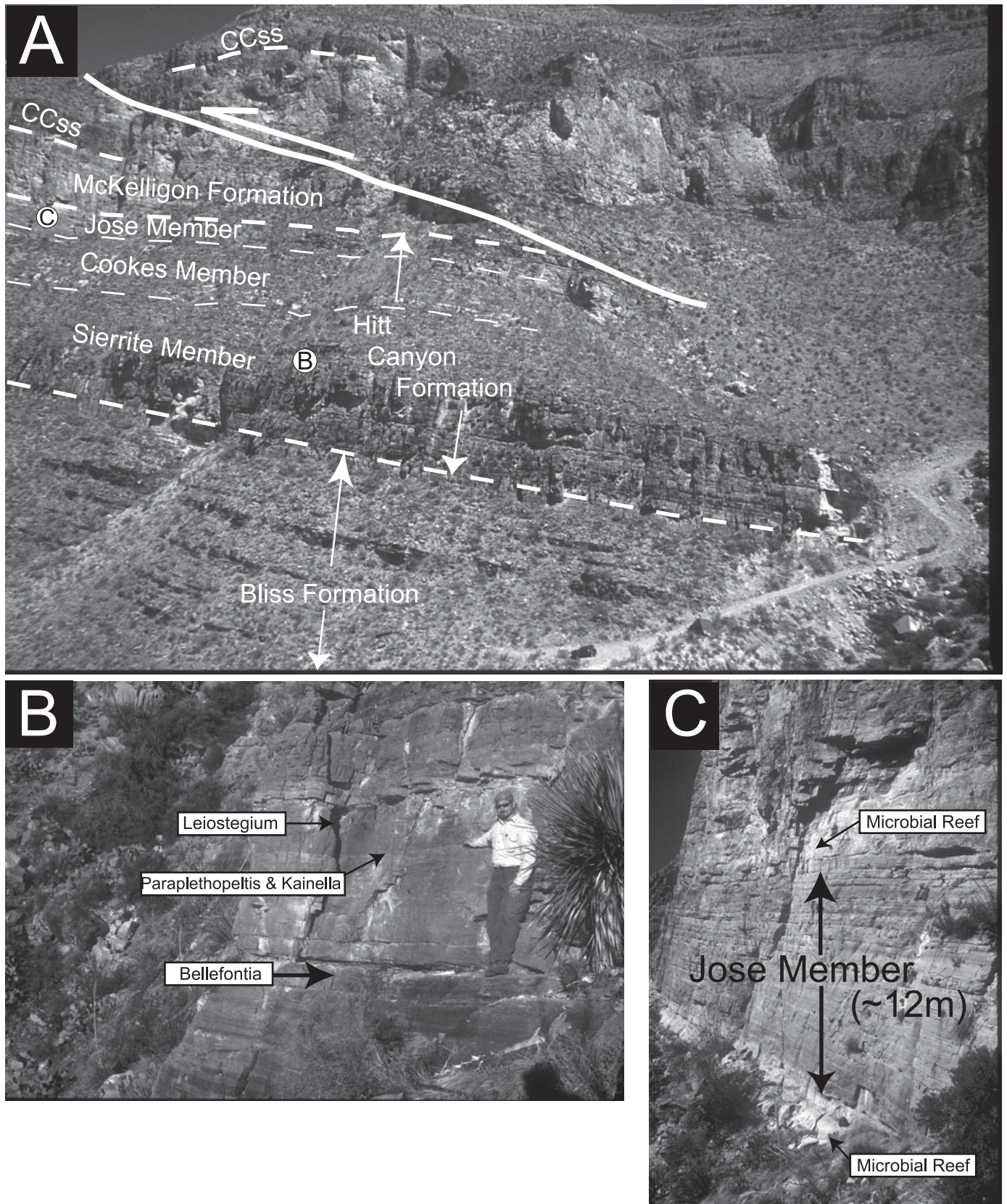


Figure 8. (A) View northeast (from Sierrite Mine) showing the Cable Canyon section in the Bliss studied by Taylor and Repetski (1995) and unit boundaries in the overlying El Paso Group used in the present study. CCss—Cable Canyon Sandstone. B and C in photo A mark the *stratigraphic* levels of the other photos; actual locations lie out of view to north. (B) Base of Stairsian Stage in the Bat Cave Gulch (BCG) section (Stop 3c); the bioclastic lag with lowest Stairsian fauna at the person's right hand; possible disconformity (top of lower Sierrite cliff) at parting just below knee. (C) Dark band formed by the Jose Member near the top of the BGC section.

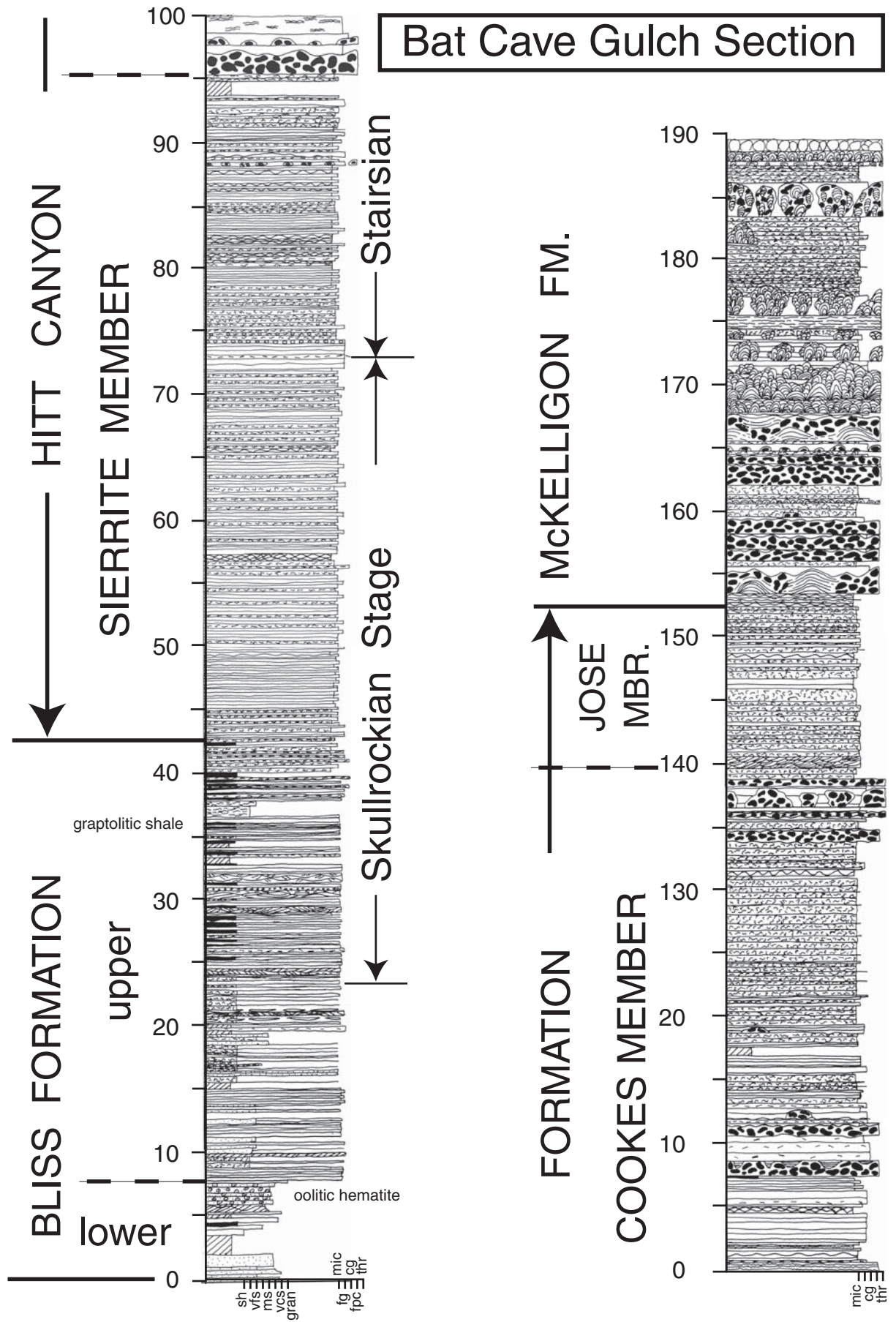


Figure 9. Lithologic column for the Bat Cave Gulch measured section in the Caballo Mountains, New Mexico. See Figure 5 caption for lithologic abbreviations.

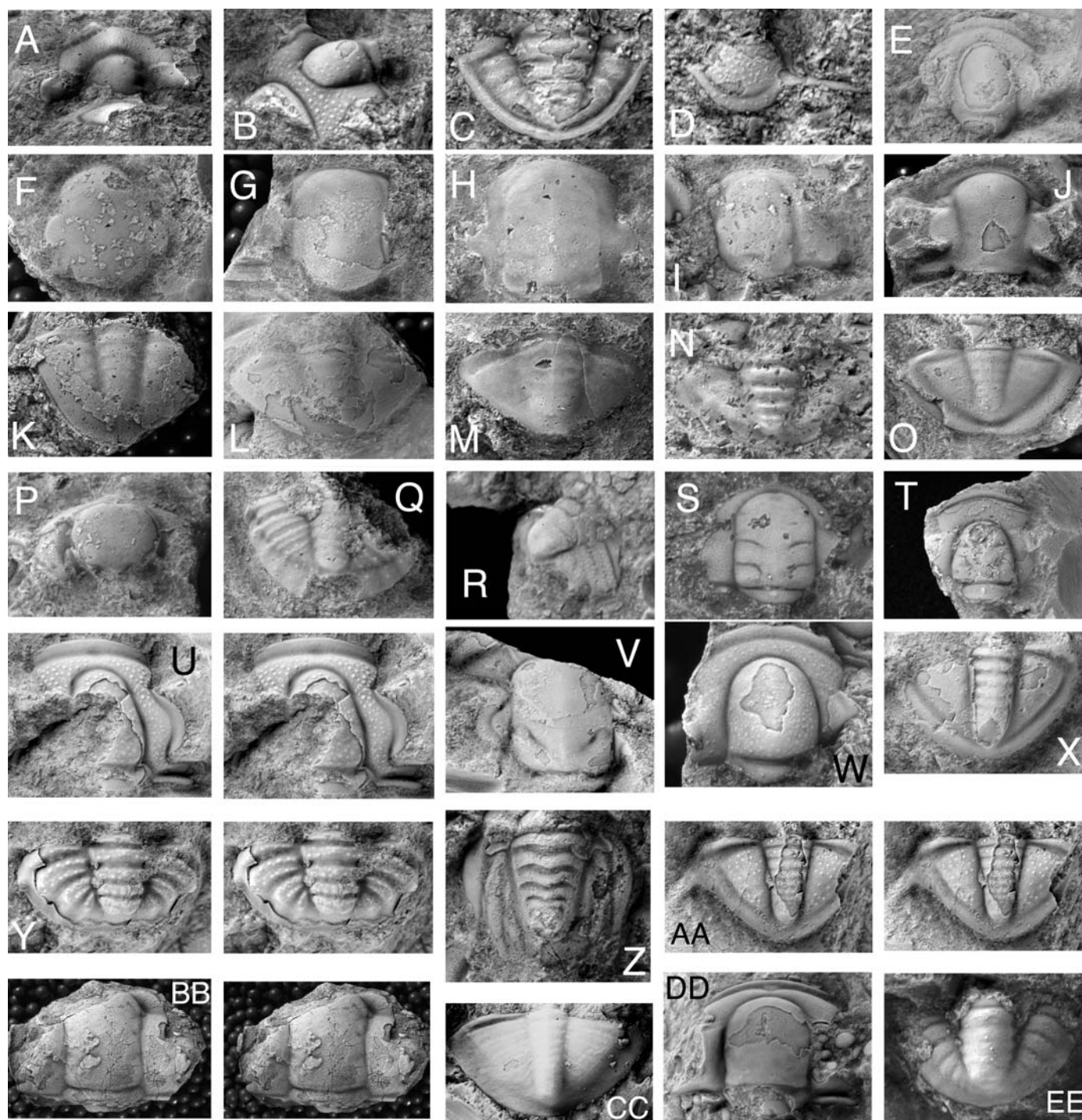


Figure 10. Selected trilobite cranidia (cr), pygidia (py) and librigenae (lib) from the Bliss and Hitt Canyon Formations. Dorsal view unless indicated otherwise. (A) *Highgatella cordilleri*, cr, X4.5, Bat Cave Gulch (BCG) 29.37 m. (B–D) *Politicurus* sp., BCG 71.45 m: (B) cr, X11.5, anterior oblique view; (C) py, X11, and (D) lib, X8. (E) *Parplethopeltis* sp. 1, cr, X2.5, BCG 72.92 m. (F, K) *Symphysurina* n. sp. 6, BCG 37.85 m: (F) cr, X2.5; (K) py, X2. (G, L) *Symphysurina* n. sp. 1, BCG 31.34 m: (G) cr, X2; (L) py, X2. (H, M) *Symphysurina* n. sp. 5, BCG 36.63 m: (H) cr, X3.5; (M) py, X3.5. (I, N) *Jujuyaspis borealis*, BCG 36.63 m: (I) cr; (N) py, X5.5. (J, O) *Bellefontia* sp., BCG 66.54 m: (J, X2.5) cr; (O) py, X2. (P) *Euptychaspis kirki*, cr, X6, BCG 23 m. (Q) *Missisquoia depressa*, py, X6.5, BCG 24.08 m. (R) *Eurekia apopsis*, py, X8, BCG 23.6 m. (S) *Triarthropsis nitida*, cr, X8, BCG 23.6 m. (T) *Apoplanias rejectus*, cr, X2.5, BCG 25.45 m. (U, Y) Stereopairs of *Hystricurus* n. sp. A, BCG 135.6 m: (U) cr, X2.5; (Y) py, X4.5. (V, Z) *Kainella* sp.: (V) cr, X2, BCG 75 m; (Z) py, X3.5, BCG 72.92 m. (W) *Parplethopeltis* sp. 2, cr, X5, BCG 72.92 m. (X) *Leiostegium manitouensis*, py, X4.5, BCG 75 m. (AA) Stereopair of *Perischodory* sp., py, X3.5, HUT1 32.22 m. (BB) Stereopair of *Leiostegium* sp., cr, X1, HUT 190.61. (CC) *Aulacoparia? huygenae*, py, X1.5, MCN 141 m. (DD, EE) *Jeffersonia* n. sp.: (DD) cr, X3, BCG 153.45m; (EE) py, X6, MCN 141 m.

**Ibexian Series—Skullrockian Stage.** Trilobites (Fig. 10) and conodonts from Bat Cave Gulch constrain the position of the base of the Skullrockian Stage to <0.5 m and the top of the stage to <1.5 m (Fig. 9). The stage is nearly 50 m thick, spanning the highest 19.3 m of the upper member of the Bliss Formation and the basal 29.95 m of the Sierrite Member of the Hitt Canyon Formation. Nearly all Skullrockian trilobite and conodont zones have been identified, although those within the Bliss are anomalously thin, reflecting the very low rock accumulation rates typical of glaucarenite-rich facies. The extinction horizon that defines the base of the Ibexian lies within an essentially monofacial interval of interbedded recessive glaucarenites and rippled, medium to coarse-grained bioclastic grainstone. Aside from a decrease in the degree of dolomitization of the grainstone beds, lithologies in uppermost Sunwaptan and basal Skullrockian strata are identical, providing no evidence to support models that invoke either a rise or fall in sea level as the cause of faunal change. Although condensed, the boundary interval at Cable Canyon is complete to the extent that the three thin trilobite subzones at the base of the Ibexian are all represented, including the basal *Eureka apopsis* Subzone of the *Saukia* Zone, which was not discovered in previous work at this locality (Taylor and Repetski, 1995). The lowest *E. apopsis* collection (Bat Cave Gulch [BCG], 23.67 m) was recovered 40 cm above the top of a conspicuous, 20–30 cm, orange-weathering dolomite bed that serves as a useful marker for relocating the base of the Skullrockian on each visit and that is helpful in tying collections from the older Cable Canyon section into the newer BCG section. Closely spaced collections locate precisely the bases of the *Missisquoia depressa* (BCG 24.08 m) and *M. typicalis* (BCG 24.6 m) Subzones of the *Missisquoia* Zone. The base of the *M. typicalis* Subzone, which defines the top of the Ptychaspis Biome, is marked as it is throughout Laurentian North America by coquinas of the olenid trilobite *Apoplanias rejectus* (Fig. 10T) and the brachiopod *Apheoorthis*.

The  $\delta^{13}\text{C}$  profile through the upper Sunwaptan and basal Ibexian at Cable Canyon does not approach the quality of those developed for this interval elsewhere (Ripperdan et al., 1992; Ripperdan and Miller, 1995), probably due to the extremely heterolithic character of the upper Bliss Formation at this locality. One feature that appears consistent with profiles developed elsewhere is the steady rise in values from  $-0.8\text{‰}$  to  $+0.6\text{‰}$  through the basal 5 m of the profile. That segment might represent the uppermost part of the strongly negative “HERB event” (see Ripperdan, 2002), which reached peak negative values just below the base of the *Cambroistodus minutus* Subzone of the *Eoconodontus* Zone.

The appearance of *Highgatella cordilleri* (Fig. 10A) at 29.2 m marks the base of the *Symphysurina* trilobite Zone. Although many *Symphysurina*-rich collections were recovered from the upper Bliss, placement of the boundaries of the three subzones recognized in this zone in Oklahoma (Stitt, 1977, 1983) and Utah (Loch et al., 1999) has proven difficult. The defining species—*S. brevispicata*, *S. bulbosa*, and *S. woosteri* (in ascending order)—have not been identified with confidence, in part because the Bliss material does not adequately preserve prosopon

(surface texture), which is important in species diagnosis. However, even without prosopon, most of the *Symphysurina* material clearly represents undescribed species (e.g., Figures 10F–H and 10K–M). Of particular interest in the Bliss fauna are two cosmopolitan species that allow correlation with non-Laurentian successions: the olenid trilobite *Jujuyaspis borealis* and the dendroid graptolite *Rhabdinopora flabeliformis*. *R. flabeliformis*, which is abundant in two thin shale packages between 35 and 36 m, is noteworthy because this is the only known occurrence of this important Lower Ordovician index species anywhere within a paleoequatorial shelf sequence (Cooper et al., 1998). *J. borealis* (Figs. 10I and 10N), which occurs less than half a meter above the graptolitic shale, is a widely distributed species that allows correlation of a thin interval near the middle of the *Symphysurina* Zone from central Texas (Stitt and Miller, 1987) to Alberta (Norford, 1969). The presence of the graptolitic shale, typically a deepwater facies, in the Bliss is extraordinary. Interestingly, the associated conodonts represent the *Cordylodus angulatus* Zone, the interval in which evidence of a significant submergence (the Stonehenge Transgression) has been documented in platform sequences throughout North America (Taylor et al., 1992). The base of the *Bellefontia-Xenostegium* trilobite Zone lies very near the base of the Hitt Canyon Formation, and the top of the zone corresponds precisely with the top of the cliff (i.e., the top of the Sierrite Limestone as originally defined by Kelly and Silver [1952]).

Follow the base of the Sierrite cliff south for a short distance to the head of the next gully where a notch in the cliff provides access to the units above the Bliss. The climb up through the notch to the top of the cliff is not too difficult but is recommended only for those comfortable with heights.

### **Stop 3c. Upper Segment of Bat Cave Gulch Section—Hitt Canyon Formation**

**Skullrockian-Stairsian Stage boundary.** Although macrofossil recovery is sparse through the Sierrite Member, the position of the Skullrockian-Stairsian boundary (the base of the *Leioptegium-Kainella* Zone) has been established to within <1.5 m in this section, 1.7 m in the Hueco Mountains, and <5 m at Hitt Canyon in the Franklin Mountains. This boundary, the top of the “Symphysurinid Biome” of Stitt (1983), elsewhere is characterized by a thin zone dominated by the hystricurid genus *Paraplethopeltis*, separating the pre-extinction fauna of the underlying *Bellefontia-Xenostegium* Zone from the overlying replacement fauna of the *Leioptegium-Kainella* Zone. Here at Cable Canyon, the faunal turnover is accompanied by a lithologic change from the cliff-forming fine grainstone containing the pre-extinction *Bellefontia-Xenostegium* Zone fauna to a 1.7 m package of coarser bioclastic grainstone that includes centimeter to decimeter-scale skeletal lags of brachiopod and trilobite debris (Fig. 8B) similar to the coquinas that characterize biome boundaries in the Upper Cambrian. The lowest post-extinction trilobite lag yielded a nearly monogeneric fauna dominated by *Paraplethopeltis* (Figs. 10E and 10W), suggesting that it might represent the *Paraplethopeltis* Zone. However, it also yielded

two specimens of *Kainella* (Figs. 10V and 10Z) and is assigned accordingly to the *Leiostrigium-Kainella* Zone.

It appears, therefore, that there is a small stratigraphic break in the Sierrite Member that omits the very highest beds of the Skullrockian Stage: the *Paraplethopeltis* Zone is missing and the *Leiostrigium-Kainella* Zone rests unconformably directly on top of the *Bellefontia-Xenostegium* Zone. Hematitic staining of surfaces within the highest meter of the *Bellefontia-Xenostegium* Zone at Cable Canyon, and the occurrence of a thin interval with abundant quartz sand between the highest Skullrockian and lowest Stairsian collections in the Franklin and Hueco Mountain sections, support this interpretation. Some part of the *Bellefontia-Xenostegium* Zone might also be missing; however, the highest Skullrockian collection contains the hystricurid *Politicurus* (Fig. 10B–D), which is restricted to roughly the upper quarter of that zone in Utah (Adrain et al., 2003), suggesting that at least three quarters of the zone is present. Trilobites and conodonts recovered from the lowest Stairsian strata at Cable Canyon and Hitt Canyon indicate that little, if any, of the basal Stairsian is omitted. The presence of *Paraplethopeltis*, which ranges upward only a few meters into the *Leiostrigium-Kainella* Zone in the Manitou Formation in Colorado (Berg and Ross, 1959), confirms that basal Stairsian strata are present in New Mexico and Texas. These strata also yield conodonts of the *Rossodus manitouensis* Zone, which barely extends upward into the Stairsian Stage, rather than those of the overlying Low Diversity Interval. The persistence across the study area of a 2‰ positive  $\delta^{13}\text{C}$  excursion just above the base of the Stairsian, and its resultant utility as a datum on which to hang the isotopic profiles (Fig. 4), also suggests little if any loss of section from the base of the stage due to erosion or non-deposition. That excursion, which is the only level within the Stairsian where positive values are reached, is conspicuous in the middle of the La Silla Formation in the profile published by Buggisch et al. (2003) for the Argentine Precordillera.

The position of the base of the Low Diversity Interval at BCG 77 m, just a few meters above the base of the *Leiostrigium-Kainella* Zone in the upper Sierrite Member (Fig. 9), is consistent with the relationship established for these zonal boundaries in previous studies (Ross et al., 1997; Miller et al., 2003). In contrast, the relative positions within the Hitt Canyon Formation of the next higher conodont and trilobite zones, the *Macerodus diana*e and *Tesselecauda* Zones, differs significantly from that reported from Utah, where Ross et al. (1997) reported that the base of the *M. diana*e Zone lies somewhere within the upper half to third of the *Tesselecauda* Zone. In Texas and New Mexico, the base of the *M. diana*e Zone was found consistently 15–20 m above the base of the Cookes Member. The only trilobite species recovered from the Hitt Canyon Formation that also occurs in Utah and Idaho, where the *Tesselecauda* Zone has been described, is *Hystricuris* sp. nov. A of Adrain et al. (2003) (Figs. 10U and 10Y). The occurrence of that species slightly more than 40 m above the base of the Cookes Member at Cable Canyon (BCG 135.6 m) places the base of the *Tesselecauda* Zone well above the base of the *M. diana*e Zone. The data currently available are insufficient to determine

whether the base of the *M. diana*e is older and/or the base of *Tesselecauda* is younger in the El Paso Group than in Utah and Idaho, or whether the discrepancy is an artifact of imprecision in the sampling or compositing of data in one or both areas.

What correlates very well across the southwest and into the Ibexian standard succession in Utah is the initiation of microbial reef growth during deposition of the Low Diversity Interval. The horizon that represents that event in the El Paso Group (base of the Cookes Member; Figs. 8A and 9) occurs consistently 15–20 m below the base of the *Macerodus diana*e Zone, supporting the assertion that the onset of reef growth was synchronous across the area. In Utah, prominent microbial reefs also appear in the Low Diversity Interval near the base of the Fillmore Formation (Evans et al., 2003), above a relatively thick succession of Skullrockian and basal Stairsian non-reefal carbonates. Another parallel between the reefs of the El Paso Group and the Fillmore Formation is a change in the structure and composition of the reefs up-section. In both areas, the alga *Calathium* is conspicuous and abundant in the higher reefs (“Church’s Reef” in the Fillmore and reefs in the McKelligon Formation) but absent from those lower in the section (“Miller’s Reef” and “Hintze’s Reef” in the Fillmore and those in the Cookes Member). If the lower and upper reefs of the two areas are correlative as their similarities suggest, then any geochemical or lithologic evidence of the paleoceanographic event(s) that produced the Jose Member and associated isotopic excursion should be found in the Fillmore between “Hintze’s Reef” and “Church’s Reef.” We propose Bat Cave Gulch as the type section for the Cookes Member owing to poor exposure and structural complications in the Cookes Range. Both contacts are well exposed at Cable Canyon: the base at the lowest meter-scale reef at BCG 95 m and the top (= base of the Jose Member) at the base of a prominent, dark, cross-stratified grainstone 139.75 m above the base of the section.

Continue upslope through the highest part of the Sierrite Member and intervals of well-preserved microbial reefs at the base and near the top of the Cookes Member. The dark band of non-reefal limestone at the base of the next set of tall cliffs (Fig. 8C) is the Jose Member.

**Medial to upper Stairsian strata—Jose Member and McKelligon Formation.** The sheer cliff at the top of the Bat Cave Gulch section exposes the entire Jose Member and all of a relatively thin McKelligon Formation, including the sharp contact with the resistant, brown-weathering Cable Canyon Sandstone at the base of the Montoya Group. The Jose lacks the ribbon limestone facies that it contains in Texas, but still has a deep subtidal aspect in the abundance of carbonate mud, much of it distributed as selectively dolomitized centimeter-scale patches in conspicuously burrow-mottled intervals of oolitic packstone. The dark color and absence of microbial reefs also reinforce the interpretation of this unit as representing deeper conditions than the units above and below it. Dominance of the trilobite fauna by an asaphid (*Aulacoparia? huygenae*; Fig. 10CC) also is consistent with a deeper water assignment. The unusual biofacies of the Jose Member has hampered attempts to assign a precise age to

this unit based on its trilobites; however, the first thorough study of its trilobite fauna is in progress. Conodonts from the Jose assign it to the medial Stairsian *Macerodus diana* Zone, but collections from the basal 5 m of the overlying McKelligon Formation might represent the overlying *Acodus deltatus* Zone, and it is possible that the very highest beds of the Jose do as well. Several collections from 15 or more meters above the base of the McKelligon contain *Oneotodus costatus* and are more confidently assigned to the *A. deltatus* Zone. Trilobites recovered from the McKelligon in the present study include the bathyurid trilobite genera “*Peltabellia*” (from this section, Scenic Drive, Cookes Peak, and Mescal Canyon), *Bolbocephalus* (Hitt Canyon, Mescal Canyon), *Petigurus* (Mescal Canyon), *Benthamaspis* (Scenic Drive, Mescal Canyon), and *Jeffersonia* (Scenic Drive). These genera are characteristic of the Jeffersonian Stage (Loch, 1995) of eastern Laurentia.

Allow enough time for a cautious climb back down to the vehicles while there is sufficient daylight to avoid the cacti. We will return to El Paso (135 mi, 217 km) via I-25 and I-10.

### DAY 3—HUECO MOUNTAINS, TEXAS

From its intersection with Airway Boulevard, follow Montana Boulevard (U.S. Route 62) east for 19.5 miles, then turn right (southeast) off Route 62. Note the windmills on the southeastern skyline after ~4.5 mi; go straight through the four-way intersection 6.9 mi from Route 62, continue for another 3.4 mi, and turn left toward the windmills. Proceed 0.4 mi, turn right near the power poles, go 0.3 mi, turn left (upslope), and park. Distance from the Airway-Montana intersection: 30.5 mi (19 km).

### STOP 3. Hueco Mountains Measured Section

#### Stop 3a. Bliss Formation

In contrast to the completed work in the sections to the west, what we present here in the Huecos is more of a work in progress. The Bliss is considerably thicker than it is to the west, with over 90 m of sandstone assigned to the lower member, much of it completely homogenized by burrowing. It is well exposed in the gully leading up to the notch in the cliffs through which the section was measured. The base of the upper member is marked by the appearance of recessive glaucarenite intervals just above a 7.65 m hematitic zone that caps that lower member. The upper member is a heterolithic mix of glaucarenite, quartz sandstone, and varied carbonate lithologies. The carbonates increase in relative abundance toward the intercalated contact with the Hitt Canyon Formation. Moldic specimens of *Symphysurina* were recovered from a thick sandstone bed low within the upper member of the Bliss, 95–100 m above the base of the section. This assigns those strata to either the *Symphysurina* or *Bellefontia-Xenostegium* Zone within the Skullrockian Stage. The biostratigraphic data confirm that the base of the Hitt Canyon Formation, again placed at the base of the pure, cliff-forming carbonate, is significantly younger than the base of the Hitt Canyon in New Mexico.

Recall that the cliff of grainstone at the base of the Sierrite Member at Cable Canyon consists entirely of upper Skullrockian strata of the *Bellefontia-Xenostegium* Zone; trilobites of the *Leiostegium-Kainella* Zone and the basal Stairsian positive  $\delta^{13}\text{C}$  excursion were found just above the top of the cliff. The trilobites and  $\delta^{13}\text{C}$  data recovered from this section in the Huecos place that faunal change and isotopic excursion at the base of the prominent cliff of Sierrite grainstone.

#### Stop 3b. Hitt Canyon Formation

The upper part of the Sierrite Member, above the cliff of fine grainstone, includes numerous meter-scale cycles, each of which shallows upward from lime mudstone at its base to a cap of coarse grainstone and/or microbial boundstone. The cyclic upper Sierrite is overlain by well-developed microbial reefs at the base of the Cookes Member, which include some remarkable stromatolites nearly 2 m tall. As elsewhere, the Cookes contains two prominent intervals of reefs and associated grainstone, one at the base and another high within the member. Thinly bedded lime mudstone with prominent burrows that often weather in relief dominates the intervals between the reefs. Isolated trilobite collections recovered so far from the Cookes offer promise of more recovery than has been typical of this member in sections to the west (e.g., Figs. 10AA and 10BB). The top of the Cookes is placed at the base of an 80 cm interval of dark ribbon limestone at the bottom of a cliff formed by the highest beds preserved at this locality. We interpret this recessive ribbon limestone as the base of the Jose Member, a correlation supported by the strongly negative ( $<-3\%$ ) C-isotopic values acquired from this interval (Fig. 4). Except for a prominent 80 cm thrombolitic reef that sits directly on top of the ribbon limestone, the cliff is a thick package of non-reefal grainstone that displays light and dark banding on a 0.5 m scale. The banding is caused by alternation of dark medium to coarse grainstone with lighter, burrow-mottled intervals similar to those common in the Jose Member in New Mexico, although no oolitic textures have yet been found, and none of the grainstone is quite as dark as the typical Jose.

Allow sufficient time to descend the slope to be at the vehicles for departure at noon.

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