CAMBRIAN STRATIGRAPHY AND PALEONTOLOGY OF NORTHERN ARIZONA AND SOUTHERN NEVADA

THE 16TH FIELD CONFERENCE OF
THE CAMBRIAN STAGE SUBDIVISION WORKING GROUP
INTERNATIONAL SUBCOMMISSION ON CAMBRIAN STRATIGRAPHY
FLAGSTAFF, ARIZONA, AND SOUTHERN NEVADA, UNITED STATES

Edited by
J. Stewart Hollingsworth
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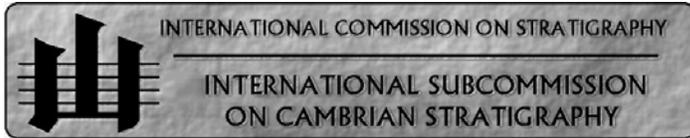
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ARTICLE 7
TRILOBITE BIOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY OF THE UPPER DYERAN
(TRADITIONAL LAURENTIAN "LOWER CAMBRIAN") IN THE SOUTHERN GREAT BASIN,
U.S.A.

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ABSTRACT—The desire for high-resolution biostratigraphic zonation, combined with uncertainty in the true range of the eponymous genus, requires that the "*Olenellus* Zone" be abandoned as the highest zone of the Dyeran Stage (Waucoban Series, traditional "lower Cambrian") of Laurentia. Six new biostratigraphic zones are established within the upper part of the Dyeran Stage: the *Arcuolenellus arcuatus* (oldest), *Bristolia mohavensis*, *Bristolia insolens*, *Peachella iddingsi*, *Bolbolenellus euryparia*, and *Nephrolenellus multinodus* (youngest) zones. The base of each zone is defined by the first appearance datum of the eponymous species. Sequence stratigraphic analysis reveals the presence of four depositional sequences within the upper Dyeran of the southern Great Basin. Sequence boundaries are often marked by erosion surfaces within successions deposited on the craton and the inner and middle shelf, but do not show strong association with observed range ends of olenelloid species and do not correspond to zonal boundaries within the upper Dyeran. Sequence I spans the *A. arcuatus* Zone to the lowermost *Bo. euryparia* Zone; Sequence II is contained entirely within the *Bo. euryparia* Zone; Sequence III spans the upper part of the *Bo. euryparia* Zone and lower part of the *N. multinodus* Zone; and Sequence IV corresponds to the upper part of the *N. multinodus* Zone. The extinction of the Olenelloidea is contained within Sequence IV, but the completeness of this sequence is unknown and the nature of the extinction (abrupt or more protracted) cannot be determined.

INTRODUCTION

THE IMPORTANCE of biostratigraphy to the study of Earth history cannot be overstated. The resolution of biostratigraphic zones typically determines the precision with which past biological or geological events can be correlated between localities, and often provides a practical limit to the temporal fineness at which change in biotic diversity can be studied. Cambrian strata record many significant evolutionary events, including the early diversification of animal phyla (e.g., Valentine, 2004) and dramatic faunal turnovers within particular clades (e.g., trilobites; Palmer, 1965, 1979, 1984, 1998a). Precise calibration of the rate and timing at which such events occurred requires a finely resolved biostratigraphic zonation of the Cambrian System.

Cambrian biostratigraphy is in a state of flux. Work is under way to establish a globally applicable zonation of the System based on the first occurrences of widespread species (e.g., Peng and Babcock, 2008). Such work is rendered difficult on account of the high degree of provinciality of Cambrian faunas (e.g., Palmer, 1998c): very few fossil species are known from more than one paleocontinent, especially prior to the mid-Cambrian radiation of agnostine arthropods. Indeed, this high degree of endemism even creates difficulty when attempting to correlate among regions of single paleocontinents. The fact that many clades were limited in their paleogeographic distribution justifies an effort to improve Cambrian biostratigraphic resolution at various spatial scales. A high-resolution zonation for a single paleocontinent such as Laurentia has great merit for studying evolutionary events that occurred on that paleocontinent, and is likely to provide a more refined framework than a globally applicable scheme.

Previous workers defined biostratigraphic zones for the Cambrian of Laurentia based primarily on generic occurrences (e.g., Deiss, 1939; Howell et al., 1944; Lochman-Balk and Wilson, 1958; Fritz, 1972). This lessens the problem of provinciality to a degree, because the geographic distribution of a genus often exceeds that of any of its constituent species. A genus-level zonation also has some appeal

from a practical perspective: at any locality the chance of sampling any specimen of a given genus is likely to be greater than the chance of sampling any specimen of a given species; and it is often easier to identify a fossil to the genus level than to the species level while in the field. But the broader utility of such a scheme comes at a cost of precision. The first occurrence of a given genus in two regions has a higher potential to be strongly diachronous than does the first occurrence of a given species, because (1) genera have longer stratigraphic durations, and (2) the lowest occurring species within that genus may differ between the regions. The desire for ever more precise correlation now provides an impetus to replace the genus-level biostratigraphic zonation of the Cambrian System of Laurentia with a higher resolution, species-level zonation scheme. A species-level zonation scheme has recently been developed for the Delamaran Stage (Eddy and McCollum, 1998; Sundberg and McCollum, 2000, 2003a; McCollum and Sundberg, 2007), and Hollingsworth (this volume, Article 2) develops one for the former "*Nevadella* Zone" within the Montezuman Stage (Fig. 1).

FIGURE *1*.—Biostratigraphic zonation of the Cambrian System on Laurentia, including the new zonation of the Dyeran Stage proposed herein. The region highlighted in gray represents the interval shown in Fig. 3. The upper Dyeran interval discussed herein will likely fall within provisional Stage 4 or Stage 5 of the developing global chronostratigraphic nomenclature of the Cambrian (Peng and Babcock, 2008; the base of Stage 5 is likely to be defined as the FAD of *Oryctocephalus indicus* (Reed, 1910) [as depicted here] or of the stratigraphically older *Ovatoryctocara granulata* Chernysheva, 1962). Globally significant open shelf index species that are unknown from Laurentia are named in parentheses. *The utility of the *Peronopsis bonnerensis* Zone has recently been questioned (see McCollum and Sundberg, 2007).

A new, species-level biostratigraphic zonation scheme is presented here for the upper part of the Dyeran Stage (Waucoban Series) of Laurentia. Each zone is defined based on the first appearance datum (FAD) of a particular species within the southern Great Basin, although at least two of the zones can be recognized in the central Great Basin and another can be recognized in the Canadian Rockies. A sequence

stratigraphic framework for the upper Dyeran of the southern Great Basin is also presented. The sequence boundaries do not correspond to the biostratigraphic zone boundaries, and therefore provide another means of correlation between localities. Finally, the nature of environmental change during the Dyeran-Delamaran boundary interval, and of the extinction of olenelloid trilobites, are reinterpreted in light of these new biostratigraphic and sequence stratigraphic frameworks.

PREVIOUS WORK

The Waucoban Series spans the interval from the first appearance of what were thought to be the stratigraphically oldest trilobites to the base of the Lincolnian Series of the traditional "middle" Cambrian of Laurentia (defined by the first appearance of *Eokochaspis nodosa* Sundberg and McCollum, 2000) (Fig. 1; Palmer, 1998b; but see Hollingsworth [2007] for a description of a pre-Waucoban trilobite assemblage). Three biostratigraphic zones are traditionally recognized within the series: the "*Fallotaspis* Zone", the "*Nevadella* Zone", and the "*Olenellus* (or *Bonnia-Olenellus*) Zone" (Deiss, 1939; Rasetti, 1951; Fritz, 1972). As originally conceived, each zone was based on the stratigraphic range of a particular genus. However, each of these genera has undergone considerable systematic revision since Fritz's (1972) work, and the currently accepted ranges of these genera are now markedly different (see below). As a result, the tripartite biostratigraphic scheme devised by Fritz (1972) must be revised. The "*Fallotaspis* Zone" and "*Nevadella* Zone" are discussed and revised by Hollingsworth (this volume, Article 2; also Hollingsworth, 2007). The present paper is concerned only with the informal "upper *Olenellus* Zone" as recognized by Palmer and Repina (1993; also Palmer and Repina in Whittington et al., 1997).

The "*Olenellus* Zone" was defined as the full range zone of *Olenellus* Hall, 1862 (Palmer and Repina, 1993), and its base was believed to be coincident with the base of the Dyeran Stage (defined by the "dramatic change in olenelloid faunas between older beds with Nevadiidae and younger beds with Olenellidae"; Palmer, 1998b, p. 326; Fig. 1). However, recent systematic work has led to many species formerly assigned to *Olenellus* being reassigned to other genera (e.g., Fritz, 1992; Palmer and Repina, 1993; Palmer and Repina in Whittington et al., 1997; Lieberman, 1998, 1999). Many more *Olenellus* species are in need of modern systematic treatment, and the genus, although more tightly diagnosed now, is still likely to be polyphyletic (unpublished data). As a result of these recent and pending systematic revisions, the base of the "*Olenellus* Zone" is poorly constrained. Given this fact, and the desire to adopt a more refined, species-level zonation scheme, I propose that use of the "*Olenellus* Zone" (= "*Bonnia-Olenellus* Zone") be abandoned.

Characteristic trilobite faunules based on species-level occurrences have been recognized in upper Dyeran strata in the Canadian Rocky Mountains (e.g., the *Bonnia fieldensis* Faunule [Rasetti, 1951]) and in the Taconics of New York State (e.g., the *Elliptocephala asaphoides* Fauna, *Neopagetina taconica* Faunule, and *Pagetides elegans* Faunule [Rasetti, 1967]). However, these faunules are recognized over a limited geographic area, and are of only local biostratigraphic utility. The thick, fossiliferous, well exposed, and well-studied outcrops of the southern Great Basin (Fig. 2) make this region appropriate for establishing a formal zonation for the upper Dyeran (as predicted by Rasetti, 1951, p. 82). Within that study area, Palmer and Halley (1979) recognized three distinctive faunal assemblages within the upper part of the former "*Olenellus* Zone", and used those to define the "*Olenellus arcuatus* Zonule", the "*Bristolia* Zonule" (also recognized by Nelson, 1976), and the "*Olenellus multinodus* Zonule". However, the second of those zonules was based on the full range of a genus, and an unnamed interval separated each zonule.

The author's own fieldwork in the upper Dyeran of the southern Great Basin began in 1997, as part of graduate studies of the paleobiology and evolution of olenelloid trilobites (Webster, 1999; 2003a), and continues to this day. This has involved study and detailed measurement (often at a centimeter scale) of upper Dyeran strata at many sections (Fig. 2), and collection of several thousands of specimens from more than 700 tightly constrained horizons. These new data, combined with examination of material collected by other workers, offer a level of biostratigraphic and stratigraphic precision that was not available to previous workers.
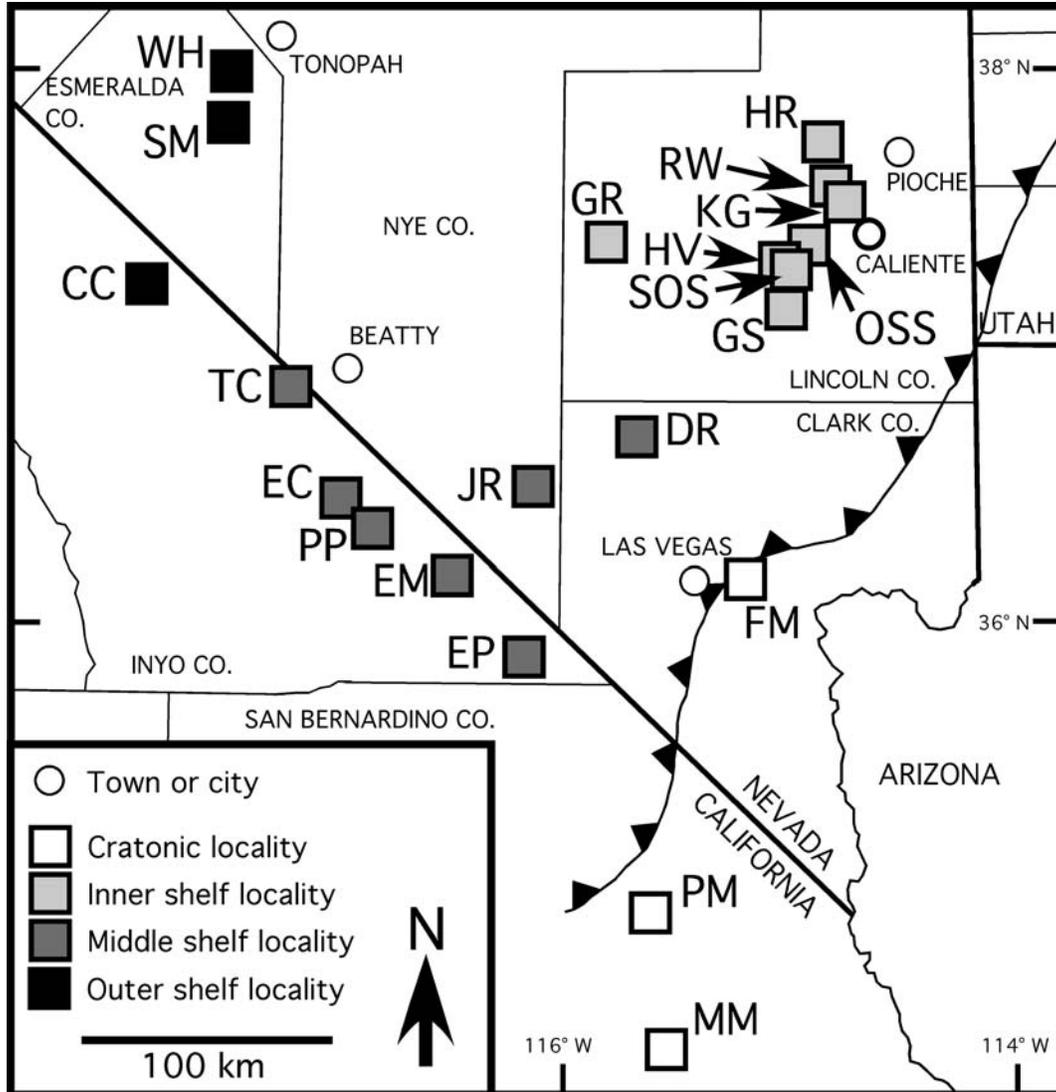
FIGURE *2*.—Map of the southern Great Basin, showing the location of upper Dyeran localities that provided data for the present study. Localities are shaded according to their general position on the shelf, as discussed in the text. Black line with triangles marks the eastern limit of the Sevier Thrust Belt (overthrust blocks to the west; see text). Abbreviations: CC, Cucomungo Canyon (northern Last Chance Range); DR, Desert Range; EC, Echo Canyon (Funeral Mountains); EM, Eagle Mountain; EP, Emigrant Pass (Nopah Range); FM, Frenchman Mountain; GR, northern Groom Range; GS, Grassy Spring (Delamar Mountains); HR, Highland Range; HV, Hidden Valley (Burnt Springs Range); JR, Jaybird Ridge (Spring Mountains); KG, Klondike Gap (Chief Range); MM, Marble Mountains; OSS, Oak Spring Summit (Delamar Mountains); PM, Providence Mountains; PP, Pyramid Peak (Funeral Mountains); RW, Ruin Wash (Chief Range); SM, Split Mountain (Clayton Ridge); SOS, Seven Oaks Spring (Burnt Springs Range); TC, Titanothere Canyon (Grapevine Mountains); WH, Weepah Hills.

GEOLOGICAL SETTING

The present paper focuses on the well-exposed upper Dyeran strata of northwestern Arizona, southern Nevada, and southeastern California (Fig. 2). This area is herein referred to as the "southern Great Basin" (but see Appendix 1 for a more accurate description of the region). The tectonic history of the study area is summarized in Appendix 1.

Upper Dyeran paleogeography and lithostratigraphy.—Late Precambrian and early Cambrian strata in the southern Great Basin record the initial encroachment of marine environments onto the western margin of Laurentia. By the end of the Dyeran, the shelf was flooded well into present-day Utah (Stewart and Poole, 1974). The late Dyeran shelf was environmentally heterogeneous both spatially and temporally, and this complexity is reflected in the number of upper Dyeran lithostratigraphic units that are recognized (Fig. 3). Details of particular lithostratigraphic units, including summaries of previous work, are provided elsewhere (for Harkless Formation—Mule Spring Limestone—Emigrant Formation succession, see Webster [this volume, Stops 7A-C]; for Carrara Formation, see Palmer and Halley [1979]; for Pioche Formation, see Webster [this volume, Stop 4B], Webster [this volume, Stops 5A, 5B, 6A] and Webster et al. [this volume, Stop 6B]; for Latham Shale—Chambless Limestone—Cadiz Formation succession, see Webster et al. [2003]).

Stage	Trilobite Zones	Upper Dyeran Depositional Sequences	Shelf — Outer (Split Mountain Area)	Shelf — Middle (Emigrant Pass, Eagle Mountain)	Shelf — Inner (Northern Groom Range)	Shelf — Inner (Pioche-Caliente Region)	Craton — Marble Mountains	Craton — Frenchman Mountain	Craton — Grand Canyon
Delamaran	Glossopleura walcotti		Emigrant Formation	Bonanza King Formation; DR LST Mb.; Jangle LST Mb.; PHS Mb.; Red Pass LST Mb.	April Fool Oolite; Rachel Limestone; Tikaboo Oncolite	Highland Peak Formation; Chisholm Shale; Lyndon Limestone; Grassy Spring Mb.	Bonanza King Formation	Muav Limestone; Chisholm Shale; Lyndon Limestone	Muav Limestone; Bright Angel Shale
Delamaran	Mexicella mexicana				Log Cabin Mb.; Susan Duster LST Mb.	Log Cabin Mb.; Susan Duster LST Mb.	Cadiz Formation	Pioche Formation	Bright Angel Shale
Delamaran	Poliella denticulata			Pyramid Shale Mb.	Comet Shale Mb.	Comet Shale Mb.			
Delamaran	Amecephalus arrojoensis								
Delamaran	Eokochaspis nodosa								
upper Dyeran	Nephrolenellus multinodus	IV	Mule Spring LST — Upper unit	Gold Ace LST Mb.; Echo Shale Mb.	Combined Metals Mb. (Stop 6B)	Combined Metals Mb. (Stops 5A, 5B, 6A)	Chambless Limestone		
upper Dyeran	Bolbolenellus euryparia	III / II							
upper Dyeran	Peachella iddingsi	I	Middle unit	Thimble Limestone Mb.					Tapeats Sandstone
upper Dyeran	Bristolia insolens	I							
upper Dyeran	Bristolia mohavensis	I	Lower unit	Eagle Mountain Shale Mb.	Delamar Mb. equivalent	Delamar Mb.	Latham Shale	Tapeats Sandstone	
upper Dyeran	Arcuolenellus arcuatus		Harkless Formation				Zabriskie Quartzite		
upper Dyeran	[not defined]			Zabriskie Quartzite	Zabriskie Quartzite	Zabriskie Quartzite	Zabriskie Quartzite		

FIGURE *3*.—Biostratigraphic zonation of the upper Dyeran and Delamaran, and its relation to lithostratigraphy on the shelf and craton in the southwestern United States. Upper Dyeran zones are new and defined herein; Delamaran zonation follows Eddy and McCollum (1998), Sundberg and McCollum (2000, 2003a), and McCollum and Sundberg (2007). Upper Dyeran depositional sequences I to IV are defined herein. Gray boxes indicate upper Dyeran intervals that will be visited on the 2011 ISCS field conference (Webster, this volume, Stops 4B, 5A, 5B, 6A, 6B, 7A-C). The portion of the upper Dyeran and Delamaran shown here spans approximately 8 million years of time (i.e., from c. 515 to c. 507 million years before present; Shergold and Cooper, 2004; Peng and Babcock, 2008). However, the absolute time represented by each trilobite zone within this interval is essentially unconstrained. The vertical scale of this chart is therefore arbitrary (all zones except the *Glossopleura walcotti* Zone shown at equal thickness). The relative thickness of lithostratigraphic units is distorted accordingly. Northern Groom Range lithostratigraphy follows McCollum and McCollum (this volume, Article 8). Lithological contacts that are biostratigraphically poorly constrained are indicated with question marks. Lithostratigraphic abbreviations: DR LST Mb., Desert Range Limestone Member; PHS Mb., Pahrump Hills Shale Member; LST, limestone; Mb., Member.

Studies of sediment transport direction reveal that the Pioche Formation was deposited closer to shore than the correlative Carrara Formation (Stewart, 1970, 1980; Stewart and Poole, 1974; Fedo and Prave, 1991). This is also supported by the westward increase in carbonate content of strata deposited during particular intervals (e.g., the siliciclastic-dominated upper part of the Delamar Member [Pioche Formation] correlates with the Thimble Limestone Member [Carrara Formation] and with the middle unit of the Mule Spring Limestone during the *Peachella iddingsi* Zone; Fig. 3). The Pioche Formation, Carrara Formation, and Mule Spring Limestone—Emigrant Formation are here interpreted as inner, middle, and outer shelf deposits, respectively (Figs. 2, 3). The only exception to this is the upper Dyeran succession mapped as the Pioche Formation at Frenchman Mountain, which lacks carbonate beds altogether and is essentially cratonic in nature (Webster, this volume, Stop 4B; Stewart, 1970). The middle shelf deposits equate to the "Death Valley Facies" of Nelson (1976) and the "Central Region" of Stewart (1970); the outer shelf deposits equate to the "White-Inyo Facies" of Nelson (1976) and the "Western Region" of Stewart (1970).

The upper Dyeran Latham Shale—Chambless Limestone—Cadiz Formation succession of the Marble Mountains and Providence Mountains (Fig. 3) is considered cratonic because it is separated from the erosional contact with Precambrian basement by only a relatively thin quartzite and siltstone interval (Stewart, 1970; Palmer, 1971; Nelson, 1976). (Stewart [1970] mapped this quartzite and siltstone interval as the Tapeats Sandstone, but identified the upper part as being equivalent to the Zabriskie Quartzite [see also Fedo and Prave, 1991]. This latter name is applied herein.) However, presence of the Chambless Limestone suggests close proximity to the shelf, because correlative successions elsewhere on the craton are purely siliciclastic (e.g., Webster, this volume, Stop 4B).

SEQUENCE STRATIGRAPHIC FRAMEWORK FOR THE UPPER DYERAN OF THE SOUTHERN GREAT BASIN

An understanding of the stratigraphic record brings better understanding of the fossil record. Variation in environmental factors such as relative sea level is intimately coupled to the spatial and temporal distribution of fossil taxa. Such environmental change can drive change in the geographic distribution of taxa; can cause lineages to evolve, diversify, or become extinct; and can affect the fidelity of the fossil record (e.g., when environmental change results in altered preservation potential or sedimentation rate, or even removal of strata by erosion; Peters, 2008). A sequence stratigraphic framework for the upper Dyeran of the southern Great Basin is presented below, within which the stratigraphic and geographic distribution of trilobite species may be better understood.

The sequence stratigraphic approach adopted herein identifies four depositional sequences within the upper Dyeran, numbered I to IV (oldest to youngest; Figs. 3, 4; discussed below). Palmer and Halley (1979) recognized only three (two full and one partial) depositional cycles in this same interval and study area. However, their depositional model characterized a cycle as a sedimentary couplet, tens of meters thick, comprising a lower siliciclastic part and an upper carbonate part (Palmer and Halley, 1979, p. 51). Sequences III and IV as defined herein would not be detectable under such a model, because the highstand system tract of each of these sequences is not represented by a thick limestone; these sequences correspond to the partial (siliciclastic-only) cycle of the uppermost "*Olenellus* Zone" recognized by Palmer and Halley (1979). McCollum and colleagues (McCollum, 1994; McCollum and McCollum, 1994; McCollum et al., this volume, Stops 5, 6A) also failed to distinguish Sequence IV from Sequence III. The significance of this distinction to our understanding of the nature of the Dyeran-Delamaran boundary and the extinction of olenelloid trilobites is discussed in a later section.

In the following sections I define the four depositional sequences within the upper Dyeran of the southern Great Basin. The absolute time represented by each is unknown, and I make no attempt to rank them in terms of relative duration. The absolute magnitude of change in water depth within each sequence is also unknown.

Sequence I.—Sequence I spans the *Arcuolenellus arcuatus* Zone to the lowermost part of the *Bolbolenellus euryparia* Zone (Fig. 3; all zones defined below). The Zabriskie Quartzite is a sand sheet that comprises environments ranging from fluvial braid plain (pebbly tabular and channeled beds) to high-

energy nearshore (piperock) to shallow subtidal (horizontal burrows)(Barnes and Klein, 1975; Fedo and Prave, 1991). At least the upper part of the Zabriskie Quartzite represents a generally deepening facies, and is thus considered part of the transgressive system tract of this sequence. On the inner shelf this generally deepening facies continues upward through the lower two-thirds of the Delamar Member of the Pioche Formation. It extends to the middle of the Latham Shale in the Marble Mountains. On the middle shelf, the top of the transgressive system tract is poorly constrained, but is likely near the top of the Eagle Mountain Shale Member. On the outer shelf, the transgressive system tract begins in the uppermost Harkless Formation and extends into the middle unit of the Mule Spring Limestone. However, the lower unit of the Mule Spring Limestone represents a carbonate bank that developed during this interval (Fig. 4.1; Webster, this volume, Stop 7A). Presence of very shallow subtidal to supratidal facies within this carbonate bank (Webster, this volume, Stop 7A) suggests that the general deepening trend was interrupted by at least one shallowing event, and/or that growth of the bank was (at least for a time) sufficient to keep pace with the change in sea level.
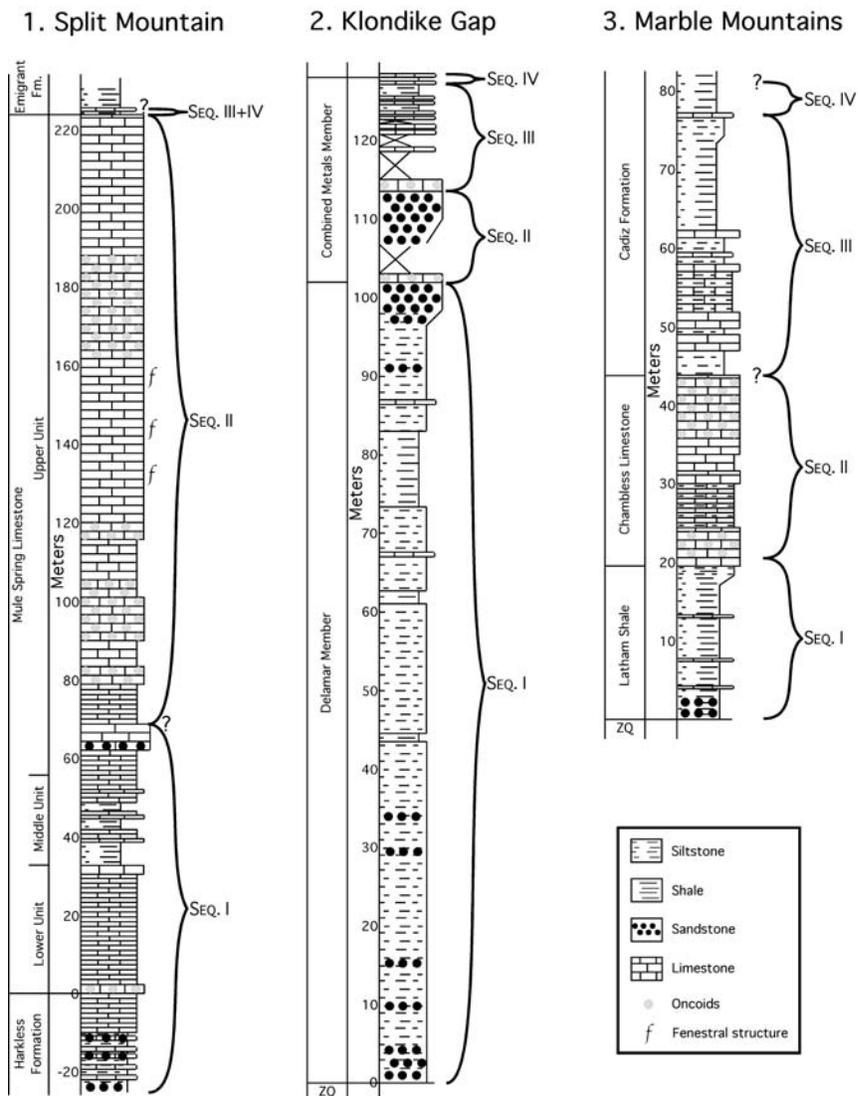
FIGURE *4*.—Lithologic columns for the upper Dyeran at Split Mountain (*1*, outer shelf), Klondike Gap (*2*, inner shelf), and the Marble Mountains (*3*, craton), showing depositional sequences I to IV (defined herein). Vertical scale differs among sections. See text for details.

The interval of maximum flooding of Sequence I is characterized by shelf-wide shale, mudstone, or claystone deposits, and corresponds to the *Bristolia insolens* Zone (Fig. 3). This drowning was sufficient to terminate growth of the carbonate bank on the outer shelf (above), as marked by the transition into the mixed carbonate-siliciclastic middle unit of the Mule Spring Limestone (Fig. 4.1; Webster, this volume, Stops 7A, 7B). Articulated olenelloid trilobites are relatively abundant in this stratigraphic interval within the Latham Shale and the Delamar Member. The typically small species *Mesonacis fremonti* (Walcott, 1910) and *Olenellus nevadensis* (Walcott, 1910) attained relatively huge maximum size (cephalic length exceeding 5 cm) during this interval; unusually large specimens of *Bristolia bristolensis* (Resser, 1928) also occur. Such "gigantism" likely represents ecophenotypy rather than evolution.

The highstand system tract of Sequence I is represented by the shallowing facies within the upper third of the Delamar Member, the upper third of the Latham Shale, and the upper part of the middle unit of the Mule Spring Limestone (Fig. 4). It likely corresponds to most of the Thimble Limestone Member in the Carrara Formation. In the Pioche-Caliente region, the shallowing culminates in an erosion surface below oncolitic limestones of the lower part of the Combined Metals Member (Webster, this volume, Stops 5A, 5B, 6A). This surface represents removal of section during lowstand, and thus represents the sequence boundary between Sequences I and II. Sundberg and McCollum (2000) interpreted the surface as a paleokarst. An erosion surface also occurs below the lowest oncolitic bed of the Chambless Limestone in the Marble Mountains (Fig. 5) and Providence Mountains (personal observation), and is deemed to represent the same sequence boundary. Many erosion surfaces and intraformational conglomerates are known within the Thimble Limestone Member of the Carrara Formation (Palmer and Halley, 1979), but the top of the sequence has not been precisely located within the unit.
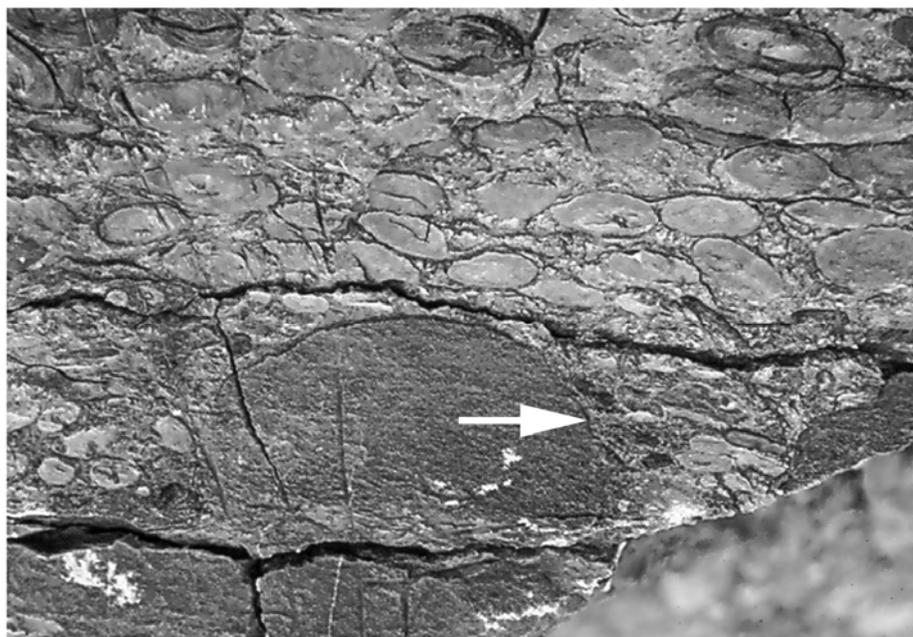
FIGURE *5*.—Erosion surface (arrowed) below the lowermost oncolitic limestone within the Chambless Limestone at the Marble Mountains, marking the base of Sequence II. Vertical relief on the surface is approximately 5 cm.

At least one erosion surface has also been identified in the basal few meters of the upper unit of the Mule Spring Limestone at Split Mountain (Webster, this volume, Stop 7B), although this surface occurs in the middle of what appears to be a shallowing upward succession and may represent a storm bed rather than sequence boundary. The top of the sequence at this locality is ambiguous, and is provisionally

placed approximately 13 m above the erosion surface, at the transition from a cliff-forming interval of thickly-bedded, burrow mottled, bioclastic limestone (that includes a carbonate sand) to a more recessive interval of thinly-bedded, sparsely bioclastic, peloidal(?) limestone (Fig. 4.1).

Sandy beds and thin carbonates within the siltstones of the Delamar Member, oncolitic, oolitic, and fenestral carbonates representing shallow-subtidal to supratidal facies within the lower and middle units of the Mule Spring Limestone, and sandy limestone beds within the Latham Shale (Fig. 4) all suggest that the general deepening-to-shallowing cycle of Sequence I was interrupted by several shorter-lived shallowing events. No attempt has been made to correlate these events on a regional scale. If such correlation proves possible, it may be possible to define higher-order sequences within Sequence I.

Sequence II.—Sequence II is entirely contained within the *Bolbolenellus euryparia* Zone (Fig. 3). In the Pioche-Caliente region, the lowest oncolitic limestones of the Combined Metals Member are assigned to the transgressive system tract of this sequence because they overlie the erosion surface representing the sequence boundary. The transition from these oncolitic limestones to the overlying sandy interval (Figs. 4.2, 6, 7) is interpreted as a continuation (rather than onset) of the transgressive system tract. The sandy interval has received little study, and it is unclear whether it contains evidence of shallowing upward prior to being overlain by an oncolitic limestone that marks the base of the superjacent sequence.

In the Marble Mountains, Sequence II spans much of the Chambless Limestone. Conditions are assumed to have slightly deepened to permit accumulation of the lowest oncolitic limestone on top of the erosion surface (Fig. 5), and the oncolitic interval is therefore assigned to the transgressive system tract of Sequence II. Continued deepening resulted in the deposition of the overlying fossiliferous interbedded mudstone-limestone interval, somewhere within which the maximum flooding interval is represented. The subsequent upward transition back into oncolitic beds represents the highstand system tract (Fig. 4.3).

In middle shelf settings, the transgressive system tract of Sequence II is represented by interbedded shale and limestone comprising the Echo Shale Member of the Carrara Formation (Fig. 3; Palmer and Halley, 1979). The Echo Shale Member becomes more silty eastwards (Palmer and Halley, 1979), a trend consistent with the deposition of correlative sandstone in the Pioche-Caliente region. The transition into the overlying oncolitic limestone of the Gold Ace Limestone Member represents the highstand system tract.

On the outer shelf, the upper unit of the Mule Spring Limestone at Split Mountain generally comprises oncolitic and fenestral limestones. There is no obvious evidence for marked deepening within this unit, and the base of Sequence II is not clearly recognizable. It is conceivable that growth of the carbonate bank kept pace with the transgression such that shallow water conditions persisted throughout the interval. However, the lower third of the upper unit contains a slightly recessive interval (approximately 10 m thick) of thin-bedded, burrow-mottled limestone, containing relatively few oncolitic horizons, sandwiched between an underlying cliff-forming limestone and overlying oncolitic limestone (Fig. 4.1). This non-oncolitic interval is tentatively interpreted as the transgressive system tract of Sequence II, and the transition into the overlying oncolitic limestone is tentatively interpreted as the subsequent highstand system tract. The remainder of the upper unit of the Mule Spring Limestone (more than 140 m thick) is dominated by shallow subtidal to intertidal(?) facies. The boundary between Sequences II and III is provisionally placed at the top of the Mule Spring Limestone (Fig. 4.1), because the lithologic change to the overlying siliciclastics of the Emigrant Formation corresponds to a dramatic deepening event (Webster, this volume, Stops 7A-7C, and references thererin). However, it is conceivable that some deepening began prior to the lithological change, and that the sequence boundary might lie at the transition from (intertidal?) fenestral limestone to shallow subtidal oncolitic limestone, just over 160 m above the base of the Mule Spring Limestone (Fig. 4.1).

Sequence III.—Sequence III spans the upper part of the *Bolbolenellus euryparia* Zone and most of the *Nephrolenellus multinodus* Zone (Fig. 3). In the Pioche-Caliente region south of the Highland Range, this depositional sequence spans the upper oncolitic limestone of the Combined Metals Member to the base of the uppermost Dyeran nodular or ribbon limestone (approximately 0.5 m to 2 m below the basal Delamaran ribbon limestone; Figs. 4.2, 6, 7.1-7.5). The base of the upper oncolitic limestone is in

sharp and sometimes clearly erosional contact with the underlying sandstone, and is interpreted to be the initial deposit of the transgressive system tract of Sequence III rather than the expression of a shallowing facies with the underlying sandstone. Overlying the oncolitic bed is an interval of rubbly-weathering, silty, nodular limestone that is typically mostly covered except for several thin, resistant, limestone ledges (Figs. 4.2, 6, 7.1-7.5). Overlying this is shale with dispersed carbonate nodules (more nodules toward the base) that was deposited in a low-energy, deep subtidal environment, near or below storm wave base, during the interval of maximal flooding (Figs. 6, 7.1-7.5). The sequence boundary is the sharp contact with the ribbon limestone that is consistently present 0.5 m to 2 m below the basal Delamaran ribbon limestone at all sections in the Pioche-Caliente region except Log Cabin Mine, where it has been faulted out (Fig. 7). The nature of this sequence boundary, and the nature of Sequence III in the Highland Range, is discussed below ("Dyeran-Delamaran Boundary" section).

The northern Groom Range shows a similar lithological pattern to the Pioche-Caliente region through the transgressive system tract and maximum flooding interval, but then shows an upward coarsening to sandstone (Fig. 6). No such expression of upward shallowing is present in upper part of this sequence in the Pioche-Caliente region (Figs. 4.2, 6, 7; see "Dyeran-Delamaran boundary" section, below).
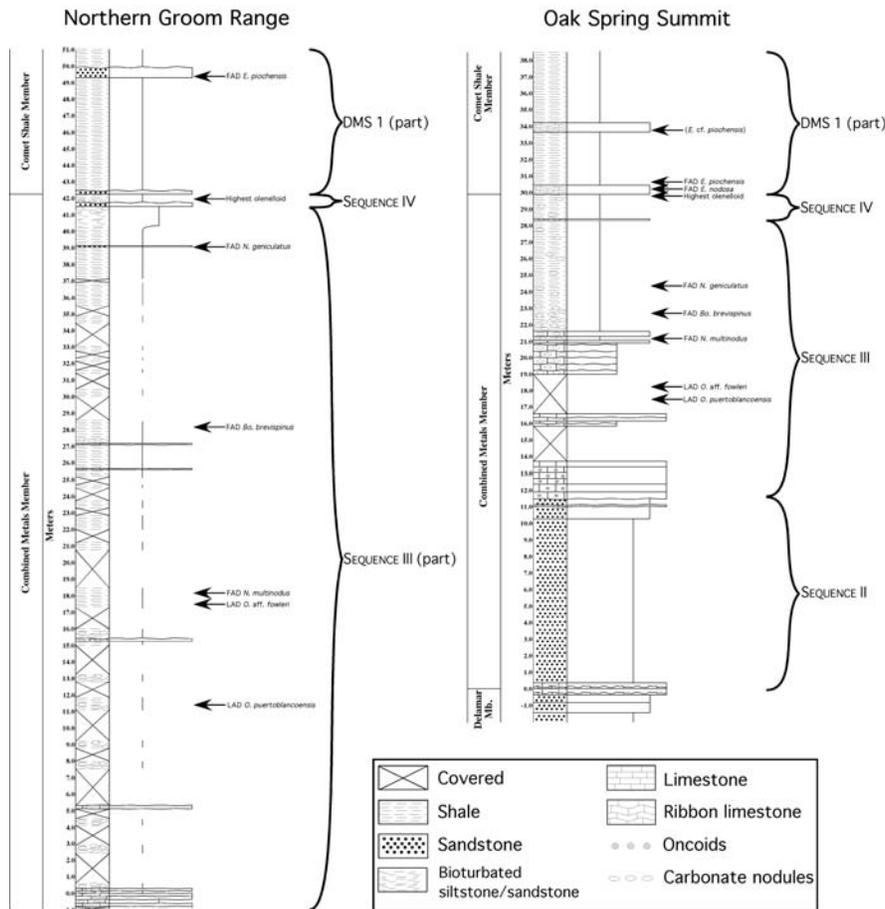
FIGURE 6.—Lithologic columns for the uppermost Dyeran and basal Delamaran at the northern Groom Range (left) and Oak Spring Summit (right). Brackets indicate strata within upper Dyeran Sequences II, III, and IV (defined herein), and lowermost part of first depositional sequence within the Delamaran (DMS 1; see McCollum and McCollum, this volume, Article 8). Key biostratigraphic events within sequences are indicated with arrows (see text for full taxon names). Vertical scale is the same on both sections.

On the craton, the base of Sequence III is seen in the transition from the upper oncolitic beds of the Chambless Limestone to the Cadiz Formation in the Marble Mountains (Fig. 4.3). The top of the sequence likely corresponds to a 0.52 m package of bioturbated sandy siltstones and interbedded sandy limestones that occurs within the Cadiz Formation, approximately 32.5 m above the top of the massive cliff of the Chambless Limestone (Fig. 4.3). The base of Sequence III has not been precisely located at Frenchman Mountain, but the top of the sequence is probably marked by a sandstone at 53 m above the base of the measured section described by Webster (this volume, Stop 4B). This sandstone represents shallowing-upward and perhaps also the lowstand deposits of the sequence.

On the middle shelf, the base of Sequence III is represented by the transition from the oncolitic Gold Ace Limestone Member to the siltstone and shale of the lower part of the Pyramid Shale Member of the Carrara Formation (Fig. 3). The top of the sequence has not been precisely located, although see McCollum and McCollum (this volume, Article 8) for progress on this front.

For the shelf edge deposits at Split Mountain, the base of Sequence III is provisionally placed at the contact between the Mule Spring Limestone and the Emigrant Formation (Fig. 4.1), although the sequence boundary could conceivably occur within the upper unit of the Mule Spring Limestone (discussed above). The top of Sequence III lies somewhere within the basal 1.4 m of the Emigrant Formation (Fig. 4.1; Webster, this volume, Stop 7C). The deepening associated with the transgressive part of this sequence therefore seems to have been sufficiently dramatic to drown the carbonate bank on the outer shelf (represented by the upper unit of the Mule Spring Limestone). Absence of the major carbonate "barrier" from the shelf during the remainder of Sequence III and Sequence IV may explain the occurrence of typical "outer shelf" trilobites such as *Bathynotus* Hall, 1860 and oryctocephalids in the uppermost Combined Metals Member on the inner shelf (Sundberg and McCollum, 1997; Palmer, 1998a; Webster, 2009b).

Sequence IV.—Sequence IV corresponds to the uppermost part of the *Nephrolenellus multinodus* Zone (Fig. 3). Where identified, this sequence contains the stratigraphically highest occurrences of olenelloid trilobites (see "Dyeran-Delamaran boundary" section, below). Sequence IV was not recognized by previous workers (Palmer and Halley, 1979; McCollum, 1994; McCollum and McCollum, 1994; McCollum et al., this volume, Stops 5, 6A).

In the Pioche-Caliente region south of the Highland Range, Sequence IV spans the thin interval between the uppermost Dyeran ribbon limestone and the basal Delamaran ribbon limestone (Figs. 4.2, 6, 7.1-7.5). The sequence is 0.67 m thick at Ruin Wash, comprising a 0.24 m thick ribbon limestone overlain by 0.43 m of carbonate nodule-bearing shale. Webster et al. (2008) conducted a detailed study of the microstratigraphy and trilobite biostratinomy of the 0.43 m shale interval. They concluded that the whole 0.43 m succession was deposited in moderately deep water, below storm wave base, and that the fine-grained siliciclastics (clay and rare silt grains) represent the distal deposits of a series of storm-induced event beds, with the majority of coarse sediment having settled from suspension up-slope from the site. Sediment winnowing during higher energy events resulted in prolonged pre-burial exposure of bioclasts on the sediment surface and generation of trilobite hash surfaces. These intervals of sediment winnowing were associated with growth of carbonate nodules below the static sediment surface. The hash surfaces and carbonate nodules are concentrated at the base and top of the 0.43 m interval, suggesting that the energy of the depositional events passing over the Ruin Wash site progressively waned then waxed (i.e., the site was blanketed by progressively more distal then proximal tempestites). The coarsest (silt-size) grain fraction present in the interval was also limited to the basal part. These data are consistent with the 0.43 m interval representing a relative deepening-to-shallowing sequence (Webster et al., 2008). Trends in the depth and extent of bioturbation, in trilobite biostratinomy (bioclast articulation, fragmentation, and orientation), and in bed thickness through the interval also support this deepening-to-shallowing interpretation (Webster et al., 2008).

The ribbon limestone underlying the shale interval is here interpreted as the basal bed of Sequence IV. This interpretation stems from the mode of formation of ribbon limestone and its relationship to underlying strata. Ribbon limestone formation requires a moderate amount of current energy. Biostratinomic and microstratigraphic facies analyses suggest that the upward transition from

nodular shale to fissile shale within the 0.43 m shale interval at Ruin Wash resulted from the effects of progressively more distal event bed deposition (above; Webster et al., 2008). A downward extrapolation of this trend can account for the presence of the ribbon limestone underlying the nodular shale. A shallower-water origin for ribbon limestones relative to the shale is consistent with the non-trivial sand fraction within the insoluble residues of ribbon limestones, and with the almost invariably disarticulated state of trilobite remains within them (personal observations; see also Velechovsky, 1985). A lithological succession from ribbon limestone to nodular shale to fissile shale therefore represents a deepening upward facies, albeit within an already deep subtidal setting (perhaps entirely below storm wave base).

In the Pioche-Caliente region, the ribbon limestone marking the base of Sequence IV can be traced from the Highland Range south to Grassy Spring, and always lies 0.5 m to 2 m below another ribbon limestone that marks the base of the Delamaran Stage (Fig. 7; see "Dyeran-Delamaran Boundary" section for a discussion). One to two more ribbon carbonates are developed in the few meters above the basal Delamaran bed (Fig. 6; Sundberg and McCollum, 2000). Velechovsky (1985, fig. 23) documented at least one example of an erosional, angular contact between the base of a ribbon limestone and the underlying shale. This provides evidence of removal of section during lowstand, although the amount of missing section cannot easily be determined. It is conceivable that each of the Delamaran ribbon carbonates also defines the base of a depositional sequence, although not all can be traced throughout the Pioche-Caliente region (Velechovsky, 1985; Sundberg and McCollum, 2000; McCollum and McCollum, this volume, article 8).

FIGURE 7 *(below)*.—Lithologic columns for the uppermost Dyeran and basal Delamaran in the Pioche-Caliente region, showing depositional sequences. Sections are arranged from the southernmost (*1*) to the northernmost (*7*). Sequences labeled I to IV refer to upper Dyeran sequences (defined herein); sequence labeled DMS 1 is lowermost Delamaran sequence (McCollum and McCollum, this volume, Article 8). Incompleteness of sections at localities in the Highland Range (1 and 2) leads to ambiguity as to the location of the sequence boundary between sequences II and III; the two alternative interpretations are shown (see text for details). Key biostratigraphic events within sequences are indicated with arrows. See Fig. 6 for lithological key.
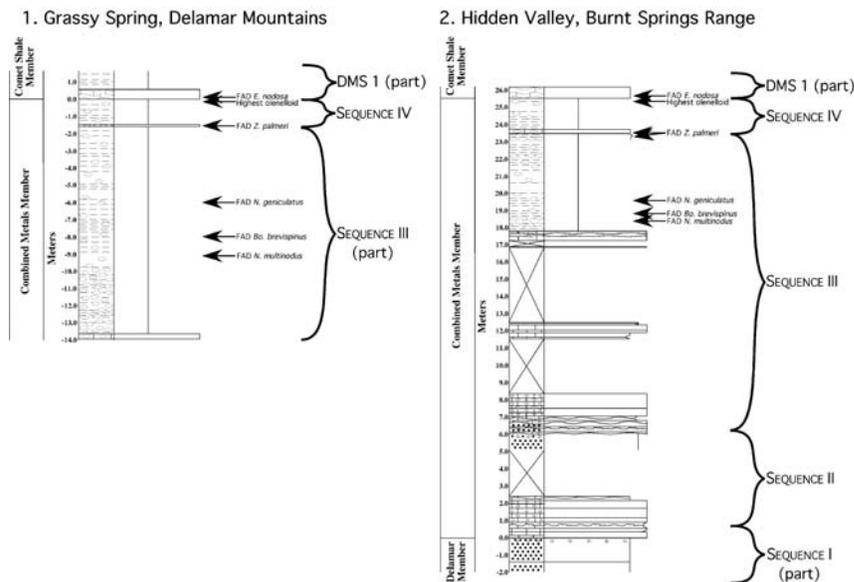
3. Oak Spring Summit, Delamar Mountains
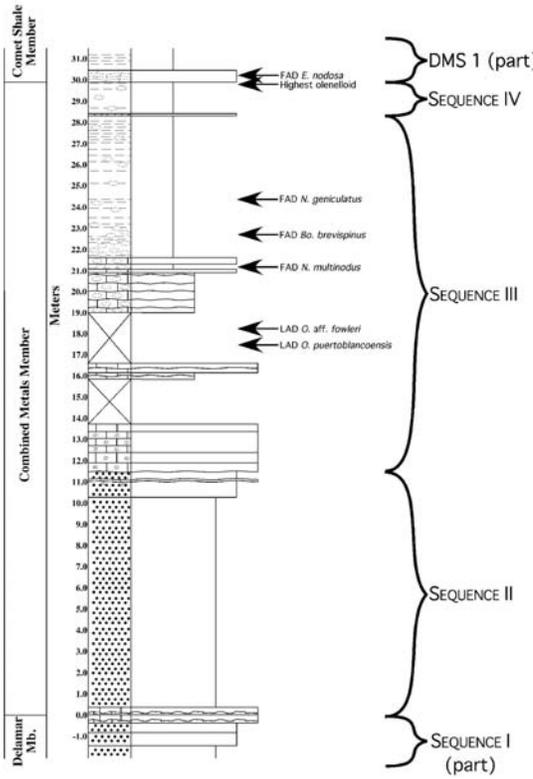
4. Klondike Gap, Chief Range
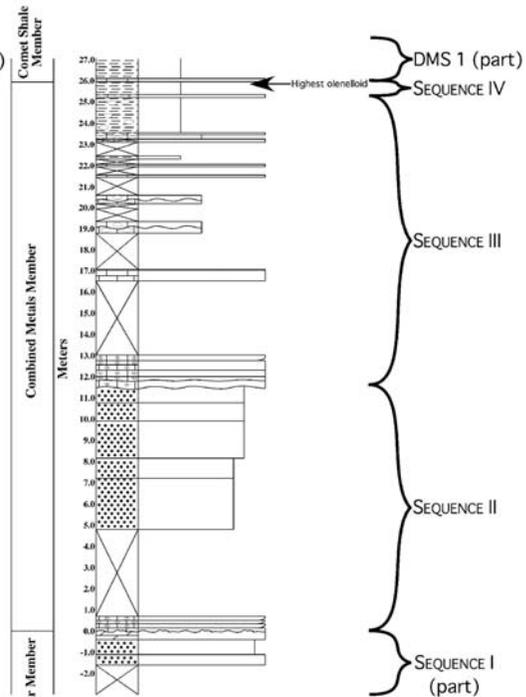
5. Ruin Wash, Chief Range
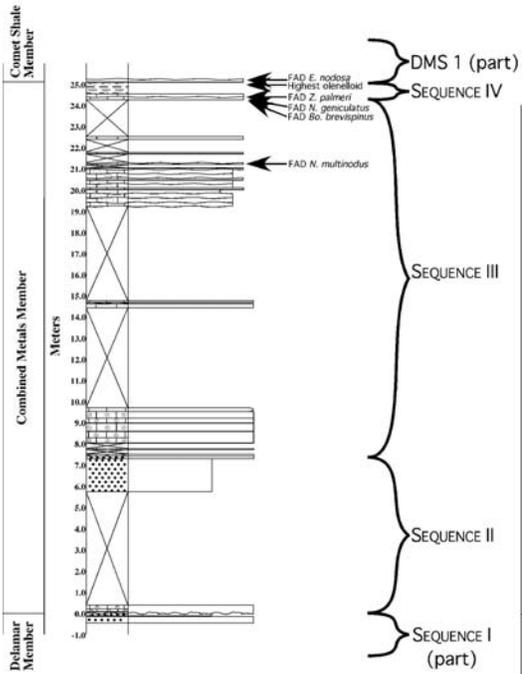
6. Log Cabin Mine, Highland Range
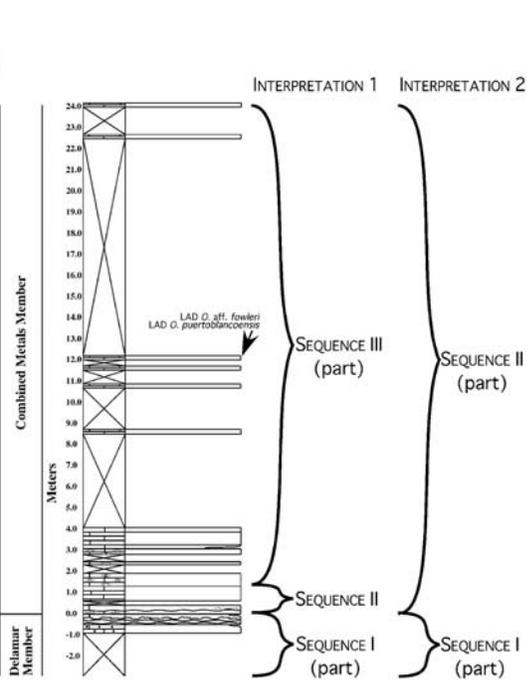
7. One Wheel Canyon, Highland Range
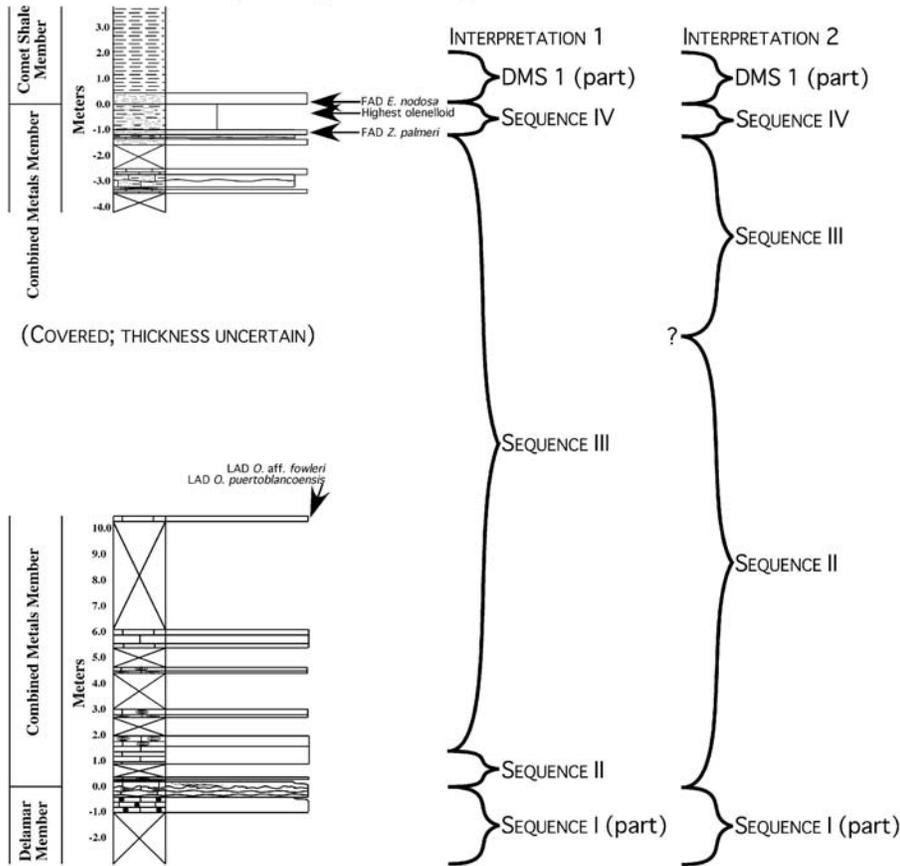
Sequence IV has also been identified in the northern Groom Range, where it is represented by a 0.74 m succession comprising 0.25 m of ledgy silty limestone to ferric dolomite, 0.14 m of meters of sandy, bioturbated shale containing dispersed carbonate nodules, 0.15 meters of fissile shale, and 0.20 meters of thinly interbedded sandy, hackly mudstone and sandstone (Fig. 6; Webster et al., this volume, Stop 6B). This succession of lithologies also represents a deepening-to-shallowing trend. The highest occurrence of olenelloids is within the fissile shale, 0.43 m above the base of the sequence.

At Frenchman Mountain, the base of Sequence IV is inferred to be the top of the sandstone 53 m above the base of the measured section described by Webster (this volume, Stop 4B). A coarsening upward trend begins approximately 10 m higher in the section, and is capped by 2 m of sandstone marking the top of the measured section (Webster, this volume, Stop 4B). The stratigraphically highest olenelloid remains known from this site were recovered from within this higher sandstone, which is hypothesized to be the top of Sequence IV (Webster, this volume, Stop 4B). Higher strata are covered.

In the Marble Mountains, Sequence IV is represented by the shale-dominated interval that begins approximately 33 m above the top of the massive cliff of the Chambless Limestone (Fig. 4.3). The top of the sequence has not been precisely located at the Marble Mountains, but olenelloids have been recovered up to 1.99 m above the base of this interval, only 2.2 m below trilobites of probable Delamaran age (Webster et al., 2003).

Sequence IV has not been identified in the Carrara Formation, but is constrained to lie within the lower part of the Pyramid Shale Member (see also McCollum and McCollum this volume, Article 8). The sequence is presumably contained within the upper part of the basal 1.4 m of the Emigrant Formation at Split Mountain, but the highly condensed nature of that unit and the low diversity fauna recovered from it render identification of the sequence difficult (Fig. 4.1; Webster, this volume, Stop 7C).

REVISED BIOSTRATIGRAPHIC ZONATION OF THE UPPER DYERAN

Each of the new species-level biostratigraphic zones within the upper Dyeran is defined below (Fig. 3). The description of each zone includes documentation of its placement within the general sequence stratigraphic framework (Fig. 3; above), the lithostratigraphic units spanned by the zone, and the trilobite species occurring within the zone (Figs. 8-12). Brief systematic comments pertaining to several of the species are provided in Appendix 2. The final sections discuss the broader geographic applicability of the zonation scheme and the relationship between trilobite biostratigraphy and sequence stratigraphy through the study interval.

Arcuolenellus arcuatus *Zone.*—This is the lowest biostratigraphic zone established within the upper part of the traditional but now defunct "*Olenellus* Zone" (upper Dyeran). Its base is defined by the FAD of *Arcuolenellus arcuatus* (Palmer in Palmer and Halley, 1979) (Fig. 8.1), and its top is delimited by the FAD of *Bristolia mohavensis* (Crickmay in Hazzard, 1933) (marking the base of the overlying zone). The *A. arcuatus* Zone as defined here therefore includes the "*Olenellus arcuatus* Zonule" plus the overlying unnamed interval recognized by Palmer and Halley (1979). It is the lowest zone recognized within Sequence I (Fig. 3), and represents an interval of general marine transgression.
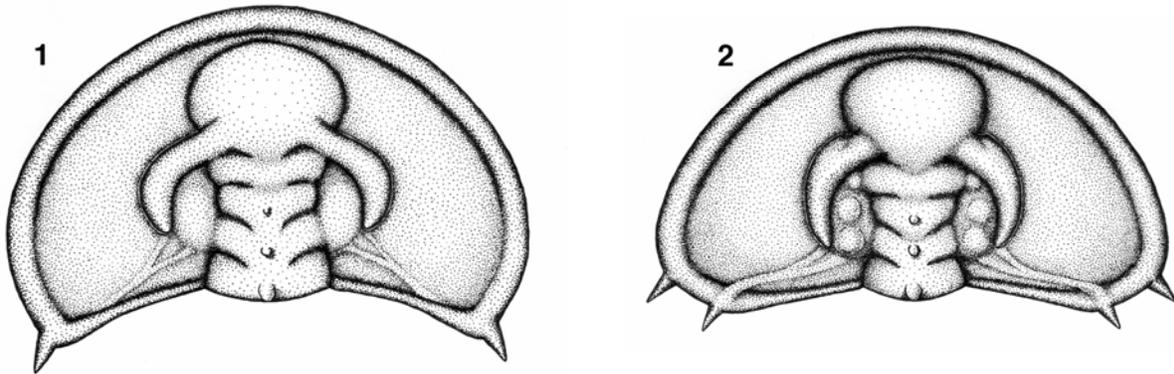
FIGURE *8.*—Biostratigraphically useful olenelloid trilobites of the *Arcuolenellus arcuatus* Zone. 1, *Arcuolenellus arcuatus*, reconstruction of cephalon approximately 7.9 mm in sagittal length. 2, *Arcuolenellus* aff. *megafrontalis*, reconstruction of cephalon approximately 6 mm in sagittal length.

Fossils characteristic of the *A. arcuatus* Zone have only been found in strata immediately overlying the Zabriskie Quartzite on the middle shelf, and in correlative strata within the upper Harkless Formation on the outer shelf. Underlying strata are typically coarse siliciclastics and barren of trilobite remains. The zone has not been identified within the Tapeats Sandstone at Frenchman Mountain and sections on the Colorado Plateau. *Arcuolenellus arcuatus* is known from rare cephala in the basal Eagle Mountain Shale Member of the Carrara Formation at Echo Canyon (stratotype section; Funeral Mountains) and Titanothere Canyon (Grapevine Mountains), both in Inyo County, California (Fig. 2; Palmer and Halley, 1979). At both these localities, *A. arcuatus* co-occurs with *Arcuolenellus* aff. *megafrontalis* (Fig. 8.2; Appendix 2). This latter species is more widespread, occurring in the uppermost Harkless Formation at Split Mountain (Webster, this volume, Stop 7A) and the Weepah Hills (unpublished observation), the basal 10 m of the Carrara Formation at Emigrant Pass (Nopah Range; Fowler, 1999), and questionably from the upper Buelna Formation near Caborca (Sonora, Mexico; Lochman in Cooper et al., 1952, pl. 18, fig. 4).

Mesonacis cylindricus (Palmer in Palmer and Halley, 1979) and *Olenellus nevadensis* also co-occur with *A. arcuatus* at Echo Canyon and Titanothere Canyon (Palmer and Halley, 1979; personal observation). Fowler (1999) also reported *M. cylindricus* from strata just below the FAD of *A.* aff. *megafrontalis* in the lowermost Carrara Formation at Emigrant Pass. *Mesonacis cylindricus* was considered characteristic of the *A. arcuatus* Zone by Palmer and Halley (1979). However, recently

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collected specimens seem to blur the distinction between this species and a stratigraphically higher form previously considered to represent a distinct species (below; unpublished data). Like the long-ranging *O. nevadensis*, *M. cylindricus* therefore may not be restricted to the *A. arcuatus* Zone.

   Olenellus clarki (Resser, 1928) co-occurs with *A.* aff. *megafrontalis* in the basal Cararra Formation at Emigrant Pass (Fowler, 1999), and both *O. clarki* and *Mesonacis fremonti* have been recovered below the FAD of *Bristolia mohavensis* in the Delamar Member of the Pioche Formation at Klondike Gap (Webster, 2007b). These long-ranging taxa therefore also apparently range down into the *A. arcuatus* Zone, although they have not been found in direct association with *A. arcuatus*. A new species of *Olenellus* makes its first appearance in the upper part of the *A. arcuatus* Zone ("*Olenellus* n. sp. 3" on Fig. 12; previously identified as "*Olenellus gilberti*" Meek in White, 1874 by Palmer and Halley [1979] and Fowler [1999], and as "*O.* aff. *gilberti* A" by Webster et al. [2003]).

   Bristolia mohavensis *Zone.*—The base of this new zone is defined as the FAD of *Bristolia mohavensis* (Fig. 9.1; Appendix 2), and its top is delimited by the FAD of *Bristolia insolens* (Resser, 1928) (marking the base of the overlying zone). *Bristolia mohavensis* is the stratigraphically oldest member of the genus, and the base of the *Br. mohavensis* Zone therefore equates to the base of the "*Bristolia* Zonule" recognized by Palmer and Halley (1979). Strata of the *Br. mohavensis* Zone represent a continuation of the transgressive system tract of Sequence I (Fig. 3), and exhibit a general deepening-upward trend at most localities. However, shallow subtidal, intertidal, and supratidal facies occur in the lower unit of the Mule Spring Limestone (Webster, this volume, Stop 7A). The presence of such facies may result from short-term regression(s) interrupting the general transgression (i.e., higher-order depositional sequences), or may result from the ability of the outer shelf carbonate bank to grow at a pace equal to or exceeding relative sea level change through much of the *Br. mohavensis* Zone.

   The base of the *Br. mohavensis* Zone occurs approximately 18 m above the base of the Carrara Formation at Emigrant Pass (Fowler, 1999), approximately 48 m above the base of the Delamar Member of the Pioche Formation at Klondike Gap (Webster, 2007b), and almost 2.5 m above the base of the Latham Shale at the Marble Mountains (stratotype section; Webster et al., 2003). *Bristolia mohavensis* occurs in the uppermost Harkless Formation at Split Mountain (although the base of the zone is poorly constrained), and the *Br. mohavensis* Zone spans the entire lower unit of the Mule Spring Limestone at this locality (Webster, this volume, Stop 7A). The zone has not been identified within the Tapeats Sandstone at Frenchman Mountain and sections on the Colorado Plateau.

   The *Br. mohavensis* Zone contains at least eight olenelloid species, although not all temporally co-occur (Fig. 12). Thus the lower part of the zone is characterized by *Br. mohavensis* (Fig. 9.1); the middle part is characterized by *Br. harringtoni* Lieberman, 1999 (Fig. 9.2 ; Appendix 2), and the upper part by *Br. bristolensis* (Fig. 9.3 ; Appendix 2). *Olenellus clarki*, *O. nevadensis*, *Olenellus* n. sp. 3, and *M. fremonti* range through the zone (Fowler, 1999).

   A species of *Mesonacis* co-occurs with *Br. harringtoni* and *Br. bristolensis* in the Pioche Formation and Latham Shale ("*Mesonacis* sp. A" of Webster et al. [2003] and Webster [2007b]). This species appeared to represent a distinct morphotype, and Webster (2003b) used its FAD to define the base of a "*Mesonacis* n. sp. Zone" between the *Br. mohavensis* Zone and *Br. insolens* Zones. However, specimens recently recovered from stratigraphically lower horizons in the Carrara and Harkless Formations cast some doubt on the supposed distinction between this form and *M. cylindricus* (above; unpublished data). Morphometric analyses are needed to determine the number, morphological bounds, and stratigraphic range of species within this genus. Until such analyses are complete, the identity of this species of *Mesonacis* remains equivocal and the "*Mesonacis* n. sp. Zone" is abandoned.

   Bristolia insolens *Zone.*—The base of this new zone is defined as the FAD of *Bristolia insolens* (Fig. 10.1), and its top is delimited by the FAD of *Peachella iddingsi* (Walcott, 1884) (marking the base of the overlying zone). The *Br. insolens* Zone is contained within the "*Bristolia* Zonule" recognized by Palmer and Halley (1979). Strata of the *Br. insolens* Zone represent the maximum flooding interval and initial part of the highstand system tract of Sequence I (Fig. 3).
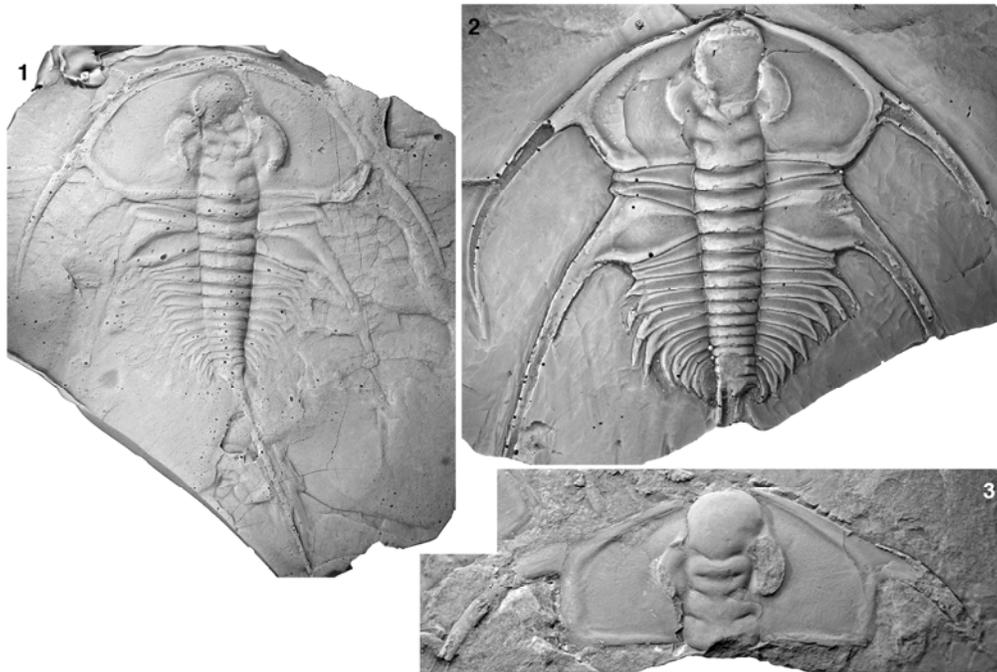
FIGURE *9.*—Biostratigraphically useful olenelloid trilobites of the *Bristolia mohavensis* Zone. *1*, *Bristolia mohavensis*, latex cast of dorsal exoskeleton, ICS collections, x2. *2*, *Bristolia harringtoni*, internal mold of dorsal exoskeleton, UCR 10/10 (holotype), x2. *3*, *Bristolia bristolensis*, internal mold of cephalon, UCR 10/10, x2. All from the Latham Shale, Marble Mountains (California).

The base of the *Br. insolens* Zone occurs approximately 34 m above the base of the Carrara Formation at Emigrant Pass (Fowler, 1999), approximately 62 m above the base of the Delamar Member of the Pioche Formation at Klondike Gap (Webster, 2007b), and almost 10 m above the base of the Latham Shale at the Marble Mountains (stratotype section; Webster et al., 2003). The lowest occurrence of *Br. insolens* at Split Mountain is 5.5 m above the base of the middle unit of the Mule Spring Limestone, although lower beds within the middle unit have not been sampled (Webster, this volume, Stops 7A, 7B). The zone has not been identified within the Tapeats Sandstone at Frenchman Mountain or in sections on the Colorado Plateau.

The *Br. insolens* Zone contains at least 13 olenelloid species, although not all temporally co-occur (Fig. 12). *Bristolia insolens* is restricted to the lower part of the zone. The last appearance datum (LAD) of *Br. bristolensis* also occurs in the lower part of the zone. *Bristolia anteros* Palmer in Palmer and Halley, 1979 (Fig. 10.2) is locally abundant in the upper part of the zone, and shows range overlap with *Br. insolens* at some localities (e.g., Split Mountain; Webster, this volume, Stop 7B). Two new species of *Bristolia* Harrington, 1956 occur high in the zone. ("*Br.* aff. *fragilis* A" and "*Br.* aff. *fragilis* B" of Webster et al. [2003], Webster [2007b], and Webster [this volume, Stop 7B]). *Bristolia harringtoni* makes a re-appearance in the upper part of the *Br. insolens* Zone, despite being unknown from the upper part of the underlying *Br. mohavensis* Zone and from the lower part of the *Br. insolens* Zone. A similarly disjunct stratigraphic distribution has been documented in the Latham Shale (Webster et al., 2003), Delamar Member of the Pioche Formation (Webster, 2007b), Carrara Formation (Fowler, 1999), and Mule Spring Limestone (Webster, this volume, Stops 7A, 7B), and appears to be a shelf-wide phenomenon. This Lazarus-like pattern of occurrences may have resulted from migration out of, then

back into the study area, changes in abundance (exceedingly rare and thus unsampled between the lower and higher intervals of occurrence), or convergent evolution of the morphotype from a *Br. bristolensis* ancestor (Webster, 2001, 2002).
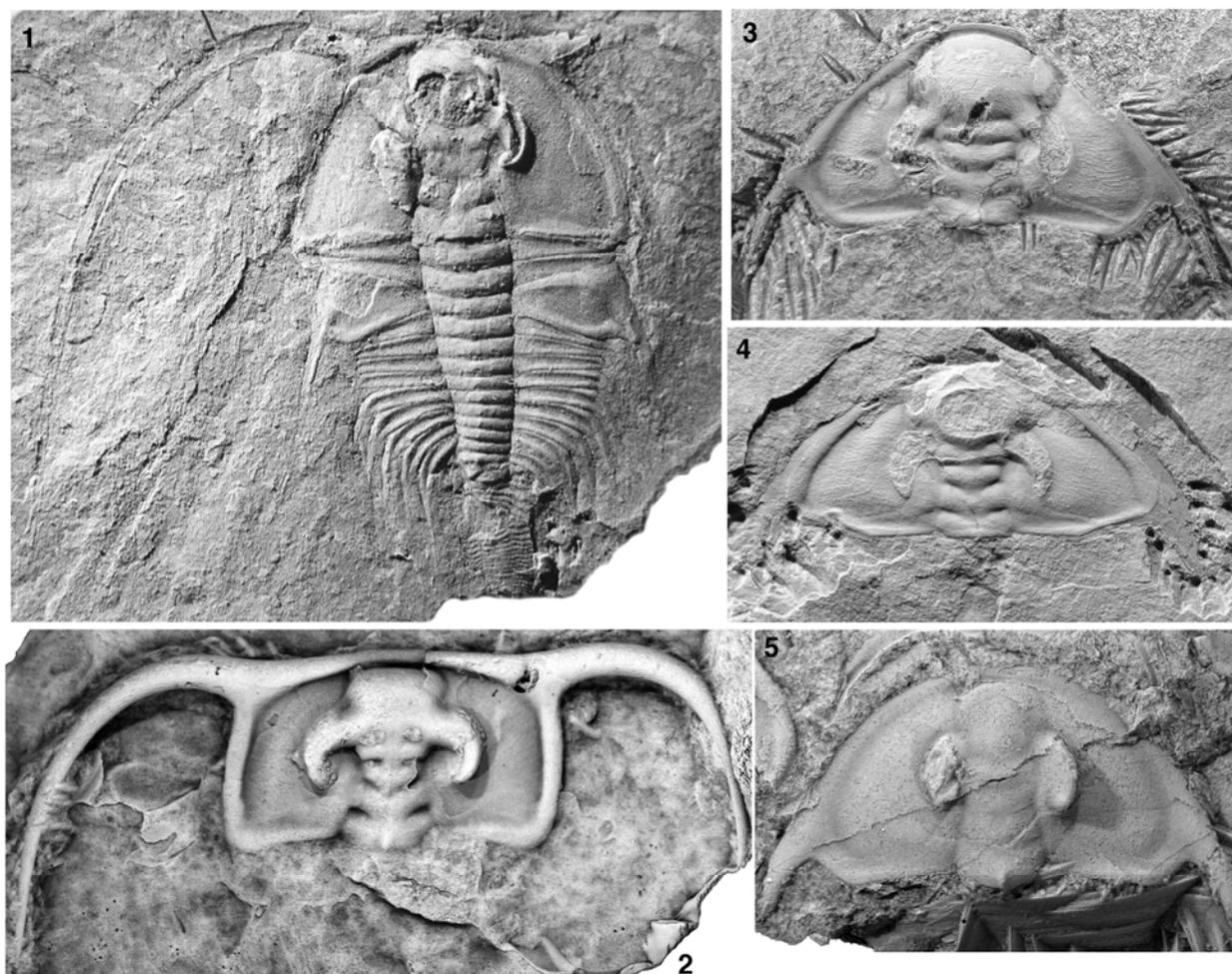
FIGURE *10*.—Biostratigraphically useful olenelloid trilobites of the *Bristolia insolens* Zone. *1*, *Bristolia insolens*, internal mold of dorsal exoskeleton from Latham Shale, Marble Mountains (California), Norm Brown Collection, x2. *2*, *Bristolia anteros*, latex cast of cephalon from Thimble Limestone Member of Carrara Formation, Titanothere Canyon, (Grapevine Mountains, California), USNM 177181 (holotype), x4. *3*, *Paranephrolenellus klondikensis*, internal mold of cephalon from Delamar Member of Pioche Formation, Klondike Gap (Chief Range, Nevada), UCR 10074.237 (holotype), x3. *4*, *Paranephrolenellus inflatus*, internal mold of cephalon from Delamar Member of Pioche Formation, Klondike Gap (Chief Range, Nevada), UCR 10077.49 (holotype), x3. *5*, *Eopeachella angustispina*, cephalon from Oak Spring Summit (Delamar Mountains, Nevada), FMNH PE58061 (holotype), x3.

The LAD of *Olenellus* n. sp. 3 occurs in the upper part of the zone. The known occurrences of *Paranephrolenellus klondikensis* Webster, 2007b (Fig. 10.3) and *Paranephrolenellus inflatus* Webster, 2007b (Fig. 10.4) are restricted to the *Br. insolens* Zone (Webster, 2007b). The lowest occurrence of *Eopeachella angustispina* Webster, 2009a (Fig. 10.5) is poorly constrained, but predates the FAD of *Pe. iddingsi* and is inferred to lie within the *Br. insolens* Zone (Webster, 2009a). *Mesonacis fremonti*, *O. clarki*, and *O. nevadensis* range through the zone (Fowler, 1999; Webster, 2007b).
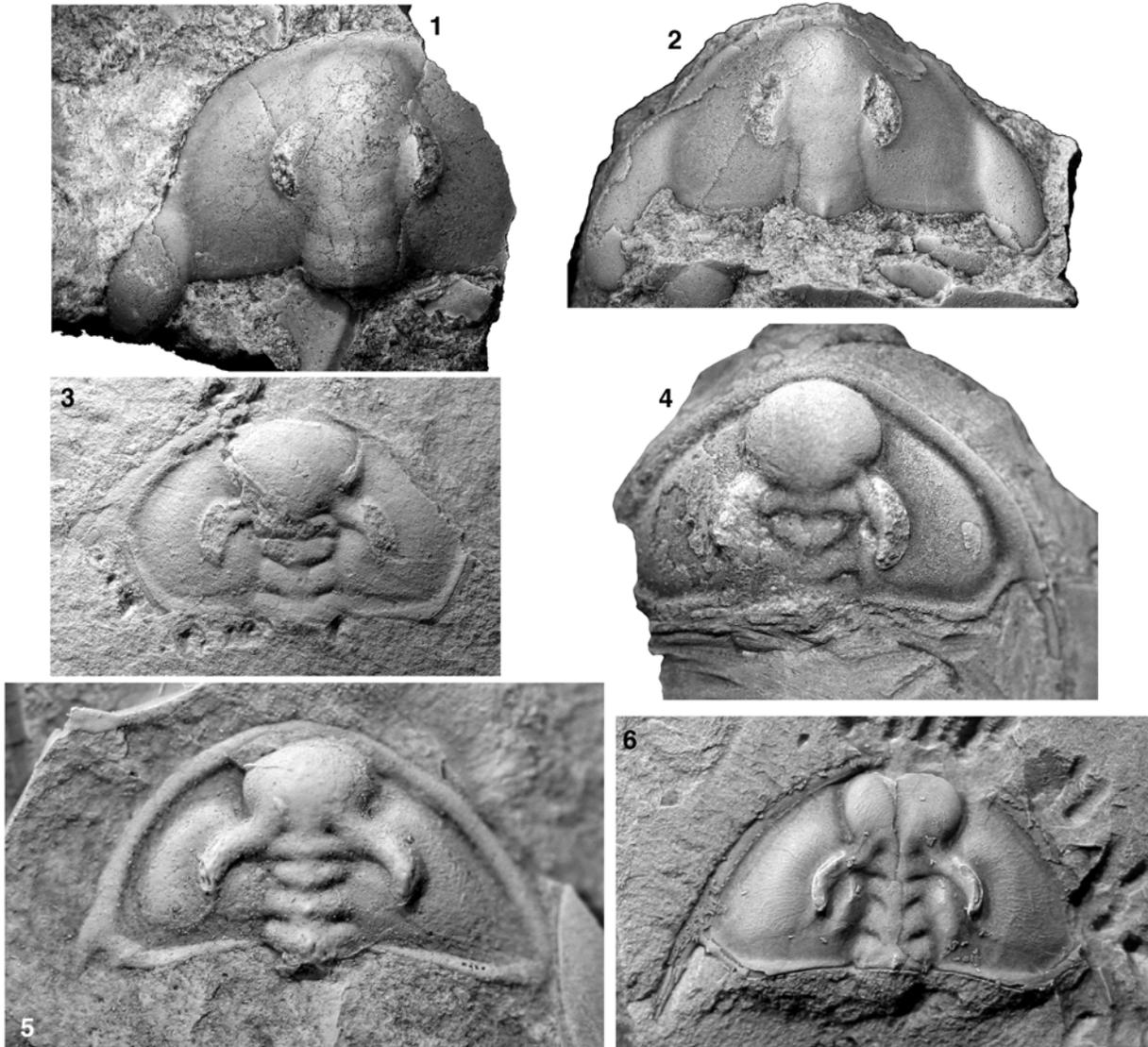
FIGURE *11.*—Biostratigraphically useful olenelloid trilobites of the *Peachella iddinsgi* Zone, *Bolbolenellus euryparia* Zone, and *Nephrolenellus multinodus* Zone. *1, Peachella brevispina*, mostly exfoliated cephalon from the Delamar Member of the Pioche Formation, Ruin Wash (Chief Range, Nevada), FMNH PE58085, x3. *2, Peachella iddingsi*, mostly exfoliated cephalon from the Delamar Member of the Pioche Formation, Big Lime Mountain (Delamar Mountains, Nevada), FMNH PE 58078, x4. *3, Paranephrolenellus besti*, internal mold of cephalon from Delamar Member of Pioche Formation, Klondike Gap (Chief Range, Nevada), UCR 10216.2 (holotype), x3. *4, Bolbolenellus euryparia*, exfoliated cephalon from Thimble Limestone Member of Carrara Formation, Eagle Mountain (California), USNM 177202, x3. *5, Nephrolenellus multinodus*, latex cast of external mold of cephalon from Pyramid Shale Member of Carrara Formation, Echo Canyon (Funeral Mountains, California), USNM 177225 (holotype), x7. *6, Nephrolenellus geniculatus*, internal mold of cephalon from uppermost Combined Metals Member of Pioche Formation, Ruin Wash (Chief Range, Nevada), FMNH PE57995, x4.

Peachella iddingsi *Zone.*—The base of this new zone is defined as the FAD of *Peachella iddingsi* (Fig. 11.2), and its top is delimited by the FAD of *Bolbolenellus euryparia* (Palmer in Palmer and Halley, 1979) (marking the base of the overlying zone). The *Pe. iddingsi* Zone is contained within the "*Bristolia* Zonule" recognized by Palmer and Halley (1979). Strata of the *Pe. iddingsi* Zone were deposited as part

of the highstand system tract of Sequence I (Fig. 3; above), and represent a continuation of the general shallowing-upward facies that began in the upper part of the *Br. insolens* Zone.

Peachella iddingsi is common within the Thimble Limestone Member of the Carrara Formation and lateral equivalents, and has been found at many localities across the shelf (Palmer and Halley, 1979; Webster, 2009a). The base of the *Pe. iddingsi* Zone occurs approximately 45 m above the base of the Carrara Formation at Emigrant Pass (Fowler, 1999), approximately 75 m above the base of the Delamar Member of the Pioche Formation at Klondike Gap (Webster, 2007b), and 15.8 m above the base of the Latham Shale at the Marble Mountains (stratotype section; Webster et al., 2003; Webster, 2009a). The base of the zone has not been precisely located at Split Mountain, although olenelloids indicative of the zone have been found in float likely sourced from the upper part of the middle unit of the Mule Spring Limestone (Webster, this volume, Stop 7B). *Peachella iddingsi* occurs in a similar stratigraphic position within the Mule Spring Limestone at Cucomungo Canyon (Palmer and Halley, 1979). An olenelloid fauna indicative of the *Pe. iddingsi* Zone has been found in the transitional beds between the Tapeats Sandstone and Pioche Formation at Frenchman Mountain (Webster, this volume, Stop 4A), but the zone has not been identified within the Tapeats Sandstone at sections on the Colorado Plateau.

The *Pe. iddingsi* Zone contains at least 11 olenelloid species, although not all temporally co-occur (Fig. 12; Palmer and Halley, 1979; Fowler, 1999; Webster et al., 2003; Webster, 2007b). The LADs of *Br. anteros*, *Br.* aff. *fragilis* A, and *Br.* aff. *fragilis* B, and the FAD of *Br. fragilis* Palmer in Palmer and Halley, 1979 all occur within this zone. The LAD of *Eopeachella angustispina* also occurs within this zone. All known occurrences of *Peachella brevispina* Palmer in Palmer and Halley, 1979 (Fig. 11.1) and *Paranephrolenellus besti* Webster, 2007b (Fig. 11.3) are restricted to this zone. A potentially new species of *Olenellus* belonging to an evolutionary complex that includes *O. terminatus* Palmer, 1998a, *O. clarki*, and *O. puertoblancoensis* (Lochman in Cooper et al., 1952) also makes its first appearance in the *Pe. iddingsi* Zone ("*O.* aff. *terminatus*" of Webster et al., 2003; Fig. 12). *Olenellus nevadensis* and *M. fremonti* range through the zone.

Bolbolenellus euryparia *Zone.*—The base of this new zone is defined as the FAD of *Bolbolenellus euryparia* (Fig. 11.4), and its top is delimited by the FAD of *Nephrolenellus multinodus* (Palmer in Palmer and Halley, 1979) (marking the base of the overlying zone). The *Bo. euryparia* Zone therefore includes the upper part of the "*Bristolia* Zonule" plus the overlying unnamed interval recognized by Palmer and Halley (1979).

Strata of the *Bo. euryparia* Zone span parts of three depositional sequences (Fig. 3). Beds in the lowermost part of the zone were deposited as part of the highstand system tract of Sequence I, and represent a continuation of the general shallowing-upward facies that began in the upper part of the *Br. insolens* Zone. Sequence II is entirely contained within the *Bo. euryparia* Zone. Beds in the upper part of the *Bo. euryparia* Zone were deposited as part of the transgressive system tract of Sequence III.

Bolbolenellus euryparia is a locally abundant but short-ranging species. It bears a distinctive rugose ornament that allows tentative identification even of incomplete cephala. The base of the *Bo. euryparia* Zone occurs approximately 67 m above the base of the Carrara Formation at Emigrant Pass (stratotype section; Fowler, 1999), approximately 95.5 m above the base of the Delamar Member (7.5 m below the base of the Combined Metals Member) of the Pioche Formation at Klondike Gap (based on a tentative identification of incomplete cephala; Webster, 2007b), and approximately 12 m above the base of the Chambless Limestone at the Marble Mountains (Webster et al., 2003). (Lieberman [1998, 1999] documented *Bo. euryparia* from the middle part of the Latham Shale in the Marble Mountains, but the specimen on which this was based cannot be relocated and the record is considered unreliable.) The base of the zone has not been precisely located at Split Mountain, although incomplete cephala tentatively identified as *Bo. euryparia* have been found in float sourced from the basal part of the upper unit of the Mule Spring Limestone (Webster, this volume, Stop 7A). *Bolbolenellus euryparia* also occurs in the Thimble Limestone Member of the Carrara Formation at Eagle Mountain (Palmer and Halley, 1979). In the in northern Groom Range it occurs in strata below the Combined Metals Member of the Pioche
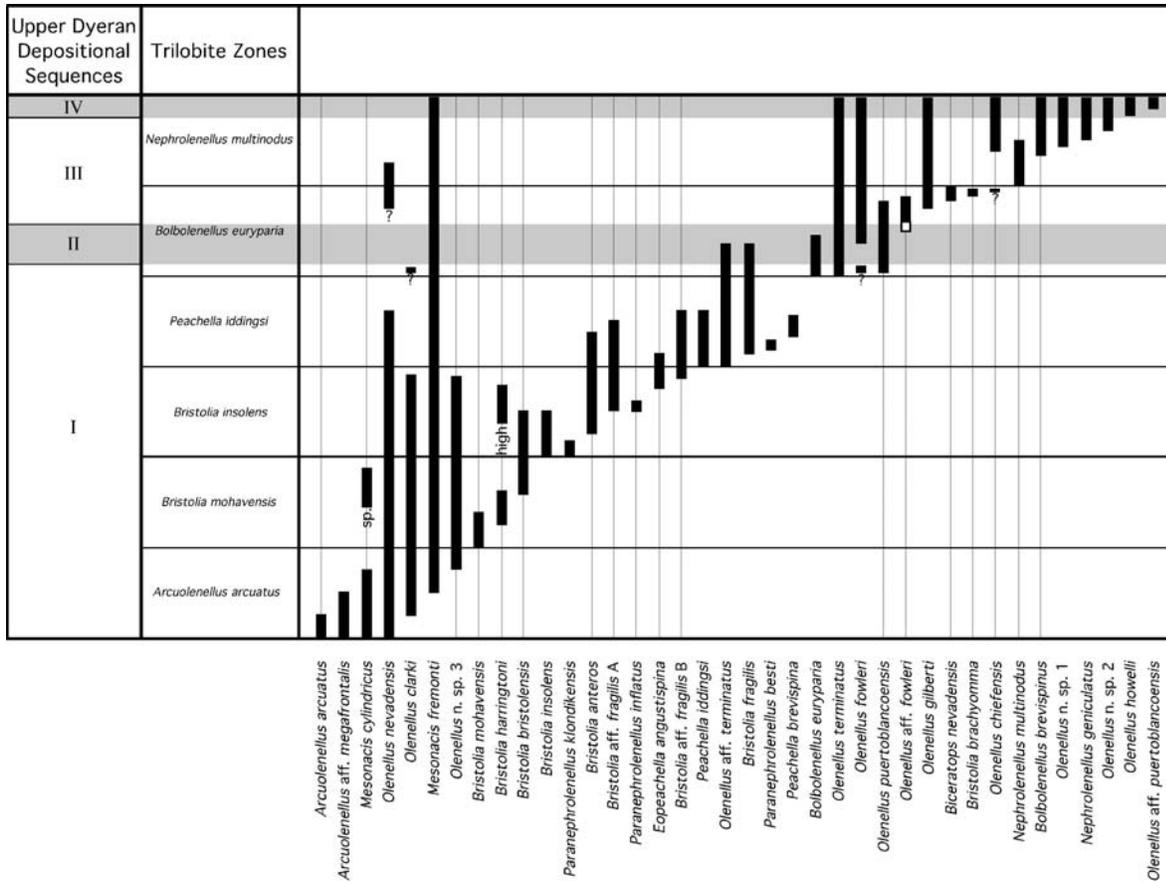
FIGURE *12*.—Range chart of olenelloid trilobites in the upper Dyeran of the southern Great Basin. Horizontal lines through range chart indicate bases of biostratigraphic zones; alternate white and grey shading through range chart indicates depositional sequences. *Olenellus* aff. *fowleri* would occur in Sequence II if "interpretation 2" of Highland Range sequence stratigraphy is correct (see Fig. 7); this potential downward range extension is indicated by the white bar. Range of a species of *Mesonacis* that may be conspecific with *Mesonacis cylindricus* is labeled "sp."; this represents "*Mesonacis* sp. A" of Webster et al. (2003) and Webster (2007b). Disjunct range of *Bristolia harringtoni* is shown as such (see text). Question marks indicate tentative identifications. Occurrences based on Webster (this volume, Stops 4B, 5A, 5B, 6A, 7A-C), Webster et al. (this volume, Stop 6B), Webster et al. (2003), Webster (2007b), and collections held at the Institute for Cambrian Studies (University of Chicago) and at the Geology Museum, University of California, Riverside (all identifications made by MW); occurrence data were also extracted from Palmer and Halley (1979) and Fowler (1999) (with most identifications checked by MW through direct examination of specimens or through photographs, and revised when necessary). The absolute time represented by each trilobite zone within this interval is essentially unconstrained. The vertical scale of this chart is therefore arbitrary (all zones shown at equal thickness). The relative thickness of species ranges is distorted accordingly.

Formation (lithologically equivalent to the Echo Shale Member of the Carrara Formation; Webster et al., this volume, Stop 6B).

The base of the *Bo. euryparia* Zone is not tightly constrained in cratonic sections. A fauna characteristic of the upper part of the zone occurs 42.95 m above the base of the measured section in the Pioche Formation at Frenchman Mountain (Webster, this volume, Stop 4B), and elements of this fauna are known from poorly constrained horizons within the Tapeats Sandstone at localities on the Colorado Plateau (Resser in McKee and Resser, 1945).

At virtually all localities for which well-constrained biostratigraphic data are available, the FAD of *Bo. euryparia* occurs a few meters below the oncolitic limestones marking the base of Sequence II. The

only exception to this occurs in the Marble Mountains and Providence Mountains, where the FAD of *Bo. euryparia* occurs well into Sequence II (several meters above the lowest oncolitic cliff and recessive interbedded mudstone-limestone interval of the Chambless Limestone; Webster et al., 2003). However, sampling of the interbedded mudstone-limestone interval is sparse, and there is a prominent erosion surface just below the lowest oncolitic bed of the Chambless Limestone that truncates the top of Sequence I (Fig. 5). It is possible that the lower end of the range of *Bo. euryparia* was not sampled and/or was removed during lowstand at this locality.

The *Bo. euryparia* Zone contains at least 16 trilobite species (12 olenelloids, 3 ptychoparioids, and a corynexochid; Fig. 12), although not all temporally co-occur. The zone can be informally divided into "lower" and "upper" intervals. The lower part of the zone spans the highstand system tract of Sequence I and all of Sequence II. *Bolbolenellus euryparia* is restricted to this interval. Other events within this interval include the highest occurrences of *Br. fragilis* and "*O.* aff. *terminatus*" (see above) and the lowest occurrences of *Olenellus fowleri* Palmer, 1998a (Appendix 2), *O. terminatus*, and *O. puertoblancoensis* at many localities (Fowler, 1999; Webster, 2007b; Webster, this volume, Stops 5A, 5B; the FAD of the last two species is below the FAD of *Bo. euryparia* in the Marble Mountains [Webster et al., 2003], but see above).

The upper part of the *Bo. euryparia* Zone equates to the transgressive system tract of Sequence III, and is characterized by a distinctive assemblage comprising *O.* aff. *fowleri* (Appendix 2), *Crassifimbra*? *metalaspis* (Sundberg and McCollum 2000), *Crassifimbra walcotti* (Resser, 1937), a new species of kochaspid, and *Zacanthopsis "levis"* (Walcott, 1886) (Appendix 2). *Olenellus puertoblancoensis*, ranging through from the lower part of the zone, also occurs in this assemblage. This assemblage occurs in both carbonate and shale facies in the Combined Metals Member of the northern Groom Range (Webster et al., this volume, Stop 6B), the Delamar Mountains (Webster, this volume, Stop 6A), and the Highland Range (Palmer, 1957, 1958; Webster, 2011; Webster and Zelditch, 2011, in press; Webster, this volume, Stop 5A, 5B). The lowest occurrence of *O. gilberti* s.s. is in the upper part of the *Bo. euryparia* Zone (Fowler, 1999; Webster et al., 2003; Webster, this volume, Stop 6A; Webster et al., this volume, Stop 6B).

Specimens tentatively assigned to *O. nevadensis* also occur in the upper part of the *Bo. euryparia* Zone in the Delamar Mountains and northern Groom Range (Webster, this volume, Stop 6A; Webster et al., this volume, Stop 6B), although the species has yet to be found in the lower part of the zone and it remains to be determined whether these specimens are conspecific with the "typical" forms of the species from the *Br. mohavensis* through *Pe. iddingsi* zones.

Bristolia brachyomma (Palmer in Palmer and Halley, 1979) occurs in the uppermost part of the *Bo. euryparia* Zone, typically just a few meters below the FAD of *N. multinodus* (Fowler, 1999; Webster et al., 2003; Webster, this volume, Stop 4B; Appendix 2). Webster (2003b) used the FAD of this species to define the base of a "*Bristolia brachyomma* Zone" between the *Bo. euryparia* and *N. multinodus* zones. However, *Br. brachyomma* has a rather limited geographic distribution, and the "*Bristolia brachyomma* Zone" is here abandoned.

The stratigraphic range of *Biceratops nevadensis* Pack and Gayle, 1971 is only well documented at Frenchman Mountain, where it occurs in association with *Br. brachyomma* (Webster, this volume, Stop 4B); this species therefore also appears to be restricted to the uppermost part of the *Bo. euryparia* Zone. *Mesonacis fremonti* ranges through the zone (Fowler, 1999; Webster et al., 2003; Webster, 2007b; Webster et al., this volume, Stop 6B).

Nephrolenellus multinodus *Zone.*—The base of the *Nephrolenellus multinodus* Zone (= "*Olenellus multinodus* Zonule" of Palmer and Halley, 1979) is defined as the FAD of *N. multinodus* (Fig. 11.5), and its top is delimited by the FAD of *Eokochaspis nodosa* (marking the base of the overlying zone and the base of the Delamaran Stage). The extinction of olenelloid trilobites occurred at or near the top of the *N. multinodus* Zone (Fig. 12). The bearing that the new, high-resolution biostratigraphic data have on our understanding of the extinction of the olenelloids is discussed below ("Dyeran-Delamaran Boundary" section).

Strata of the *N. multinodus* Zone span two depositional sequences (Fig. 3). Beds in most of the zone represent the transgressive system tract, interval of maximum flooding, and highstand system tract of Sequence III. Beds in the uppermost part of the zone were deposited during Sequence IV.

Nephrolenellus multinodus is a distinctive and well-known species (Palmer in Palmer and Halley, 1979; Webster, 2007a). The base of the *N. multinodus* Zone occurs approximately 109 m above the base of the Carrara Formation at Emigrant Pass (Fowler, 1999), 18.2 m above the highest ledge-forming limestone marking the top of the carbonate-dominated lower interval of the Combined Metals Member of the Pioche Formation in the northern Groom Range (stratotype section; Fig. 6; Webster et al., this volume, Stop 6B), 21.06 m above the base of the Combined Metals Member at Oak Spring Summit (Fig. 6; Webster, this volume, Stop 6A), and 16.93 m above the top of the Chambless Limestone cliff (within the Cadiz Formation) at the Marble Mountains (Webster et al., 2003; Webster, 2007a). The base of the zone is also well constrained in a measured section through the Pioche Formation at Frenchman Mountain (Webster, this volume, Stop 4B). Species characteristic of the zone occur in the basal 1.4 m of the Emigrant Formation at Split Mountain (Webster, this volume, Stop 7A) and in a poorly-constrained horizon within the Tapeats Sandstone in the Grand Canyon region (Resser in McKee and Resser, 1945, pl. 19, fig. 23; Webster, 2007a), although *N. multinodus* itself has not been found at either place. Occurrences of *N. multinodus* within the Pyramid Shale Member of the Carrara Formation and the Combined Metals Member of the Pioche Formation are documented at many other localities in the southern Great Basin (Webster, 2007a). The species also occurs 10 m above the base of the Gog Group in Jasper Park, Alberta (Webster, 2007a).

At least 13 species of olenelloid trilobites occur within the *N. multinodus* Zone, although not all temporally co-occur (Fig. 12). *Nephrolenellus multinodus* is restricted to the lower part of the zone, and the upper part is characterized by the presence of *Nephrolenellus geniculatus* Palmer, 1998a (Fig. 11.6). The FAD of *N. geniculatus* lies within the interval of maximum flooding or lower part of the highstand system tract of the Sequence III (above; Figs. 6, 7), and the species then ranges through the rest of that sequence and into Sequence IV.

Detailed biostratigraphic range charts for the *N. multinodus* Zone have been compiled for many localities (see Palmer, 1998a; Fowler, 1999; Webster, 2007a, 2007b; 2009b; Webster, this volume, Stops 4B, 5A, 5B, 6A, 7C; Webster et al., this volume, Stop 6B). *Olenellus gilberti*, *O. terminatus*, *O. fowleri*, *M. fremonti*, a form tentatively identified as *O. nevadensis*, and *Z. "levis"* (Appendix 2) range into the zone from below. The FAD of *Olenellus chiefensis* Palmer, 1998a occurs within the zone at virtually all localities (although there is a questionable occurrence of this species within the uppermost *Bo. euryparia* Zone in northern Groom Range; Webster et al., this volume, Stop 6B). The lowest occurrence of *Bolbolenellus brevispinus* Palmer, 1998a is also within the zone, just below the LAD of *N. multinodus*. The FADs of *N. geniculatus* and *Zacanthopsis palmeri* Hopkins and Webster, 2009 are consistently slightly above the LAD of *N. multinodus* (Fig. 7).

Although these observations hold true at all localities, intriguing among-locality differences are apparent in the precise patterns of occurrence and in the relative abundance of species throughout the zone (see also Webster et al., this volume, Stop 6B). For example, the uppermost part of the *N. multinodus* Zone in the Pioche-Caliente region (within Sequence IV) is characterized by a diverse assemblage comprising abundant *N. geniculatus*, *O. gilberti*, *O. terminatus*, *O. fowleri*, *O. chiefensis*, and *Bo. brevispinus*, plus less abundant *Z. palmeri* and rare specimens representing *Bathynotus granulatus* Lermontova, 1940, *Bathynotus* sp. indet., *Oryctocephalites palmeri* Sundberg and McCollum, 1997, *Olenellus howelli* Meek in White, 1874, and *Olenellus* n. sp. 2 (Webster, this volume, Stop 6A; Palmer, 1998a; Webster, 2009b; Hopkins and Webster, 2009). However, the uppermost part of the *N. multinodus* Zone in the northern Groom Range is characterized by *Olenellus* aff. *puertoblancoensis* (Appendix 2) and *Olenellus* n. sp. 1 (Webster et al., this volume, Stop 6B). At that locality, the FAD of each of these species is stratigraphically above the LAD of *N. geniculatus*, *O. gilberti*, *O. terminatus*, *O. fowleri*, *O. chiefensis*, and *Bo. brevispinus* (Webster et al., this volume, Stop 6B). *Olenellus gilberti* is a long-ranging species in both regions, but in the northern Groom Range it occurs only sparsely and is never dominant within

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collections while in the Pioche-Caliente region it is often the most abundant species (e.g., Webster et al., 2008).

Such among-locality differences in assemblage composition and species abundance likely represent either local sampling failures or genuine spatio-temporal variation in species distribution. For example, *Olenellus* n. sp. 1 co-occurs with *N. geniculatus* at the Hidden Valley locality in the Pioche-Caliente region (Webster, 2009b), but this co-occurrence has not been documented in the northern Groom Range. Additional examples are provided by Webster et al. (this volume, Stop 6B).

Broader applicability of the revised biostratigraphic scheme.—The species-level zones defined above will necessarily be of narrower geographic applicability than previous genus-level zones (e.g., the "*Olenellus* Zone" or the "*Bristolia* Zonule"). The biostratigraphic zones defined herein are nevertheless applicable across the southern Great Basin, a region that provides unrivaled exposure of thick, upper Dyeran strata spanning a spectrum of depositional environments from the craton to the shelf edge. The new zones therefore permit more thorough documentation and understanding of late Dyeran events in an ideal study area.

Furthermore, several of the zones can be identified beyond the southern Great Basin. *Paranephrolenellus inflatus* (characteristic of the *Br. insolens* Zone) and *Peachella iddingsi* are known from the Eureka mining district of central Nevada (Webster, 2007b; Webster, 2009a), and *Nephrolenellus multinodus* is also known from Alberta (Webster, 2007a). Such occurrences extend the area of recognition of the *Br. insolens* and *Pe. iddingsi* zones to the central Great Basin, and the *N. multinodus* Zone to the Canadian Rockies. Ongoing field work in Vermont suggests that species characteristic of the *N. multinodus* Zone in the southern Great Basin may also be present in eastern Laurentia (personal observation).

On a global scale, the occurrence of *Bathynotus granulatus* in the Pioche-Caliente region provides a species-level correlation between the uppermost *N. multinodus* Zone of Laurentia, the Amgan(?) of the Altay-Sayan Foldbelt of Siberia, and the upper Duyunian (*Ovatoryctocara granulata-Bathynotus holopygus* Zone) of the Kaili Formation of eastern Guizhou Province, South China (Webster, 2009b).

Trilobite turnover and sequence stratigraphy.—Sequence stratigraphic boundaries can coincide with observed faunal turnover in the fossil record, because they correspond to change in the physical environment that can drive evolution and extinction, and/or remove strata. However, the vast majority of observed range ends (FADs and LADs) for the 38 olenelloid species documented herein occur within sequences rather than at sequence boundaries (Fig. 12). To the extent that observed stratigraphic ranges represent a reasonable approximation of (at least local) true ranges, the (local) origination or extinction of only a few species was closely coincident with sequence boundaries.

A cluster of four FADs is shown at the base of the *Arcuolenellus arcuatus* Zone (Fig. 12), but the base of this zone is unlikely to correspond exactly to the base of Sequence I (above). Furthermore, this depiction of clustered FADs is as much based on ignorance as data, because very few precisely constrained fossil collections have been made from this interval. The LAD of *O. clarki* may just precede the sequence boundary at the top of Sequence I, if poorly preserved specimens from the uppermost Delamar Member in the Highland Range truly represent this species.

The FAD of *O. howelli* and of *O.* aff. *puertoblancoensis* may lie a short distance above the base of Sequence IV (Fig. 12). However, the former species is extremely rare (giving very little confidence as to how its observed FAD matches its true FAD) and there is ambiguity regarding the regional FAD of the latter species (see Webster et al., this volume, Stop 6B). The FAD of *Z. palmeri* is also associated with the base of Sequence IV at virtually all localities (Fig. 7; not shown on Fig. 12), although specimens tentatively identified as this species occur just below the sequence boundary at Hidden Valley (Fig. 7.2). The LADs of at least six olenelloid species are clustered at the top of Sequence IV in the Pioche-Caliente area (Palmer, 1998a; Webster et al., 2008; Webster, this volume, Stops 5A, 5B, 6A). The importance of this last depositional sequence to our understanding of the nature of the Dyeran-Delamaran boundary and the extinction of olenelloid trilobites is discussed below.

PREVIOUS INTERPRETATIONS OF THE NATURE OF THE DYERAN-DELAMARAN
BOUNDARY AND THE EXTINCTION OF THE OLENELLOIDEA

A major topic of debate on this field trip is the nature of the Dyeran-Delamaran boundary in the
southern Great Basin. The presence or absence of an unconformity at this contact has major implications
regarding inferred environmental change across the Dyeran-Delamaran boundary, and the tempo and
mode of the extinction of olenelloid trilobites (McCollum, 1994; McCollum and McCollum, 1994;
Palmer, 1998a; Montañez et al., 2002; McCollum et al., this volume, Stops 5, 6A). The debate is
summarized below, and key sequence stratigraphic and biostratigraphic data upon which the debate has
centered are identified. The following section then presents a new interpretation of the nature of the
Dyeran-Delamaran boundary interval in the southern Great Basin, based on the new high-resolution
biostratigraphic and microstratigraphic data.

Summary of the debate.—Palmer (1998a) described a diverse olenelloid fauna from the
uppermost shale of the Combined Metals Member in the Pioche-Caliente region, comprising common *N.
geniculatus*, *O. gilberti*, *O. terminatus*, *O. fowleri*, *O. chiefensis*, and *Bo. brevispinus* plus two rare species
of *Olenellus* (Webster, this volume, Stops 5, 6A). This assemblage is characteristic of the upper *N.
multinodus* Zone as defined herein. In the Pioche-Caliente region, this olenelloid assemblage immediately
underlies the basal Delamaran ribbon limestone (henceforth referred to as the "boundary limestone").
Palmer (1998a) interpreted the coincident disappearance of all species within this "terminal Dyeran"
olenelloid assemblage, with no preceding decline in their abundance, as evidence for an abrupt extinction
event.

However, McCollum and colleagues have claimed that the Dyeran-Delamaran contact in the
Pioche-Caliente region is in fact a cryptic unconformity, and that uppermost Dyeran strata may have been
removed by erosion prior to deposition of the boundary limestone (McCollum, 1994; McCollum and
McCollum, 1994; McCollum et al., this volume, Stops 5, 6A). They interpreted the coincident
disappearance of the "terminal Dyeran" olenelloid fauna in the Pioche-Caliente region as an artifact of
erosion-related range truncation (contra Palmer, 1998a). Instead, they suggested that the extinction of the
group was gradual. This conclusion was based on the staggered, non-coincident LADs of upper *N.
multinodus* Zone olenelloid species in the northern Groom Range, which they consider to represent a
more complete section (McCollum, 1994). It is important to note that the purported erosion is of sub-
biostratigraphic scale; thus all trilobite zones are represented, and only the upper portion of the *N.
multinodus* Zone is inferred to have been removed (McCollum et al., this volume, Stops 5, 6A).

Key sequence stratigraphic and biostratigraphic data in the debate.—McCollum et al. (this
volume, Stops 5, 6A) provide justification for their interpretation and give an account of the development
of their ideas over the last two decades. Their argument is based on regional-scale consideration of the
sequence stratigraphic architecture of the strata between the uppermost oncolitic limestone of the
Combined Metals Member and the boundary limestone (which they interpreted as a single depositional
sequence), and is summarized below.

McCollum and colleagues (McCollum, 1994; McCollum and McCollum, 1994; McCollum et al.,
this volume, Stops 5, 6A) based their interpretation on three key observations: (1) the depositional
sequence contains upward coarsening in the northern Groom Range, but evidence for coarsening or
shallowing upward is absent in the Pioche-Caliente region; (2) the depositional sequence thins in a
northeastward (shoreward) direction from the northern Groom Range to the Pioche-Caliente region; and
(3) the thickness of shale deposited during the interval of maximum flooding within the sequence
decreases in a northward direction within the Pioche-Caliente region (i.e., the shale forms a "siliciclastic
wedge", thickening to the south), such that the stratigraphic separation between the underlying nodular
carbonate and the boundary limestone decreases to the north. They interpreted the first observation as
evidence for removal of strata during lowstand in the nearer-shore Pioche-Caliente region. They
interpreted the second observation in the same light because, to the extent that sedimentation rates are
higher in nearer-shore settings (being closer to the source of sediment input), a thicker sequence would be
expected to have accumulated in the Pioche-Caliente region than in the northern Groom Range. They
favored interpretation of the third observation in terms of removal of progressively more shale in more

northerly localities, although they conceded that lateral facies change (from siliciclastic facies in the south to carbonate facies in the north) is possible (McCollum et al., this volume, Stops 5, 6A).

Palmer (1998a) countered the sequence stratigraphic arguments of McCollum (1994; McCollum and McCollum, 1994) with biostratigraphic data. He noted that the observed FADs of two new brachiopod species ("*Eothele* sp. 1" and an undescribed linnarssoniid) were consistently located 2 to 3 m below the boundary limestone at several localities along the entire north-to-south outcrop belt in the Pioche-Caliente region, irrespective of lithology (nodular carbonate or shale). Palmer (1998a, p. 651) concluded that these biostratigraphic data were evidence that the northward thinning of the siliciclastic wedge was due to lateral facies change, and that there was a "lack of significant erosional relief at the trilobite turnover".

However, Palmer (1998a) did not address the key issue of the absence of upward coarsening in the Pioche-Caliente region and, prior to the present paper, no new biostratigraphic or sequence stratigraphic data have been brought to bear on the issue (see the review by McCollum et al., this volume, Stops 5, 6A). Thus, the original observations and interpretations presented by McCollum (1994; McCollum and McCollum 1994) still provide the primary support for the presence of an unconformity at the Dyeran-Delamaran boundary (McCollum et al., this volume, Stops 5, 6A; but see geochemical study of Montañez et al. [2002]).

NEW INTERPRETATION OF THE NATURE OF THE DYERAN-DELAMARAN BOUNDARY AND THE EXTINCTION OF THE OLENELLOIDEA

The new sequence stratigraphic framework and biostratigraphic zonation of the upper Dyeran (Fig. 3) allows more detailed dissection of physical and biological events at and around the Dyeran-Delamaran boundary. Such work leads to a novel interpretation of the nature of the Dyeran-Delamaran boundary and the extinction of the Olenelloidea in the southern Great Basin, which is summarized below as five points.

1. The interval between the uppermost oncolitic limestone of the Combined Metals Member and the boundary limestone spans two depositional sequences.—These are identified as Sequences III and IV (above; Figs. 3, 4, 6, 7). McCollum and colleagues (McCollum, 1994; McCollum and McCollum, 1994; McCollum et al., this volume, Stops 5, 6A) treated this interval as a single depositional sequence, but a case is presented above for the existence of two distinct deepening-to-shallowing cycles based on detailed microstratigraphic and biostratinomic analyses.

Correlation of Sequence III between the northern Groom Range and the Pioche-Caliente region is supported by several biostratigraphic events that occur within the sequence at both localities: the LADs of *O.* aff. *fowleri* and *O. puertoblancoensis*, and the FADs of *N. multinodus*, *Bo. brevispinus*, and *N. geniculatus* (Fig. 6). However, biostratigraphy is of little use in the correlation of Sequence IV between these sites. The FADs of *O. howelli* and *Z. palmeri* might occur within Sequence IV in the Pioche-Caliente region (although neither case is unambiguous; above), but these species have not been found in the northern Groom Range. Sequence IV in the northern Groom Range is characterized by a different olenelloid fauna, comprising only *Olenellus* n. sp. 1 and *O.* aff. *puertoblancoensis*. Neither of these species has been sampled in the underlying depositional sequence at the northern Groom Range, but *Olenellus* n. sp. 1 has been sampled within Sequence III in the Pioche-Caliente region, and the regional FAD of *O.* aff. *puertoblancoensis* is ambiguous (Webster et al., this volume, Stop 6B). Correlation of Sequence IV among all these areas (and also to Frenchman Mountain, where only indeterminate olenelloid debris has been found within the sequence) is therefore based purely on sequence stratigraphic criteria.

2. The highstand system tract of Sequence III was removed during lowstand in the Pioche-Caliente region.—This represents a refined interpretation of the first key observation made by McCollum and colleagues (McCollum, 1994; McCollum and McCollum, 1994; McCollum et al., this volume, Stops 5, 6A; summarized above). The author concurs with their observation that upward coarsening is expressed in the northern Groom Range but is absent in the Pioche-Caliente region (Fig. 6). However, this interval represents the highstand system tract of Sequence III (Fig. 6). The unconformity therefore underlies the

ribbon limestone at the base of Sequence IV (uppermost Dyeran), rather than the boundary limestone (contra McCollum, 1994; McCollum and McCollum, 1994; McCollum et al., this volume, Stops 5, 6A). Like the argument made by McCollum and colleagues, this conclusion is based on the assumption that sediments were sourced from the east (shoreward), and therefore that strata representing upward coarsening did accumulate in the Pioche-Caliente region during the highstand system tract of Sequence III (just as they did in the more distal setting in the northern Groom Range). The present-day absence of such coarsening upward in the Pioche-Caliente region can then only be explained by the subsequent removal of strata during the ensuing lowstand. This assumption, and the conclusion relying upon it, could be invalidated if the northern Groom Range was closer to a sediment source than was the Pioche-Caliente region (e.g., if a land promontory or river delta projected into southern Nevada), or if sediments bypassed the Pioche-Caliente region. Generalized sediment transport directions certainly seem to have been from the east during the latest Precambrian and early Cambrian (Stewart, 1970, 1980; Stewart and Poole, 1974; Fedo and Prave, 1991; see also discussion of Sequence II, above), and the author is unaware of any firm evidence favoring alternative patterns of sedimentation (but see point 3, below). However, development of more detailed regional paleogeographic maps and spatial analysis of sedimentation patterns to test this assumption is encouraged.

3. The cause behind the northward thinning of the "siliciclastic wedge" in the Pioche-Caliente region cannot be unambiguously determined based on currently available data.—In terms of the new sequence stratigraphic data presented above, this "siliciclastic wedge" represents the deposits of the maximum flooding interval of Sequence III and the deepening-to-shallowing cycle of Sequence IV. Most of the northward thinning of this "siliciclastic wedge" is accounted for by a dramatic decrease in thickness of the shale of Sequence III. The shale of Sequence III is approximately 12 m at Grassy Spring (Fig. 7.1), 5.5 m thick at Hidden Valley (Fig. 7.2), 7 m thick at Oak Spring Summit (Fig. 7.3), and 2 m thick at Klondike Gap (Fig. 7.4). This interval is covered at Ruin Wash, but is certainly less than 3.5 m thick (Fig. 7.5). Below the shale, the rubbly-weathering, nodular limestone interval actually thickens from south to north, so that the stratigraphic separation between the top of the oncolitic limestone (at the base of Sequence III) and the ribbon carbonate marking the base of Sequence IV remains more-or-less constant (15 m at Hidden Valley, 14.5 m at Oak Spring Summit, 12.5 m at Klondike Gap, and 14.5 m at Ruin Wash; Fig. 7).

The FAD of *N. multinodus* at each of these localities also offers a potential point of correlation within Sequence III. This occurs just over 4 m above the highest ledge of the rubbly-weathering, nodular limestone interval at Grassy Spring, less than 1 m above this same ledge at Hidden Valley, just below this ledge at Oak Spring Summit, and within the nodular limestone interval at Ruin Wash (Fig. 7). The FAD of *N. multinodus* is also closer to the basal ribbon limestone of Sequence IV in the Chief Range than in sections to the south (Fig. 7). If the FAD of *N. multinodus* represents a reasonably isochronous event, these observations would suggest that (1) the transition from rubbly-weathering, nodular limestone to shale is diachronous, younging to the north from Grassy Spring to Ruin Wash; and (2) the part of Sequence III that overlies the FAD of *N. multinodus* is either more condensed or was subject to more severe lowstand erosion northward from Grassy Spring to Ruin Wash. It should be noted, however, that the nodular limestone interval has not been heavily sampled at many of these localities, and it is conceivable that future work will result in stratigraphically lower discoveries of *N. multinodus*. The conclusions drawn above would then have to be re-evaluated.

By contrast, the thickness of strata representing Sequence IV decreases only slightly from the Delamar Mountains to the Chief Range, being roughly 1.5 m thick at Grassy Spring, 2 m thick at Hidden Valley, 1.5 m thick at Oak Spring Summit, 0.75 m thick at Klondike Gap, and 0.67 m thick at Ruin Wash (Fig. 7). This more subtle thinning may also be explained in terms of more severe northward erosion of Sequence IV strata prior to deposition of the boundary limestone, or of more extreme northward condensation of Sequence IV strata. Northward condensation could result from sediment starvation if the tempestites responsible for siliciclastic deposition were sourced from the south. Such a current direction is contrary to the general east-to-west transport direction that characterizes much of the late Precambrian and early Cambrian in the southern Great Basin (Stewart, 1970, 1974; Stewart and Poole, 1974; Fedo and

Prave, 1991; see also point 2, above). A hypothesis of south-to-north current direction in the Pioche-Caliente region makes the testable prediction that average grain size within Sequence IV increases south of Ruin Wash. This should be investigated.

Identification of the depositional sequences in Highland Range is rendered difficult by the incomplete and partially covered sections there. Only one oncolitic interval within the Combined Metals Member is exposed at Log Cabin Mine and One Wheel Canyon (Figs. 7.6, 7.7). Above this is a mostly covered interval that likely comprises rubbly-weathering, nodular limestone. The few exposed limestone ledges within this interval yield a silicified trilobite fauna that includes *O.* aff. *fowleri* and *O. puertoblancoensis*. These species co-occur in the nodular limestone interval of Sequence III at Oak Spring Summit. If these limestone ledges in the Highland Range also represent Sequence III, then Sequence II is very thin or absent in the Highland Range, presumably as a result of removal of section during lowstand. In this interpretation, Sequence II is represented at most by the lowermost part of the oncolitic interval at the base of the Combined Metals Member ("Interpretation 1" of Figs. 7.6 and 7.7).

However, McCollum and colleagues indicate the presence of a second oncolitic interval that crops out just 3 to 4 m below the basal Delamaran boundary limestone at another section in the Highland Range (McCollum et al., this volume, Stops 5A-5D, 6A, fig. 3). They correlate this to the upper oncolitic interval at the base of Sequence III in sections to the south (McCollum et al., this volume, Stops 5A-5D, 6A, fig. 3). If their correlation is correct, then the silicified beds mentioned above (which must underlie the second oncolitic interval) were deposited as part of Sequence II, and would not correlate to the nodular limestone interval that contains the same olenelloid species in sections to the south ("Interpretation 2" of Figs. 7.6 and 7.7). The FAD of *O. puertoblancoensis* is known to occur within the upper part of Sequence I at other localities, but all other known occurrences of *O.* aff. *fowleri* are within Sequence III. If "Interpretation 2" is correct, then the stratigraphic range of this latter species must be extended downwards (white box on Fig. 12). Resolution of this issue will require examination of more sections in the Highland Range, and more detailed biostratigraphic sampling of the Combined Metals Member therein.

Zacanthopsis palmeri has been found within and above a ribbon limestone approximately 1 m below the boundary limestone at One Wheel Canyon (Webster, this volume, Stop 5A). This ribbon limestone and the overlying nodular shale therefore appear to be equivalent to the 0.67 m interval underlying the boundary limestone at Ruin Wash, and thus represent Sequence IV. The absence of shale at the top of Sequence III at One Wheel Canyon could result from an extension of either model developed to explain the thinning of the "siliciclastic wedge" at the top of Sequence III in sections to the south (i.e., lateral facies change producing a diachronous lithological change from nodular limestone to shale that youngs to the north, and/or more pronounced northward condensation or erosion below the base of Sequence IV; discussed above).

4. The magnitude of any erosion below the base of the lowermost Delamaran depositional sequence cannot be determined based on currently available data.—There is evidence of slight shallowing in the upper part of Sequence IV in both the Pioche-Caliente region (but still within a deep subtidal setting below storm wave base; above; Webster et al., 2008) and in the northern Groom Range (discussed above). It is conceivable that the contact between Sequence IV and the overlying bed marking the base of the next sequence (the boundary limestone in the Pioche-Caliente region and the next silty limestone to ferric dolomite in the northern Groom Range) is conformable in each case. However, it is equally conceivable that some unknown thickness of strata that coarsened upward was deposited in both the Pioche-Caliente region and in the northern Groom Range, and was subsequently removed at both places during the ensuing lowstand prior to deposition of the basal Delamaran bed. Resolution of this issue requires discovery of an unambiguously conformable succession spanning the Dyeran-Delamaran boundary, to which the Pioche-Caliente and northern Groom Range sections could be compared using sedimentological, biostratigraphic, and/or geochemical data.

5. The nature of the extinction of olenelloid trilobites (abrupt versus more protracted) cannot be determined based on currently available data.—Olenelloid trilobites occur to the top of the preserved part of Sequence IV in the Pioche-Caliente region and to the middle of the preserved part of Sequence IV in

the northern Groom Range. However, the completeness of this sequence is unknown in both areas (point 4, above). The completeness of Sequence IV is also unclear in the Cadiz Formation of the Marble Mountains and in the Pioche Formation at Frenchman Mountain, because the base of the Delamaran has not been precisely identified at either of these localities. It is therefore unknown whether the 11 species of olenelloids known to occur within Sequence IV (Fig. 12) became extinct synchronously or in a staggered fashion (and if so, over what time span).

This issue can only be unambiguously settled if the stratigraphically highest olenelloid trilobites and basal Delamaran trilobites occur within the same depositional sequence rather than on opposite sides of a sequence boundary. Even then, a great sampling effort might be required to overcome the Signor-Lipps effect (by which sampling failures cause the observed LADs of taxa to occur below the actual time of extinction, thus making an extinction event appear more protracted than it perhaps was; Signor and Lipps, 1982). More fieldwork is needed.

ACKNOWLEDGMENTS

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APPENDIX 1: THE STUDY AREA

For convenience, the study area (Fig. 2) is here referred to as the "southern Great Basin", although it actually spans two provinces defined in terms of present-day hydrology: the southern Great Basin proper (an area of internal drainage, incorporating most of southern Nevada and southeastern California); and the Colorado River watershed (draining the Colorado Plateau, northwestern Arizona, and southernmost Nevada). The study area also spans two provinces defined in terms of tectonic structure: the Colorado Plateau (a stable block that experienced major uplift during the Late Cretaceous to Paleogene Laramide Orogeny, with minor uplift and tilt since); and the Basin and Range Province (characterized by north-south trending mountain ranges separated by broad valleys, produced through Neogene continental extension; below). The transition from the Colorado Plateau to the Basin and

Range Province is marked by the spectacular Grand Wash Cliffs in northwestern Arizona and the Hurricane Cliffs in Utah.

Tectonic history of the study area.—Cambrian strata of the southern Great Basin were deposited on a passive shelf on the western margin of Laurentia. Cambrian sediments record the progressive drowning of the shelf, which was experiencing thermal subsidence associated with the rifting away of a large continental fragment during the late Precambrian (Stewart, 1970; Stewart and Poole, 1974; Bond et al., 1983).

From the mid-Jurassic to early Paleogene, the area experienced crustal shortening associated with the subduction of the Farallon Plate beneath the western margin of North America. This shortening was accommodated in part by eastward thrusting of the Paleozoic shelf strata into a series of stacked thrust sheets. These thrust sheets together form the Sevier Thrust Belt, the present-day eastern limit of which is shown on Fig. 2. As a result of this displacement, Paleozoic strata within the thrust belt have been termed allochthonous relative to those east of the belt (e.g., Palmer, 1971).

Subsequently, the area west of the Colorado Plateau (including the Sevier Thrust Belt) experienced profound extension during the Neogene. This resulted in the formation of the north-south trending, fault-bounded, mountain ranges separated by wide valleys that define the present-day Basin and Range structural province (above). Some strike-slip faulting also occurred at this time (e.g., the northwest-trending, right-lateral Las Vegas Valley shear zone and Death Valley-Furnace Creek fault zone). The ranges expose the mosaic of Sevier thrust sheets that contain the classic Cambrian strata studied herein (Fig. 2).

A palinspastic reconstruction of the southern Great Basin shows that 80 percent of the present-day east-west distance between sections resulted from Neogene extensional crustal thinning, but that the relative position of sections was not markedly altered by this extension (Snow and Wernicke, 2000, figs. 2, 3). The estimated magnitude of earlier eastward crustal shortening associated with each of the thrusts in the Sevier Thrust Belt (above) is relatively small by comparison to this extension (Stewart and Poole, 1974, and references therein; Stewart, 1980). Thus, despite the complex structural history of the region, the present-day arrangement of Cambrian outcrops in the southern Great Basin is a reasonable proxy for their relative positions on the Cambrian shelf, even though absolute distances between them have been modified.

APPENDIX 2: COMMENTS ON SELECTED SPECIES MENTIONED IN THE TEXT

Arcuolenellus aff. *megafrontalis*.—Preliminary comparison suggests that *A.* aff. *megafrontalis* (Fig. 8.2) has a proportionally longer preglabellar field than the Precordilleran *A. megafrontalis* (Vaccari, 1988), although the difference is subtle and may relate to differences in preservational mode. Morphometric analyses are currently being conducted to determine whether this difference is sufficient to recognize *A.* aff. *megafrontalis* as a distinct species.

Bristolia brachyomma.—Here I follow Fowler (1999) in assigning this species (illustrated by Webster, this volume, Stop 4B, fig. 4.4) to *Bristolia* rather *Olenellus*. A full systematic revision of the species, including justification for this generic reassignment, will be published elsewhere.

Bristolia mohavensis, *Bristolia harringtoni*, and *Bristolia bristolensis*.—*Bristolia mohavensis* (Fig. 9.1) is readily distinguished from *Br. harringtoni* (Fig. 9.2) and *Br. bristolensis* (Fig. 9.3) by its retention of a preglabellar field throughout ontogeny. *Bristolia harringtoni* and *Br. bristolensis* both lack a preglabellar field at maturity, and are distinguished from each other by the strength of the adgenal angle and relative advancement of the genal spine bases; the conditions of these features in *Br. harringtoni* more closely resemble those in *Br. mohavensis* than do the conditions in *Br. bristolensis*.

Olenellus fowleri.—This species (illustrated by Webster, this volume, Stops 5A, 5B, 6A, fig. 7.1) is widespread but nowhere abundant in the upper *Bo. euryparia* Zone and the *N. multinodus* Zone. It possesses a preglabellar field of moderate length (sag.), has a stout intergenal spine located very close to the base of the genal spine, and the posterior tip of the ocular lobe is located opposite the posterior third or midlength (rarely the anterior third) of LO. The posterior tip of the ocular lobe is consistently located opposite the anterior third of LO on stratigraphically low specimens from the upper Delamar Member of the Pioche Formation (lowermost *Bo. euryparia* Zone, Log Cabin Mine section, Highland Range). Pending morphometric analysis, these lower specimens are here tentatively identified as *O. fowleri*, and the range of the species is extended stratigraphically down to unambiguously bracket the occurrences of *O.* aff. *fowleri* (below).

Olenellus aff. *fowleri*.—This form (illustrated by Webster, this volume, Stops 5A, 5B, 6A, fig. 6.7-6.12) differs from *O. fowleri* s.s. in possessing only a very short preglabellar field and in having a wider (tr.) separation between the bases of the intergenal and genal spines (more apparent on larger specimens). The cephalon of this morphotype therefore appears proportionally wider (relative to cephalic length) than typical *O. fowleri* specimens. Detailed morphometric analysis is in progress to determine whether such differences are sufficiently distinct to

warrant recognition of this form as a new species. This morphotype is moderately abundant in the upper *Bo. euryparia* Zone.

Olenellus aff. *puertoblancoensis*.—This form (illustrated by Webster et al., this volume, Stop 6B, fig. 5.3) appears to differ from the stratigraphically lower *O. puertoblancoensis* s.s. (illustrated by Webster, this volume, Stops 5A, 5B, 6A, figs. 6.1-6.6) in terms of possessing a subtly narrower (tr.) cephalon relative to cephalic length. However, given the variation in this feature resulting from both biology (including ontogeny) and taphonomy, quantitative morphometric analysis is necessary to determine whether the supposed difference is sufficiently robust to warrant species-level distinction.

Zacanthopsis "levis".—Preliminary studies suggest that specimens currently assigned to *Z. "levis"* actually represent complex of species, and that the stratigraphic succession of these morphotypes may have some biostratigraphic utility (Hopkins and Webster, 2008, 2009). The stratigraphically highest morphotype within this complex was recently described as *Zacanthopsis palmeri* by Hopkins and Webster (2009). Systematic study of the remaining members of the putative complex is ongoing.