Palaeogeography, Palaeoclimatology, Palaeoecology 277 (2009) 9–33

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Sequence stratigraphy, cyclic facies, and *lagerstätten* in the Middle Cambrian Wheeler and Marjum Formations, Great Basin, Utah

Carlton E. Brett [a,*], Peter A. Allison [b], Michael K. DeSantis [a], W. David Liddell [c], Anthony Kramer [a]

[a] Dept. of Geology, University of Cincinnati, Cincinnati OH 45221-0013, United States
[b] Dept. of Earth Science & Engineering, Imperial College London, Royal School of Mines, South Kensington Campus, London SW7 2AZ, UK
[c] Dept. of Geology, Utah State University, Logan, Utah 84322-4505, United States

ARTICLE INFO

Article history:
Accepted 5 March 2009

Keywords:
Cyclicity
Sequence stratigraphy
lagerstätten
Cambrian
Taphofacies

ABSTRACT

Recurrent taphofacies, including conservation *lagerstätten*, are identified within a spectrum of facies in fourth-order sequences in the Middle Cambrian Wheeler, and Marjum formations of the Drum Mountains and House Range, west-central Utah. These sequences are 3–20 m thick and commence with sharply-based compact, oncolitic, oolitic, or pelletal pack- and grainstones with sharply-defined, corroded and mineralized upper contacts that record drowning discontinuities and early transgressive systems tracts (TSTs). Overlying intervals of calcareous shale and thin-bedded wacke- to packstones with abundant, disarticulated polymerid and agnostoid trilobites represent late TSTs. These are commonly followed by lavender-gray mudstones rich in sponge spicules and comminuted fossil debris that reflect condensed maximum flooding zones. The overlying early highstand (HST) intervals of black, fissile shales are typically barren except for indistinct, circular carbonized algae, but in rare instances, include soft-bodied animal remains. A combination of lower dysoxic–anoxic conditions, with a fluctuating oxycline, and relatively rapid episodic influx of fine-grained detrital sediment favored repeated burial and preservation of abundant organic detritus and rarely soft-bodied animals. Interbedded dark gray, shales include abundant articulated agnostoid trilobites and diminutive polymerids (e.g., *Jenkinsonia*). Overlying platy, calcareous bedding planes covered with articulated bodies and molts of the polymerid *Elrathia* indicate rapid blanketing of undisturbed seafloors by calcareous mud layers. These beds grade upward successively into interbedded, sparsely fossiliferous platy to flaggy shale and thin, pale gray weathering calcisiltites, and burrow-mottled to nodular limestones, recording late HST to falling stage (FSST) carbonate shedding. Thin calcisiltites include fossil debris and articulated larger polymerid trilobites and the eocrinoid *Gogia*, preserved by obrutionary deposits. The repeated recurrence of these patterns provides the rudiments of a predictive model that not only explains the differing modes of preservation but may also aid in prospecting for new *lagerstätten*.

1. Introduction

Sequence stratigraphy provides an important predictive model for the interpretation of ancient marine environments and links the disparate disciplines, of sedimentology, taphonomy and paleoecology (Brett, 1995, 1998). Extraordinary fossil assemblages, *lagerstätten*, in both concentration and conservation modes may occur in predictable patterns in sedimentary cycles. It is critical that taphonomic and paleoecological studies of extraordinary fossil assemblages be placed in a sequence stratigraphic context as this is the only way to gain a predictive understanding of where such biotas may occur.

The Early to Middle Cambrian interval has proven to be the most prolific for extraordinary preservation of soft and weakly sclerotized organisms (conservation *lagerstätten*). A good deal of research has been directed toward understanding this unusual taphonomic "window" (Seilacher et al., 1985; Allison, 1986, 1988a,b; Butterfield, 1990; Allison and Briggs, 1991, 1993; Pickerill, 1994; Allison and Brett, 1995; Butterfield, 1995; Petrovich, 2001; Briggs, 2003; Orr et al., 2003; Powell et al., 2003; Gaines and Droser, 2003, 2005; Gaines et al., 2005; Caron and Jackson, 2006). However, this intense focus on the unusual biotas has eclipsed more comprehensive investigations of the full spectrum of Cambrian taphofacies (but see Gaines et al., 2005). It is clearly important to take a comparative approach that contrasts *lagerstätten*-bearing deposits with more "normal" types of Cambrian taphofacies. This paper will consider the conditions that were *not* conducive to extraordinary fossil preservation, as well as those that were.

High-resolution sequence stratigraphy of the Middle Cambrian Swasey, Wheeler and Marjum formations in the Drum Mountains and House Range, west-central Utah (Figs. 1, 2) has defined recurrent associations of litho- and taphofacies. The Wheeler and Marjum formations in the Great Basin of Utah have long been recognized as the source of exceptionally preserved trilobite and echinoderm material

---

* Corresponding author.
E-mail address: brettce@email.uc.edu (C.E. Brett).

0031-0182/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2009.02.010

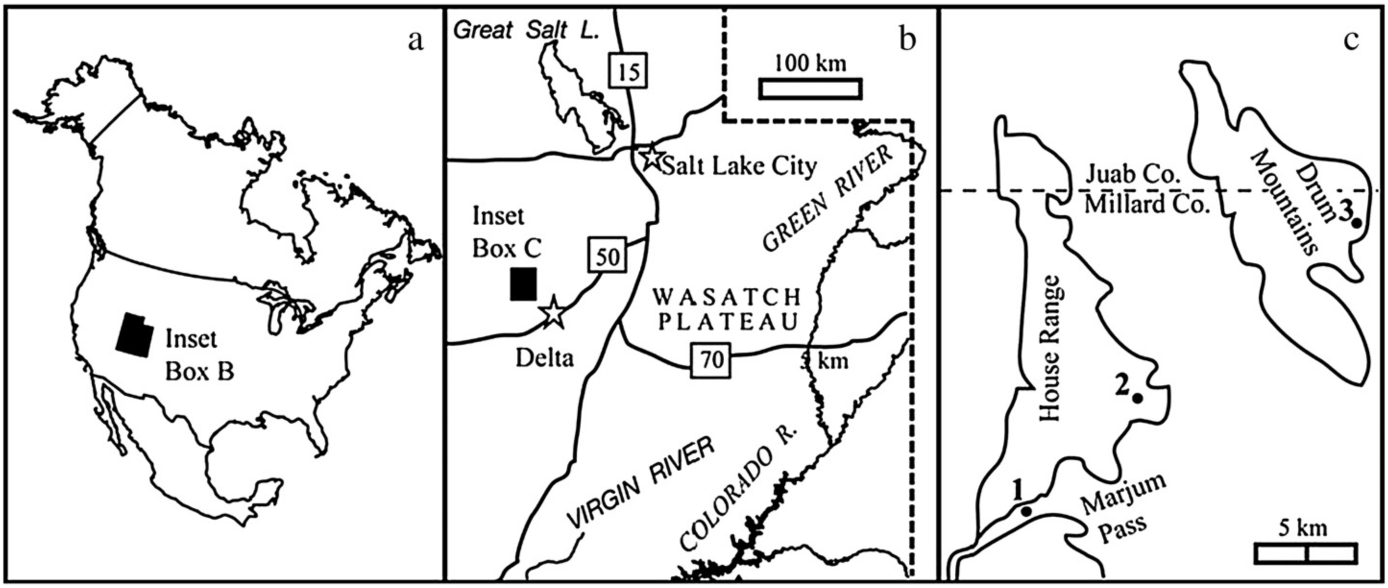


Fig. 1. Location map of study area in south-central Utah. (a) position of state of Utah in North America. (b) position of Delta and study area within Utah. (c) House Range and Drum Mountains locations, as follows: 1) Marjum Pass, 2) Wheeler Amphitheater; 3) Drum Mountains. Modified from Hintze and Robison (1975) and Hintze and Davis, (2002).

(Walcott, 1908), including beds replete with the trilobite *Elrathia kingii,* arguably the most widely recognized of trilobites (Gaines and Droser, 2003). In addition, specific shale beds yield exceptionally preserved biotas that include sponges, weakly sclerotized arthropods, anomalocarids, worms, and other soft-bodied organism remains with preservation resembling that of the slightly older Burgess Shale (Robison, 1991). These assemblages can be defined as conservation *lagerstätten*: beds characterized by unusually well preserved organism remains. It should be noted that the term *lagerstätten* has been used both to denote single bedding planes and intervals up to many meters thick that yield extraordinary fossils. We use the term to signify intervals rich in extraordinary fossils. Under this definition, at least three intervals, yielding *lagerstätten* have been described from the Wheeler and Marjum formations in the House Range (Rogers, 1984; Briggs and Robison, 1984; Robison, 1984a; Conway Morris and Robison, 1986, 1988; Robison, 1991), and recently at least two additional horizons have yielded abundant soft-bodied fossils in the Drum Mountains (S. Halgedahl and R. Garrard pers comm.; Robison, 1991; Briggs et al., 2005). The stratigraphic and sedimentological context of the fossiliferous cycles are clearly necessary for understanding the factors that promoted preservation.

In this paper we present an overview of facies, sequence stratigraphy, and sedimentary cycles in the Cambrian of the Great Basin. We then relate fossil preservation to predictable processes developed during depositional sequences and identify the parts of sedimentary cycles and facies that yield soft-bodied organisms and other types of unusual preservation. If this approach were adopted for the study of post-Cambrian *lagerstätten* it would help to define those aspects that were unique to the Cambrian and thus may further define the nature of the so-called “Cambrian preservational window”.

2. Geologic setting and stratigraphy

The Middle Cambrian Swasey and Wheeler Formations of Utah were deposited in tropical to subtropical environments about 15–20° north of the equator (Scotese, 1997; Fig. 2). Sediments, including massive shallow water carbonates and siliciclastics were deposited on the northern (western in present day directions) passive margin of the Laurentian craton. Shallow shelf carbonates, mainly microbial and/or algal in origin, accumulated in a carbonate factory, the so-called “Great American carbonate bank” (Palmer, 1960, 1971; Aitken, 1978, 1997). Micritic limestones and late diagenetic dolostones, interfinger shoreward with mixed limestones and siliciclastic muds, and sands of the “inner detrital belt” (Palmer, 1960, 1971; Robison, 1964; Aitken, 1978). These terrigenous sediments were derived from continental basement, particularly the Transcontinental Arch, a NE–SW trending gently sloping basement high in west-central Laurentia. Carbonates also pass in a basinward direction (westward in a modern sense), into calcareous shales and mudstones (e.g. Wheeler Formation) of the “outer detrital belt” (Palmer, 1960; Aitken, 1978, 1997; Elrick and Snider, 2002). The source of these sediments is disputed. They may have been sourced from the inner belt through the action of offshore winds and currents that promoted sediment bypass of the shallow carbonate shelf, but given the low content of siliciclastics in the middle carbonate belt this seems unlikely (Elrick and Snider, 2002). Moreover, despite previous extensive field study in the Cambrian of the Great Basin, no evidence has ever been identified, for possible bypass channels, that could have carried siliciclastic

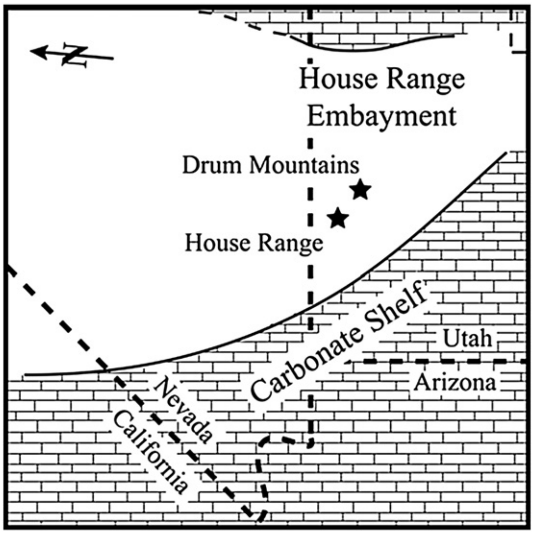


Fig. 2. The Middle Cambrian paleogeography of the study area showing the position of the House Range Embayment, general reconstruction of carbonate platform and outer detrital belt. North arrow is for reconstructed paleogeography of Middle Cambrian. After Vorwald (1983).

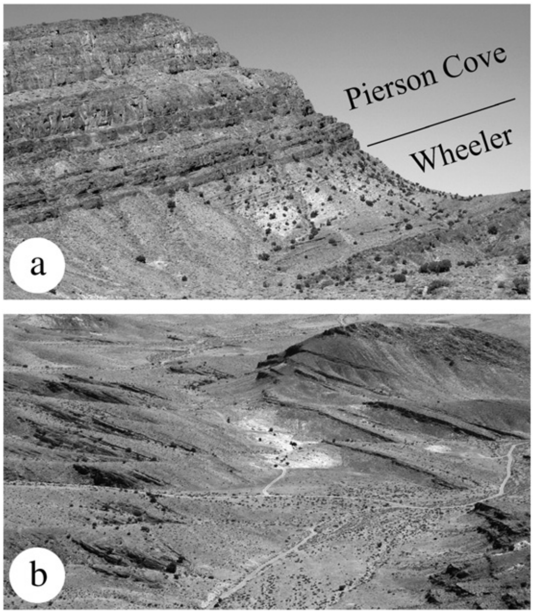


Fig. 3. Photographs of characteristic outcrops in the Drum Mountains. (a) Middle Cambrian limestones and shales, looking north at Sawtooth Ridge, calcareous shale of the upper member of Wheeler Formation forms the prominent base of slope and is about 75 m thick; cliffs are in Pierson Cove = Marjum Formation. (b) Looking south from the crest of Sawtooth Ridge depicted, shales outcrop in valley floor with limestone ledges cropping out in valley sides, unpaved road in center of field of view is 3 m wide.

sediments across the shelf from inner to outer detrital belts. Terrigenous sediments thicken to the southwest into the Patterson Pass Shale (Rees, 1986) and thus may have been derived from offshore continental fragments or island arc terranes. Alternatively the muds may have been sourced from an area near British Columbia and dispersed along the then-northern shelf by the northeast Trade Winds (Aitken, 1997; Elrick and Snider, 2002). Whatever their source, however, it is clear that muds must have been deposited episodically and accumulated rapidly in discrete event beds, as evidenced by numerous obrution beds in some intervals (see below).

The Middle Cambrian sediments discussed herein were deposited within a 40 km NE–SW trending intra-shelf basinal re-entrant on the passive Laurentian shelf margin, the House Range Embayment (Brady and Koepnick, 1979; Rees, 1986; Fig. 2). This was probably a fault-controlled basin; it possessed a sharp, distally steepened ramp at its southern boundary and deepened gradually to the SW from the Drum Mountains toward its basin axis in the House Range and Snake Range. An abrupt change to shallow water carbonates, coeval with the Wheeler Formation (Eye of Needle Formation) occurs in the Cricket and Wah Wah Mountains to the south of the southern bounding fault (Fig. 2).

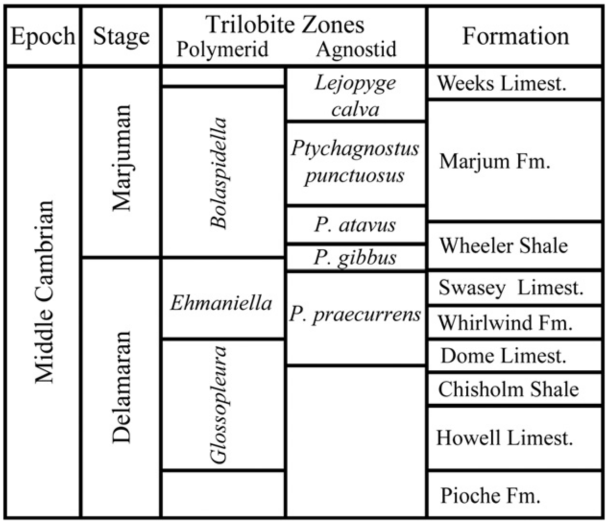
2.1. Stratigraphy of the Wheeler and Marjum formations

The study interval comprises the upper Swasey Limestone, Wheeler Shale and lower Marjum/Pierson Cove formations (Figs. 3–5). The majority of the Wheeler and Marjum formations belong to the *Bolaspidella* polymerid trilobite zone of the mid Middle Cambrian (Robison, 1964, 1976). Unfortunately there are few good radiometric dates for this time interval. The duration of the Middle Cambrian has been estimated at between ~9 million years (Bowring and Erwin, 1998; Young and Laurie, 1996; Elrick and Snider, 2002) and 12 million years (Gradstein et al., 2004). The fact that the Swasey to lower Marjum interval represents about a third of the thickness of this interval and includes portions of four agnostoid trilobite subzones, suggests that it probably represents three to four million years (Fig. 4). These sediments are exposed in a series of ranges in the Great Basin, the Drum Mountains, Fish Springs, and House Ranges in south central Utah (Palmer, 1960, 1971; Hintze and Robison, 1975; Dommer, 1980; Hintze and Davis, 2002; Fig. 1). The central House Range, near Marjum Pass and Wheeler Amphitheater exposes facies that are clearly much more shale-rich and distal relative to the equivalents in the Drum Mountains. In turn, the latter show abundant shales and are clearly much more distal than the Eye of the Needle carbonates in the Cricket Mountains or Wah Wah Mountains to the southeast.

The top of the Swasey Formation is marked by a shift to finer-grained, argillaceous carbonate and shale of the Wheeler, Patterson Pass Shale, Lincoln Peak Formation, and correlative intervals throughout the Great Basin. A diverse trilobite fauna, the *Glyphaspis* assemblage zone, typifies these Swasey–Wheeler transition beds in the Great Basin.

The Wheeler Formation comprises 140 to more than 300 m of dark gray to black shale, platy calcareous shale/argillaceous limestone, and calcisiltite (laminated pelmicrites) with minor, thin oolitic, oncolitic and fossiliferous wacke- to packstones. In the Drum Mountains, the Wheeler is more than twice as thick as in any other section and more calcareous (Crittenden et al., 1961; Dommer, 1980; Rees, 1986). This excessive thickness may represent higher limestone content and lesser compaction than shale-prone sections (Schneider, 2000); it may also in part reflect structural complications, but this issue is beyond the scope of this report and will be discussed more fully in a separate paper. The agnostoid-based *Ptychagnostus gibbus*/*P. atavus* Zonal boundary lies within the lower quarter of the Wheeler Shale and the global boundary stratotype of the Drumian Stage is placed at this boundary on "Stratotype Ridge" in the Drum Mountains (Robison, 1982; Babcock et al., 2005; Halgedahl et al., 2009). The lower third to two thirds of the Wheeler Formation includes a series of ledge- and slope-forming alternations of gray thin bedded to concretionary, agnostoid-rich platy limestones and very calcareous shales. The upper Wheeler of the Drum Mountains is about 100 m thick and comprises a lower 12 to 19 m of black platy limestone and minor shales, which gives way upward to about 20 m of distinctly cyclic ledge forming oolitic–oncolitic compact grainstones and intervening black to gray shales and cilcisilites; in turn this interval gives way abruptly to a 40–50 m succession of black to medium gray, buff weathering, calcareous, fissile to platy shales with increasing amounts of tabular rhythmically bedded calcisilites toward the top.

The cyclic Marjum Formation in its type area is up to 300 m thick and consists of about 40% slope-forming calcareous shales that alternate with intervals of about 60% cliff-forming limestones and dolostones (Robison, 1964; Elrick and Snider, 2002); the laterally



Epoch	Stage	Trilobite Zones		Formation
		Polymerid	Agnostid	
Middle Cambrian	Marjuman		*Lejopyge calva*	Weeks Limest.
		Bolaspidella	*Ptychagnostus punctuosus*	Marjum Fm.
			P. atavus	Wheeler Shale
			P. gibbus	
	Delamaran	*Ehmaniella*	*P. praecurrens*	Swasey Limest.
				Whirlwind Fm.
		Glossopleura		Dome Limest.
				Chisholm Shale
				Howell Limest.
				Pioche Fm.

Fig. 4. Stratigraphy and biostratigraphic zonation of Middle Cambrian units in the House Range and Drum Mountains.

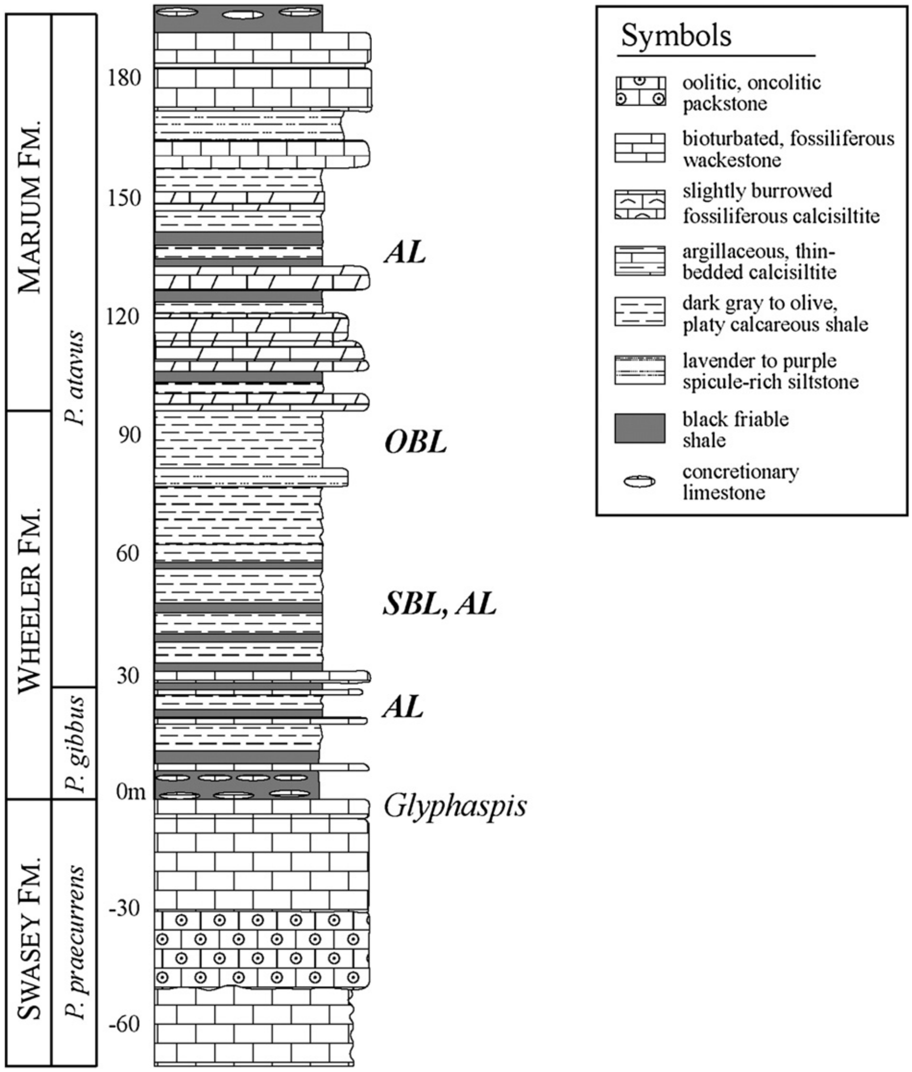


Fig. 5. General stratigraphy, biostratigraphy, and marker horizons of the Swasey, Wheeler and lower Marjum formations in the House Range, Millard County, Utah. Note: only the lower third of the Marjum Formation is shown. Second column shows approximate positions of agnostoid zones; *P.* = *Ptychagnostus*; *Glyphaspis* refers to the distinctive diverse trilobite-rich fauna characterized by the polymerid *Glyphaspis*, in the uppermost Swasey Formation. Symbols: AL: algal lagerstätten interval; SBL: soft-bodied lagerstätten interval; OBL: obrution lagerstätten (articulated eocrinoids and sponges). Note key to lithologic symbols used in this and all subsequent figures.

equivalent Pierson Cove Formation shows a much higher percentage of limestone. The latter are mainly stacked, bioturbated, thin, wavy-bedded limestones, rhythmic calcisiltites, minor intraclastic conglomerates and ledge-forming oolitic to oncolitic limestones (Dommer, 1980; Rogers, 1984). Near Marjum Pass, the Marjum Formation displays a lower, cliff-forming interval of massive, burrow-mottled wackestones and an upper succession of alternating shale-limestone cycles (Figs. 4, 5). Because of the strong southwestward deepening trend in the House Range Embayment, the Marjum Formation in the House Range records a spectrum of cyclic facies similar to those of the middle–upper Wheeler Formation in the Drum Mountains.

In the Drum Mountains the interval of the upper Wheeler Shale is abruptly overlain by about 30 m of cliff -forming, massive, burrow-mottled wackestones and oolitic grainstones with stromatolites up to a 5 to 30 m interval of highly fossiliferous dark gray, buff weathering, very calcareous shale and argillaceous dolostone, informally termed the “Trilobite quarry shale” because it is extensively quarried by amateurs for its excellently preserved trilobites, especially *Asaphiscus wheeleri* (see Vorwald, 1983). Certain previous authors have placed the 30 m carbonate interval, together with the Trilobite quarry shale (Rees and Robison, 1989), or excluding that unit (Langenburg, 2003), in the Wheeler Formation. However, in this report the 30 m interval is assigned to the Pierson Cove Formation, as it appears to be more lithologically similar to that unit and is a lateral facies equivalent of the lower cycles of the Marjum Formation, which overlie the Wheeler Shale at its type area in the central House Range.

Details of physical and sequence stratigraphy in the Swasey, Wheeler, and Marjum formations will be discussed in another paper (Brett et al., in prep.). The present paper focuses on the general facies and cyclicity of the Wheeler-lower Marjum/Pierson Cove interval in the Drum Mountains and Marjum Pass area.

3. Previous work

A number of studies have focused on the paleontology and paleoecology of the Wheeler and Marjum formations. Detailed stratigraphic studies were carried out in the Drum Mountains and House Range by Crittenden et al. (1961), Hintze and Robison (1975), Dommer (1980), and Hintze and Davis (2002). Rees (1986) mapped out the apparent geometry of the House Range embayment and discussed its origin and control on facies.

Robison (1976, 1982, 1984b) established a detailed zonation of agnostoid trilobites in the Middle Cambrian, which has recently been reviewed and updated by Babcock et al. (2005) who used the Drum

Table 1
Overall thickness and proportion of different lithologies (by thickness) in ten successive cycles of the upper part of Wheeler Formation, Sawtooth Ridge, Drum Mountains, Millard County, Utah.

Cycle	Thickness (cm)	Shale (cm)/(%)	Concretions (cm)/(%)	Nodular Ls (cm)/(%)	Planar Cs (cm)/(%)	Wavy Calc (cm)/(%)	Lam Calc (cm)/(%)	Oolitic (cm)/(%)
T-10	102.5	34/33.2	0/0.0	0/0.0	54/52.7	0/0.0	0/0.0	14/13.7
T-9	107	43/40.2	0/0.0	0/0.0	50/46.7	0/0.0	0/0.0	13/12.1
T-8	113	52/46.0	0/0.0	11/9.7	26/23.0	0/0.0	0/0.0	24/21.2
T-7	128	66/51.6	8/6.3	10/7.8	36/28.1	0/0.0	0/0.0	16/12.5
T-4 to T-6	182	102/56.0	0/0.0	0/0.0	0/0.0	0/0.0	26/14.3	54/29.7
T-3	271.5	177/65.2	14/5.2	0/0.0	0/0.0	0/0.0	40/14.7	40/14.7
T-2	615	298/48.4	29/4.7	28/4.6	41/6.7	30/4.9	137/22.3	40/6.5
T-1	201.5	75/37.2	2/1.0	30/14.9	25/12.4	22/10.9	54/26.8	14/6.9
T-0	739.5	80/10.8	0/0.0	145/19.5	304/41.0	128/17.3	84/11.4	0/0.0

Note general decrease in cycle thickness above T-2, increase in shale percentage to T-3 and high percentage of oolitic limestone in the T-4 to T-6 cluster.

Mountains as the stratotype for the Middle Cambrian Drumian Stage, the base of which lies at the *Ptychagnostus gibbus*/*P. atavus* boundary; this has been accepted internationally (L. Babcock, pers. com. 2007). Randolph (1973) and Sundberg (1994) studied the trilobites of the Whirlwind and Swasey formations.

Recent thesis studies detail the sedimentology, geochemistry, and sequence stratigraphy of the Swasey and Wheeler formation in the Drum Mountains and House Range (Schneider, 2000; Langenburg, 2003). Schneider (2000) made detailed measurements of strata and surveyed fossils and taphonomy in the Drum Mountains at "Stratotype Ridge" and "Sawtooth ridge" sections and parsed the section into large-scale cycles, which he attributed largely to pulses of subsidence in the House Range Embayment. He also examined a zone of strongly deformed strata at the base of the middle Wheeler and concluded, as had Grannis (1982), that it is not tectonic in origin, but represent a very large submarine slump related to subsidence pulses in the House Range Embayment; fold axis orientations were considered to be consistent with smaller scale slump features, i.e. overturned toward the southwest. Langenburg (2003) made a highly detailed study of petrography, total organic carbon, and carbon isotopes and used these aspects to interpret sequence stratigraphy in the Drum Mountains and Marjum Pass. She concluded that despite considerable thickness differences both sections had similar numbers of cycles in the Wheeler Formation (16 at Marjum Pass, 19 in the Drum Mountains). She also viewed the entire Wheeler Formation in both Marjum Pass and the Drum Mountains as a single depositional sequence with a maximum flooding surface near the *Ptychagnostus gibbus*/*P. atavus* boundary in the Lower Wheeler Shale. The thick package of carbonates in the middle Wheeler was interpreted as early highstand deposits; the shallowing-upward interval of platy, rhythmically bedded carbonate was attributed to highstand shedding of the carbonate platform. Moreover, Langenburg inferred that the upper member of the Wheeler Shale, which is dominated by dark, flaggy shale, records relatively shallow water, possibly lagoonal conditions, and suggested that it represents late highstand conditions, perhaps shallower than oolitic facies that underlie it.

Recently, Elrick and Snider (2002) made a highly detailed study of cycles and included mud mounds in the upper Marjum Formation of the Marjum Pass area. They concluded that the cycles were widely correlative and probably represent allocyclic, Milankovitch-driven sea-level oscillations. Shales were inferred to represent transgressive conditions when the carbonate factory retrograded, while packages of rhythmically bedded calcisiltites were interpreted as recording forced regressions that resulted in progradation of the carbonate factory toward the House Range Embayment. Mud mounds were considered to have formed by *in situ* microbial carbonate production during times of low sediment input, presumably related to flooding surfaces.

Paleoecological and sedimentological studies of the Swasey, Wheeler, and Marjum formations include those of Grannis (1982), and Rogers (1984). These studies were particularly useful in establishing a turbiditic origin for many of the thin limestones, as well as laminae within the shales. Both authors also documented SW-directed overturn directions in synsedimentary slump folds. Rogers focused on two lagerstätte levels: the Wheeler Shale at Swasey Springs and the Marjum Formation at "Sponge Gully" about a mile north of Marjum Pass. He concluded that the well-preserved fossils, including articulated trilobites and sponges, in both cases represent carcasses that were imported into deeper dysoxic settings from upslope settings by turbidity currents. A series of studies (Robison, 1984a; Conway Morris and Robison, 1986, 1988) have described soft-bodied organisms from the Wheeler Shale. Building on these studies, Robison (1991) summarized the paleoecology of four soft-bodied fossil lagerstätten of the Great Basin.

Finally, Gaines and Droser (2003, 2005) and Gaines et al. (2005) documented the microstratigraphy and ichnofabrics of the Wheeler Shale in the House Range and focused on the unusual modes of preservation. They concluded that extraordinary preservation was a result of rapid burial in anoxic muds, deflocculation of clay-rich sediment, and consequent reduction of permeability, and sealing by early carbonate cementation. Gaines et al. (2005) also presented a model of the biofacies spectrum of the Wheeler Formation in which they depicted the *Elrathia* trilobite taphofacies as representing in situ remains of an "exaerobic" (minimally dysoxic) environment and soft bodied *lagerstätten* as recording allochthonous remains of soft-bodied organisms imported into still deeper anoxic settings.

4. Materials and methods

We made detailed studies of stratigraphy, sediments, and fossils in the Drum Mountains and central House Range areas of the Great Basin in west-central Utah (Fig. 1). For the medial to proximal ramp facies of the Wheeler Formation in the Drum Mountains, 56 km northwest of Delta, Utah, we selected two localities: 1) exposures along the crest of "Stratotype Ridge" (lower 90 m thick member of Wheeler Formation; see Dommer, 1980; Schneider, 2000; Langenburg, 2003), and 2) gullies along the southeast flank of the larger, adjacent " Sawtooth Ridge" (80 to 90 m thick upper member of Wheeler Formation; see Dommer, 1980; Schneider, 2000; Langenburg, 2003; see also Halgedahl et al., 2009), Millard County, Utah (39°30.21'N, 112°59.37 W; Fig. 3; see Halgedahl et al., 2009 for detailed map).

For the distal facies of the House Range, we studied gullies along the and bare hill slopes on the south side of Marjum Pass, between first and second crossings of powerlines across the Marjum Pass Road, Millard County, Utah (39° 14' 29–40" N, 113° 22' 8–22" W). We also based our conclusions on field observations of the upper parts of the Wheeler Formation and the lower cycles of the Marjum Formation at Marjum Pass and Wheeler Amphitheater (Fig. 1).

In each section we logged the lithology at a decimeter scale and recorded details of sedimentology, taphonomy, and paleoecology (Tables 1–5). Previous detailed petrographic studies provide a

Table 2
Features of condensed, base of cycle limestones; upper member of Wheeler Formation, 10 to 20 m above contact with middle member; Sawtooth Ridge, Drum Mountains, Millard County, Utah.

Bed #	T-1	T-2A	T3	T-4	T-5	T-6A	T-6B	T-7	T-8	T-9	T-10
Thickness	48 cm	60 cm	25 cm	20 cm	20 cm	12 cm	8–10 cm	9–10 cm	11 cm	10–11 cm	16 cm
Lithology	packstn	packstn	grainstn	grainstn	grainstn	grainstn	grainstn	grainstn	grainstn	packstn	packstn
Amalgamated?	4 beds	5 beds	2 beds	2 beds	3 beds	2 beds	no	no	no	2 beds	2 beds
Base	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp
morphology	wavy	wavy	planar	wavy	prods	prods	planar	planar	planar	planar	planar
incised burrows	X (2–3 cm)	X (2–3 cm)	yes	no	X	yes	no	no	no	no	no
Top	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp	sharp
morphology	planar	planar	rippled	rippled	rippled	rippled	planar	planar	planar	planar	planar
corrosion pits	X	X	X								
runnels	X	X	X								
Fe-rich crust	X	X	X					X		x	
Sedimentary Structures											
graded bedding	X	minor	X	X							
lamination	X (wavy)	X	X	X	X	X	X	X	X	X	X
crossbedding	minor	X	X		X						
Carbonate grains					X						
ooids	c	c	X	X	X	X	X	X	X	X	X
oncolites	c (top)	c (top)	X	X							
rip-up clasts	X	X		X	X	X	X	X			
Skeletal grains											
trilobite	X	?		X							X
echinoderm	r	X	X	X	X		x	x	?		
brachiopod	r	X	X	X	X						

background for interpretating lithology (see Schneider, 2000, and Langenburg, 2003, for petrography, microfacies, total organic carbon, and carbon isotopic patterns, especially of limestones; and Gaines and Droser, 2003, 2005; Gaines et al., 2005 for very detailed studies of shale microfabrics). Our approach emphasizes detailed characterization of intermediate- to large-scale patterns of litho- and taphofacies at three scales of cyclicity.

Sequence stratigraphy was interpreted based upon several features, including: a) tracing of sharp erosional surfaces and apparent flooding surfaces, b) patterns of upward change, fining- and bedding-thinning upward patterns, c) changes in bioturbation intensity, and d) evidence of inferred water depth change. Oncolitic–oolitic limestones were interpreted as the shallowest water facies, while black, fissile shales record deepest and most dysoxic conditions.

Paleontological data, including taxa counts and taphonomic observations, were collected systematically from bedding plane surfaces several representative cycles in the Wheeler Shale and lower part of the Marjum Formation of the Drum Mountains and Marjum Pass. In thick and relatively monotonous intervals, low slope angles favored rapid scanning of large surface areas. Each interval was examined for about 15 minutes; specimens observed in a 2 m-wide tract at 1-m thickness intervals were binned; and fossil and taphonomic data gathered in that time frame from throughout the meter were tallied (Tables 3–5).

More detailed study of the informally-designated upper member of the Wheeler Formation in the Drum Mountains enabled high resolution assessment of approximately 400 successive beds through about 28 m of section. These are arrayed into a series of 1- to 7-m-scale cycles; they were studied by trenching and clearing at least 0.5 m^2, and stripping off layers at 0.5 to 1.0 cm intervals through thicker shales. Limestone beds were systematically described in the field on the basis of a number of stratinomic, sedimentological, and paleontological features (Table 2; see Figs. 6–8).

Taphonomic features recorded during this study included convex up-down orientations, frequency of disarticulated sclerites and articulated specimens of trilobites (Tables 3, 4). Degree of fragmentation and abrasion of skeletal fragments were also recorded as were trace fossils and degree of bioturbation, if any (ichnofabric indices of Droser and Bottjer, 1988). Paleoecological features noted included faunal species diversity, presence and relative abundance of algae, and evidence of trilobite molt ensembles (Tables 3–7).

In addition, gamma ray profiles were produced for two representative cycles using a hand-held scintillometer, as a proxy for clay-carbonate content, with the help of Richard Jarrard (University of Utah; see Halgedahl et al., 2009 for further discussion). Finally, representative samples of lithologies were obtained for polished sections.

5. Sedimentology and taphonomy of Wheeler and Marjum facies

Stratal sequences in the Wheeler and Marjum Formations include predictably arranged and distinctive, litho-, bio- and taphofacies. The facies are discussed and interpreted in the following sections.

Table 3
Fossil content of six proximal cycles in the upper part of the Wheeler Formation; Sawtooth Ridge, Drum Mountains, Millard County, Utah.

	Cycle					
	T-1	T-2	T-3	T-4/6	T-7	T-8
Total # Beds	34	87	74	24	55	58
Total Shale	9	34	63	12	40	40
Total Limestone	25	53	14	12	15	18
Biota						
Barren	10	22	24	10	8	22
Burrows		3			2	
Beaded algae	1	14		1	1	4
Sponge spicules	5	14				
Echinoderm debris	3	1	1	3	1	1
Inarticulate brachiopods	1	2	5	1	12	8
Articulate brachiopods	1		2			1
Stenothecoides	5	0	0	0	0	
Agnostoids	5	30	15	4	3	6
Agnostoid hash	5	2	5	4	2	3
Agnostoid (articulated)	5	2	12		2	3
Agnostoid (disarticulated)	5	28	7	3	3	6
Polymeroids	15	13	33	6	11	40
Polymeroid hash	13	12	7	2	1	22
Elrathia (articulated)		1	15	4	2	22
Elrathia (molts)	1		3		1	8
Elrathia (disarticulated)	12	13	27	2	11	20
Jenkinsonia/*Brachyaspidion*			3			3
Olenoides	3					2

Table 4
Articulation and orientation of agnostoid trilobites; *Ptychagnostus gibbus* Zone Wheeler Shale; Marjum Pass, Millard County, Utah; artic. = articulated; disart. = disarticulated; cvx = convex.

T (m)	Lithology	*N*	Art	%	Cvx up	%	Associated fossils
1	covered						
1		12	0	0	12	100	triax. spicules
0.5		15	0	0	15	100	triax. spicules (cc)
0.1	hash bed	73	3	4	73	100	triax. spicules (cc)
C-1	interval						
	thin ls.	65	0	0	65	100	
	purple shale	92	0	0	92	100	triax. spicules (c)
	calcisilt	80	0	0	75	93	triax. spicules (c)
	concret. hash	91	0	0	91	100	triax. spicules (cc)
	purple silty ls.	150	0	0	147	98	triax. (cc); monax. (c)
	purple shale	10	0	0	10	100	triax. (cc); monax. (cc)
	dk. purp. sky ls.	5	0	0	5	100	triax. (c); monax. (c)
	dk. gray, platy shale	0	–	–	–	–	barren except algal fragments
	dk. gray, platy shale	0	–	–	–	–	barren except algal fragments
T-1	marker interval						
	T-1; purp. sh.	25	0	0	24	96	triax. (cc); monax. (cc)
	T-1 calcisiltite-shale	25	0	0	25	100	spicules (x)
0.6	ocher calcisilt.	0	–	–	–	–	spicules (r)
0.5	black rusty sh.	0	–	–	–	–	algal fragments
	olive sh.	0	–	–	–	–	barren
	orange calcisilt	0	–	–	–	–	barren
	purple silty ls. bed						
	purp. silty sh.	8	1	12	8	100	triax. (cc); monax.(c); algal fragments
	purple silty ls.	4	0	0	4	100	triax. (cc); monax.(c); algal fragments
	dk. qray, platy sh.	1	1	100	1	100	algal
	dk. gray, platy sh.	4	2	50	4	100	algal blobs (cc)
1	med. gray, platy sh.	0	–	–	–	–	algal fragments (c)
1	med. qray, platy sh.	17	2	9	17	100	algal frags. (cc); spicules (r)
	med. gray, platy sh.	0	–	–	–	–	
	med. gray, platy sh.	4	0	0	4	100	algal fragments
T-2a	marker interval						
	purp. silty sh.	13	1	8	13	100	spicules present
	dk. gray concr. ls.	30	0	0	30	100	abt. polymerid frags; *Elrathia, Asaphiscus;* spicule frag (cc)
0.1	red silty shale	4	1	25	4	100	monax. (cc), algal blobs
	dk. maroon	1					triax. (c)
T-2b	marker bed						
	dk. gray calcisilt	120	0	0	120	100	abt. polymerid hash
	trilobite hash pkstn						
	oncolitic pkstn	0	–	–	–	–	trilo frags
	maroon mudst.						
1.5	lavender silty sh.						
	black fissile sh.	0	–	–	–	–	barren except algal frgs.
	lavender, platy ls.	1	–	–	1	100	triax. (c); monax (c)

5.1. Oncolitic–oolitic–skeletal pack to grainstones

5.1.1. Description

Proximal sections in the Drum Mountains typically commence with thin (0.3 to 1 m), dark gray (N4), orange-buff weathering, compact ledge-forming intervals of oncolitic to oolitic, intraclastic, and/or fossil fragmental pack- and grainstones (Figs. 6–8; Tables 1, 2). In the upper Wheeler the proportion of oolitic limestones increases with successive cycles upward to T-6 and then decreases (Table 1). Table 2 lists the characteristics of major compact limestone beds in the upper Wheeler Formation. Such beds comprise up to 30% of the thickness of proximal cycles. These beds form laterally continuous ledges up to 60 cm thick that are directly traceable for up to 3 km in the Drum Mountains outcrops. In many cases, these beds appear to be amalgamated from two or more individual graded oolitic limestones (Table 2). Disarticulated, fragmented and abraded fossil material includes trilobites, articulate brachiopods, and echinoderms in nearly all of the 13 examples studied in the Drum Mountains. Five of the beds display oncolites of 1–1.5 cm diameter typically in their upper portions. Sharply defined lower surfaces of the beds are typically planar to gently undulatory, and may show sharply incised burrows (*Planolites*; Fig. 6d) semi-angular clasts occur in the limestones immediately above this surface in 9 of 13 cases (Fig. 6d; Table 2). These clasts are erosionally derived from limestones that underlie the compact pack- to grainstone beds.

Upper surfaces of certain of the thin, compact limestone beds are also sharp and include elongate to irregular and mineralized pits (Fig. 7). Typically, these upper contacts are strongly oxidized as a result of weathering of a pyritic/dolomitic crust (Fig. 9c). Irregularly rounded pits with sharp sides (Fig. 7a) occur on at least five surfaces and in the case of beds T-1 and T-2, a series of sub-parallel runnels, up to 10 cm wide and over 50 cm long, occurs on a surface (Fig. 7b; Table 2). These are about 5–10 cm wide and run up to several meters in length and bifurcate in a single direction. Measurement of several dozen runnels on beds T-1 and T-2 in the upper Wheeler of the Drum Mountains indicates a consistent direction of elongation to the west-southwest ($N=46$; azimuth direction: $245°+/-1.7°$; see Halgedahl et al., 2009). Runnels may bifurcate, typically in a consistent direction. Some of these runnels resemble enlarged burrow galleries of *Thallasinoides*-like burrows (Fig. 7b). They are typically lined with a ferruginous crust (weathered pyrite?) and infilled with fine carbonate silt. Several examples of runnels display discrete oncolites within the silty matrix (Fig. 8b). In rare instances, the sediment fill of runnels or irregular pits has undergone concretionary cementation (Fig. 7d).

In the Marjum Formation, and perhaps the most proximal sections of the Wheeler Formation in the southeast Drum Mountains stromatolitic to thrombolitic mounds extend upward from the upper surfaces of oolitic limestones (Fig. 8a; Rees, 1986; Elrick and Snider, 2002; Westfield et al., 2005); these are discrete heads, up to a meter across, surrounded by a matrix that includes abundant ooids, oncolites, and intraclasts (Fig. 8b).

5.1.2. Interpretation

The thin limestones containing ooids, oncoids, skeletal fragments and, in some cases, clasts eroded from underlying beds occurring at the bases of these successions are interpreted as strongly reworked lag deposits. The fragmentary and comminuted condition of the fossils and the development of concretionary carbonate indicate sedimentary condensation and early diagenesis. Sharply incised burrows at the bases of these beds indicate formation in firm, over-compacted muds. In turn, this evidence indicates a period of erosive removal of surficial, soft sediments.

These thin, tabular and traceable beds are interpreted as basal transgressive lags (hence the designation as T-1, T-2, etc.) that overlie minor lowstand erosion surfaces. Oolitic sediment derived from shoal areas was probably exported to the deeper shelf by storm currents and then repeatedly reworked, together with locally derived skeletal fragments during times of lowered, but rising sea-level.

The sharp, typically corroded and mineralized tops of thin limestone beds might be interpreted as karsted surfaces. If so, then the lag beds could be treated as lowstand deposits and their sharp tops as transgressive surfaces. However, it is unlikely that clean reworked carbonates would have accumulated during lowstands. They are more readily interpreted as transgressive lags. The upper sharp surfaces are inferred to be flooding and starvation surfaces associated with rapidly rising base level. We interpret the sharply pitted tops of some limestones as indicating marine scouring and/or dissolution during exposure of the surface on the seafloor in a prolonged period of sediment starvation. Such a discontinuity would then be associated with maximum sediment starvation during marine flooding. While siliciclastic sediments may have been temporarily sequestered in coastal estuarine areas as a result of increased accommodation the seafloor also deepened below the zone of abundant carbonate production; in this sense the upper corrosion surfaces represent

Table 5
Thickness, lithology, fabric, and fossil distribution and abundance counts in medial to proximal cycles; lower 12 m of the upper Wheeler Formation; "Sawtooth Ridge", Drum Mountains, Millard County, Utah.

Unit thickness	Lithology	FABRIC	Sponge spicules	INART BRACH	Stenothecid	AGNOST ART	AGNOST DISART	POLY C/P RATIO	*Elrathia*	*Olenoldes*
T-1, 20 cm	dk, gray, oolitic, oncolitic packstone	graded	c	r	c			hash		
cycle 5										
100 cm	5–10 cm; dk gray calcisiltite, oolitic	wavy; I=2	cc	57	?		3	60/40	10	4/0
10 cm	dk. gray platy calcisilt, dk gray shale	wavy lam	cc (47)	4	70		1	6/4		0/2
4–5 cm	dk gray, calcisilt, wackestone	lam		1	125			hash		
cycle 4										
150 cm	3–5 dk gray calcisilt, lam-dolo burrowed	I=2	r	10	25		1	7/0		
70 cm	pinkish gray shale, thin platy Is.	lam		9		2	7	hash		
20 cm	med dark gray, platy Is	lam	r				15	0/1	1	
30 cm	pale pinkish gray platy Is	lam				3	25	hash	1	
50 cm	pinkish with med gray, lam. calcisiltite	lam	cc (55)	2			91	0/1	2	1/1
50 cm	med. gray to lavender, thin platy Is		r	1		2	140	0/2		
cycle 3										
20 cm	concretionary dk gray calcisiltite	I=2					10			
50 cm	black.,pyritic calcisilt	wavy lam				1	12			
70 cm	reddish, calcareous shale	lam	cc			5	33	0/1		
5 cm	dk gray calcisiltite; trilobite hash						hash	hash		
cycle 2										
30 cm	3 10-cm dk gray calcisiltite	wavy lam						0/1		
50 cm	It. gray, platy limestone	lam	c	7		1	7			
50 cm	dk gray, thin bedded calcisilte	lam					28	0/1		
45 cm	pinkish, platy shale; red agnostoids	lam				1	20			
15 cm	pinkish spicule rich mudstone	lam	cc	10+						
50 cm	10 cm, black, lam. Is; with pink shale	lam							1	
2–3 cm	dk gray calcisiltite; trilobite hash	I=1–2					hash	hash		
cycle 1										
80 cm	3–5 cm dk gray calcisilt, dolo burrows	I=2								
50	5–10 cm, dk, gray calcisilt; pyritic	lam	c		1		5			
50 cm	med. gray cs, pinkish papery shale	lam	c				25			
50 cm	purple red shale; It. gray.platy Is.						20	1		
150 cm (Glyphaspis)	oolitic, trilobite frag, burrowed pack-grainstone; massive	wavy; I=3	?	c			hash	hash		

Explanation of categories: Lithology: measurements in cm. indicate typical bed thicknesses; abbreviations: cs = calcisiltite; dk =dark; dolo = dolomitic; lam = laminated; ls = fine-grained limestone; lt = light. FABRIC: I = chnofabric index; lam = laminated, non-burrowed. Fossils: ARTIC BRACH: articulate (rhynchonelliform) brachiopod; INARTIC BRACH = acrotretetid inarticulate brachiopod; AGNOST = agnostoid trilobite, mainly Ptychagnostus); POLYM = polymerid trilobite, undifferentiated; C/P RATIO = cephalon/pygidium ratio; hash = uncounted fragmentary skeletal material; relative abundance: rare; c = common; cc = abundant; numbers in parentheses indicate counts of intact specimens.

small scale examples of "drowning unconformities". The consistently aligned runnels that occur on upper surfaces of some beds thus represent erosional to corrosional gutters or furrows associated with persistent storm generated currents flowing in a general basinward direction. We thus infer that the NE/SW orientation of these furrows records a down-ramp flow to the southwest, an interpretation consistent with paleogeographic reconstruction of the House Range embayment.

In the shallow water facies of the Wheeler–Marjum succession mounded cyanobacterial buildups, thrombolites and stromatolites, developed during periods of rising sea level at the tops of early TSTS in shallow water. These mounds predictably overlie the thin limestone beds mentioned above. This agrees with previous work suggesting that microbial carbonate mounds in the Marjum Formation formed preferentially during maximum flooding (Elrick and Snider, 2002), because of reduced sedimentation.

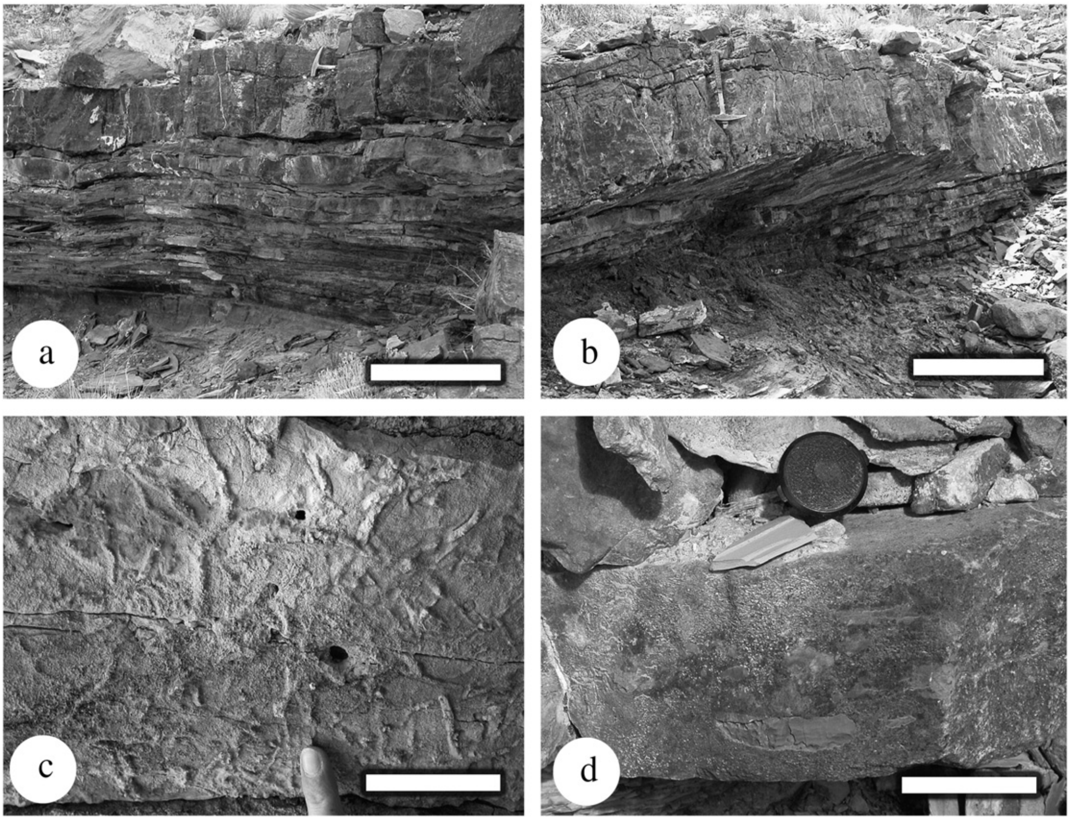


Fig. 6. Compact oolitic–oncolitic, ledge-forming limestones forming the bases of 4th order cycles in the Wheeler Shale, east flank of Sawooth Ridge, Drum Mountains. (a) T-1 marker bed sharply overlying a bundle of calcisiltites and fine calcarenites at top of underlying cycle; scale bar 50 cm. (b) T-2 limestone ledge sharply overhanging shales and calcisiltites of third upper Wheeler cycle; scale bar 50 cm. (c) detail of the base of limestone ledge showing distinctly incised *Planolites* trace fossils indicative of firmground condition of the underlying muds; scale bar 15 cm. (d) close-up of basal limestone ledge of T-3 showing intraclasts in oolitic packstone; scale bar 10 cm.

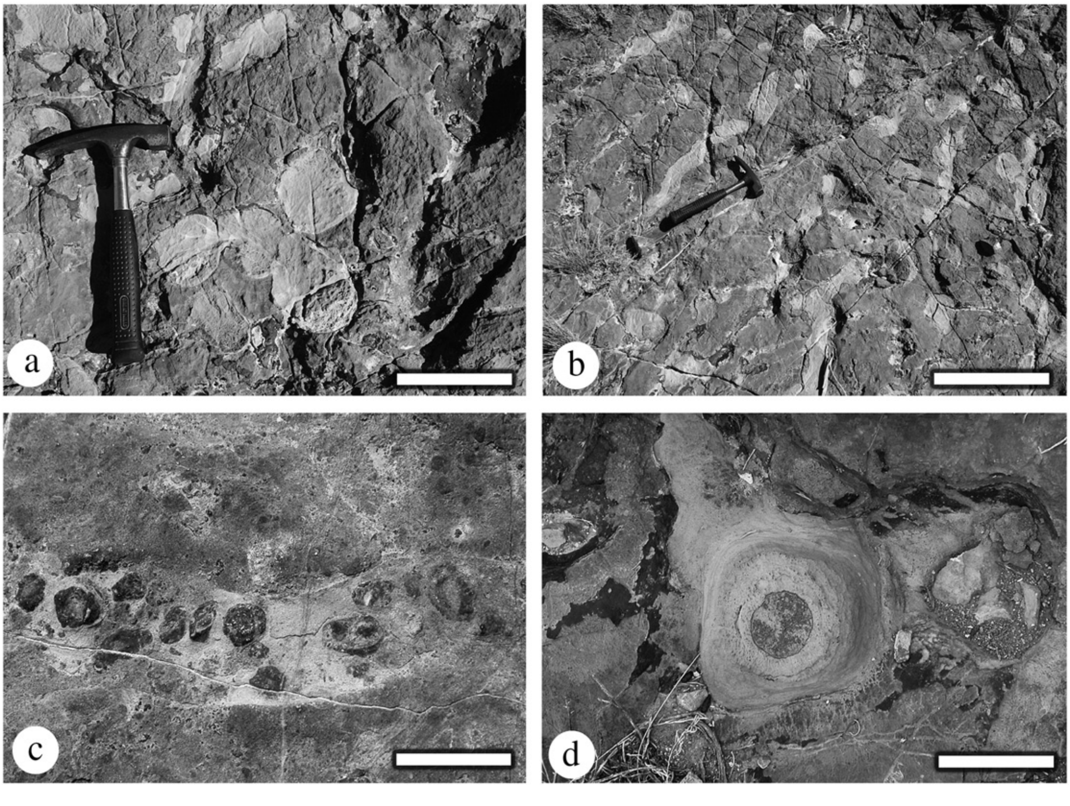


Fig. 7. Sharp upper surfaces of T-1and T-2 limestone beds showing irregular corrosion pitting. (a) series of pits lined with weathered pyrite and infilled with pale gray silty matrix, scale-bar is 15 cm. (b) Linear runnels also lined with pyrite and infilled with limestone, scale-bar is 35 cm. (c) runnel on top of bed T-1 showing filling of light colored silt with scattered oncolites; scale bar is 15 cm. (d) concretionary cementation of fill in circular pit on top of limestone T-2; scale bar is 15 cm.

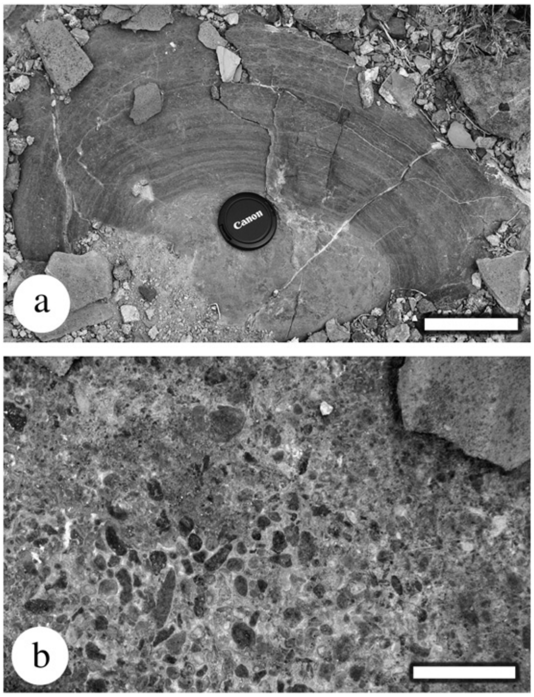


Fig. 8. Features of tops of compact limestones. Lower Pierson Cove Limestone; southern Drum Mountains. (a) Cross section of stromatolite head, scale-bar: 10 cm. (b) oncolites, scale-bar: 4 cm.

Thin hash beds of disarticulated and/or fragmented trilobite remains near the tops of some limestones in third order TSTs record highly time-averaged remains that accumulated during periods of low net sedimentation at maximum starvation surfaces.

5.2. Calcareous shale (marl) and thin oolitic to skeletal limestones

5.2.1. Description

Compact limestones near the base of the lower Wheeler Formation and the lower 30 m of the upper wheeler in the Drum Mountains are abruptly overlain by calcareous shale and dark gray thin-bedded wacke- to packstones with abundant, mainly disarticulated polymerid and agnostoid trilobite remains and sponge spicules, concentrated in thin beds and stringers (see Fig. 9, Table 3). Rarely, (four noted instances) small gutter casts, filled with ooids, silt and skeletal debris occur in immediately surrounding shales. These appear to have approximately the same SW alignment as the runnels on subjacent limestone beds. Bioturbated limestone (wacke- packstone) beds with abundant disarticulated and/or fragmented trilobite remains (up to 50 tagma per m^2), occur near the tops of some limestones. The *Glyphaspis*-bearing bioclastic beds overlying the Swasey Limestone at nearly all localities (Fig. 5), exemplify this facies. Thin oolitic wacke- to grainstones and scattered ooids may also be present within shales.

At certain levels, notably in cycles T-3 and T-4 of the upper Wheeler in the Drum Mountains, lenses of skeletal debris and gutter fills appear to be completely encased with masses of the fibrous, cone-in-cone calcite forming thin discoidal nodules up to 40 cm across; these can form up to 6% of the thickness of cycles (Table 1). In addition, some small claystone concretions are locally present (Fig. 9b).

5.2.2. Interpretation

Concentrated skeletal remains, represented by disarticulated and fragmental trilobite hash beds, are associated with the late TST. They may be mixed with thin lenses and stringers of ooids, apparently reworked from exposed up-ramp shoal areas during strong storms. These oolitic limestones are mixed with shales with diminutive trilobites indicating a deeper ramp position. Hence, we consider it most likely that the ooids were transported to this deeper setting rather than the other way around (trilobites transported upramp). These resemble shelf oolite sheets discussed by Markello and Read (1981) for the Middle Cambrian Nolichucky Formation of the Appalachian Basin. These deposits represent palimpsest sediments that were strongly reworked during intervals of relative sediment starvation. Ooids were probably transported from older, exposed shoals to offshore shelf environments during large hurricanes that reworked and redistributed ooid grains. In the absence of much carbonate mud input these grains may form extensive subtidal sheets.

The abundance of early diagenetic cements (cone-in-cone calcite, concretions) in this facies probably records calcite supersaturation in the zone of sulfate reduction during times of very low sedimentation. The mechanisms for cone-in-cone calcite formation, as opposed to concretionary cements, remain somewhat enigmatic (see review by Seilacher, 2001). They are typically associated with bituminous shales. The fibrous calcite is displacive and evidently formed prior to lithification. It is clear that in many cases these fibrous cements nucleated on buried carbonate skeletons, especially those of trilobites, and always grew from the ventral surfaces regardless of the trilobite's orientation; Seilacher (2001) postulates that organic cuticle on the exterior side of the exoskeleton prevented calcite growth.

5.3. Spicular mudstones

5.3.1. Description

Distal successions are characterized by thin (decimeter to rarely half-meter thick) intervals of pinkish gray to lavender (5RP 6/2), siliceous mudstones, and dark purplish gray to black shale, rich in sponge spicules (Figs. 10, 11). Minor stringers of pyrite crystals may be present (Fig. 11b).

Well-preserved spicules occur isolated on bedding planes, but fragmentary material may dominate the rest of the sediment. Other fossils are rare in these facies but include disarticulated and fragmentary agnostoid trilobites, showing evidence of decalcification, and, on certain bedding planes, whitish blobs that may represent algae (see Fig. 14b).

5.3.2. Interpretation

The pinkish spicule rich mudstones record condensed deposits in offshore areas; the high degree of concentration of sponge spicules in some beds coupled with the generally disarticulated and fragmentary nature of the fossils indicates gradual accumulation, possibly with a few episodes of resuspension and redeposition of sediments. During the times of maximum flooding in relatively deep and sediment starved conditions, the siliceous spicules of sponges apparently built up on the seafloor. It is somewhat surprising that these siliceous fossils did not dissolve. However, the pinkish coloration of these beds suggests low organic matter and oxidizing conditions at the sediment–water interface, which may have promoted aerobic decay and thus lower pH conditions favorable to silica preservation. The absence of chert in these beds is also notable given the evident supply of silica and this may also relate to reduced solubility of silica on these seafloors.

5.4. Platy calcareous gray shale

5.4.1. Description

Major portions of the Wheeler Formation are comprised of hard, medium to dark gray (N3-N4), platy, calcareous shales (Fig. 12) that weather pale yellowish gray (5Y 7/2). These beds, typical of the middle and upper parts of the Wheeler Formation have been quarried for flagstones in the vicinity of Wheeler Amphitheater. These flaggy gray shales generally possess >20% fine carbonate, 60 to 80 clay and fine quartz silt (average for shales at Swasey Springs quarry: 70% clay, 25% $CaCO_3$, and 10% quartz silt; Rogers, 1984). Pyrite occurs as minor

Table 6

Thickness, lithology, fabric, and fossil distribution and abundance counts for medial ramp cycles; cycles 6–8 of the lower member of Wheeler Formation, height measurements in relationship to upper contact of Swasey Limestone, 50 to 90 m above the contact; Stratotype Ridge, Drum Mountains, Millard County, Utah.

HT (m)	Lithology	FABRIC	Sponge spicule	INART BRACH	AGNOST ARTIC	AGNOST DISART	POLYM ARTIC	POLYM C/P RATIO
90	black, sooty shale	lam			0	125		
89	olive gray shale, platy ls.	lam		21	0	56	1	1/0
88	1–2 cm, med gray, buff w. platy ls/shale	lam		15	1	248		1/0
87	1–2 cm, med gray, orange w. platy ls	lam		1	0	257		
86	1–2 cm buff platy ls. sole marks	lam	r		0	221		f
85	1–2 cm buff platy ls. sole marks	lam	c		10	345		
84	1–2 cm orange platy ls. sole marks	lam			15	114		f
83	1–2 cm buff platy ls. sole marks	lam			12	178		
82	1–2 cm buff platy ls. sole marks	lam			1	232		
81	1–2 cm buff platy ls. sole marks; purple sh.	lam			7	341		
80	med gray, pale orange calc shale	lam			10	390		
79	med gray, pale buff w/ calc shale	lam			3	166		
78	med gray, pale buff calc shale	lam			6	765		
77	med gray, pale buff calc shale	lam			6	370		
76	med gray, pale buff calc shale	lam	r		2	223		
75	med gray, pale buff calc shale	lam			7	30		x
74	med gray, pale buff; sltly calc. shale	lam	c		2	200		
73	med gray, pale buff shale, small nodules	lam	r		2	100		
72.1	agnostid packstone; 40 × 50 cm	lam	r	1	5	314		
72	tabular calcisiltite with pyritic crust	lam			0	hash		
71	olive gray satiny shale; nodules	lam			1	?		
70	olive gray satiny shale; nodules	lam			0			
69	black to olive, fissile shale, gutters?	lam			0			
68.5	med dk gray lam shale	lam	r	3	1	2		
68	dk gray platy calcisiltite	lam	c (41)	4		5		3/1
67.5	med gray, thin, platy ls.; burrows	I = 2	c (21)	2		1		1/1
67	pinkish gray, silty mudstone	lam	cc (45)	3	1	36	1	4/1
66.5	dk gray pelletal pkstn,., ooids, skeletal frag	I = 2; dolo	cc (45)	8	1	14	2	2/0
65.5	weathered pinkish shale	?	c					
64.75	thin trilobite packstone; ooids	I = 2 dolo	cc	8				2/0
64.5	dk gray; pellets, ooids, spicule pkstn, ledge	I = 2–3	cc (15++)				3	4/4
64	weathered pinkish red shale	?						
62.5	dk. gray, spicule rich packstone; ledge	lam	cc (25++)	5		15		6/2
62	purple red shale	lam	cc (30++)	5	5	28	1	6/5
60–60.5	2 m covered							
59.5	purplish gray, calc shale	lam	cc (50)			41	4	10/11
59	purplish gray, calc shale, pyritic, platy ls.	lam	c (25)		2	5	2	9/0
58	dk purplish to black, calcisiltite	lam	cc (60)	6	2	39	5	7/5
57	dk purplish to black, calcisiltite	lam	cc (35)	4	13	35		8/0
56	purplish shales; minor burrows	I = 1	r		1	35		1/2
55	med dk gray calcisilt, purplish shale	lam	r (5)	2	22	47	1	0/1
54	med dk gray calcisilt, purplish shale	lam	r		3	6	3	
53	med dk gray calcisilt, purplish shale	lam	r			2	1	
52	med dk gray calcisilt, purplish shale	I = 1	r			2	1	
51	dk gray calcisiltite, shale, tiny burrows	I = 2	c (25)		2	15	1	3/9
50	dk gray calcisiltite, dk purplish shale	lam						

For explanation of categories and abbreviations see caption for Table 5.

burrow linings, and as cubic crystals in some bedding planes. Gaines et al. (2005) also note that certain of these shales may contain in excess of 13% dolomite, which probably accounts for their yellowish weathering. A few bedding planes show pyritized trilobites, typically weathered to limonite. Some of the shales show graded laminae with silt/mud couplets 0.2 to 2 mm (Rogers, 1984). Gaines and Droser (2005) indicate that their samples from distal facies contain very little or no silt, pellets, or aggregate grains, but report sub-millimetric alternations of finely burrowed and non-burrowed clay from the Wheeler Shale (Fig. 12).

Many of the shale beds are sparsely fossiliferous (approximately 20 to 60% barren in surveyed beds; Table 1). However, certain bedding planes yield abundant acrotretid brachiopods, articulated agnostoid trilobites, and/or abundant *Elrathia* (Table 3). This polymerid trilobite may occur in very dense local populations in excess of 1000 specimens per square meter (Fig. 13a; Gaines and Droser, 2003, 2005). Notably, these assemblages may include articulated molt ensembles, i.e., articulated exuviae, typically with free cheeks lying in close proximity (Fig. 14a).

In distal sections, platy shales rarely include *Elrathia*, but some bedding planes contain large numbers of agnostoid trilobites (*Peronopsis interstricta*, *Ptychagnostus* spp.; Fig. 13b) and/or diminutive polymerids (e.g., *Jenkinsonia, Brachiaspidion*). A few bedding planes in cycle T-3 of the upper Wheeler in the Drum Mountains exhibit 50–60 of these tiny trilobites per m^2, mostly in a convex upward orientation. Agnostoids are also dominantly convex upward (Table 4); generally they are randomly oriented with respect to azimuths, but rare surfaces show strong alignment of agnostoids.

A few beds in this facies show carbonized benthic branching algae (*Yuknessia, Marpolia*; Fig. 15b) associated with the small trilobites. Possible holdfast structures are present in some, which thus appear to be preserved in situ.

Both articulated and disarticulated trilobites in dark calcareous shale facies may be coated, generally on their ventral sides, with vertically aligned fibrous calcites that may show cone-in-cone patterns. These form the well-known “padded” agnostoid and *Elrathia* specimens (Bright, 1959; Seilacher, 2001; Gaines and Droser, 2005) that readily weather free from the shale matrix. Fossil material

Table 7
Thickness, lithology, fabric, and fossil distribution and abundance counts for medial ramp cycles; thick shale, ~35 m above base of lower Marjum Formation, probably equivalent to "Trilobite Quarry Shale"; Marjum Pass, House Range, Millard County, Utah.

Unit thickness	Lithology	ALGAE BLOBS	ALGAE FILAM.	Sponge spicule	AGNOST HASH	AGNOST DISART.	AGNOST ARTIC.	POLYM HASH
4.5–6 m	black papery shale	c (10)	c					
4.0 m	dk gray cailcisilt/shale	c (10)	c			2	6	
3.5 m	3–5 cm calcisiltite	c				1	1	
3.0 m	graded calcisiltite	c				2	2	
2.7 m	graded calcisilt, groove casts	c (10)	x				4	
2.5 m	dk gray calcisilt/shale	c (10)	x			1	2	
2.0 m	dk gray platy calcisilt/shale	cc (20)	x			9	6	
1.5 m	rusty, dk gray shale, papery	cc (25)	c	cc	x	2		
1.0 m	lt. gray platy calcisiltite			c (40)	x	66		
0.5 m	lt. gray platy calcisiltite			c (73)		38		
0.1 m	lavender gray, platy ls.	c		c (110)	x	229		x
2.0 m	compact, dk gray, biturb wkstn							

Abbreviations, see caption for Table 5.

typically shows padding by a thin layer of cone-in-cone calcite, which, as noted above, tends to form isopachous rinds of fibrous calcite adhering to the interiors of exoskeletons (Seilacher, 2001; Gaines and Droser, 2003). However, thick layers of cone-in-cone calcite "beef" are not common, as in the gray marly facies, noted above.

5.4.2. Interpretation

Calcareous gray shale facies may grade upward into black, fissile clay shales or into platy rhythmically bedded shales and calcisilitites. Hence, they occupy an intermediate position. Assuming that the carbonized branching fossils, such as *Marpolia* and *Yuknessia* represent *in situ* algae, there is evidence that these facies accumulated in the deeper euphotic zone environments, hence, water depths would not have exceeded a few tens of meters.

In gray shale facies, a combination of low energy and rapid deposition on moderately oxic seafloors, and a general absence of burrowing, favored preservation of articulated material, and, less commonly, soft or weakly sclerotized organisms. Soft-bodied fossils, however, typically occur on otherwise barren bedding planes interbedded with gray, fossiliferous beds. In slightly oxic environments soft parts may have been rapidly degraded by aerobic decay, especially in the presence of benthic organisms such as *Elrathia*. Importantly, the presence of trilobite molt ensembles proves that skeletal material was buried rapidly with minimal disturbance, as even slight currents would tend to disassociate the molt parts. This is a strong indication that these fossils are autochthonous and it strongly argues against interpretations that invoke transport of carcasses into these or deeper facies.

The characteristic *Elrathia* biofacies have been interpreted to represent minimally dysoxic settings with free sulfide in bottom waters, environments referred to as "exaerobic " by Gaines and Droser (2003). They clearly meant this as a distinct zone, transitional between dysoxic and anoxic bottom water conditions. Moreover, with detailed microfabric study they were able to demonstrate alternation of slightly burrowed layers with purely laminated sediment on a millimeter scale. This suggests possible fluctuation of an oxycline as in poikiloaerobic settings of Oschmann (1991).

Bedding planes covered with the diminutive trilobite (agnostoids, *Jenkinsonia*, *Brachaspidion*) preserved in interbedded shales have been interpreted as pelagic assemblages (Gaines and Droser, 2005), but the restricted occurrence of the agnostoids and small polymerids, as well as the absence of any of these trilobites in many black, fissile shales (see below) casts doubt on this inference. Censused outcrops show agnostoid remains in either random or preferred convex upward orientations, contrary to earlier assertions that these trilobites were mainly concave upward due to settling out of the water column (Table 4; see also Table 8; cf. Elrick and Snider, 2002). Small polymerids, likewise are well articulated, random to preferentially convex up and may include molt ensembles (T. Kramer, unpublished data) indicating burial *in situ* rather than from settlement out of the water column. We interpret these biofacies as representing even lower benthic oxygen levels than those dominated by *Elrathia*.

5.5. Black shales

5.5.1. Description

Dark gray to black (N1, N2), fissile, papery shales form a distinctive facies generally devoid of fossils except for carbonaceous stains of small circular blob-like to beaded fossil algae (Fig. 14b). These shales are weakly to moderately calcareous (>5% $CaCO_3$), show the highest gamma ray values (Halgedahl et al., 2009) and contain minor disseminated pyrite. Despite their nearly barren character, it is these shales that may contain carbonized fossils. These organic rich shales yield abundant carbonized algae in nearly every cycle (Tables 4, 5, 8).

Dark shales in the Wheeler and Marjum Formations contain soft-bodied and weakly sclerotized animals of Burgess Shale affinity (Fig. 15). These beds have yielded over 45 species, including *Anomalocaris* and a

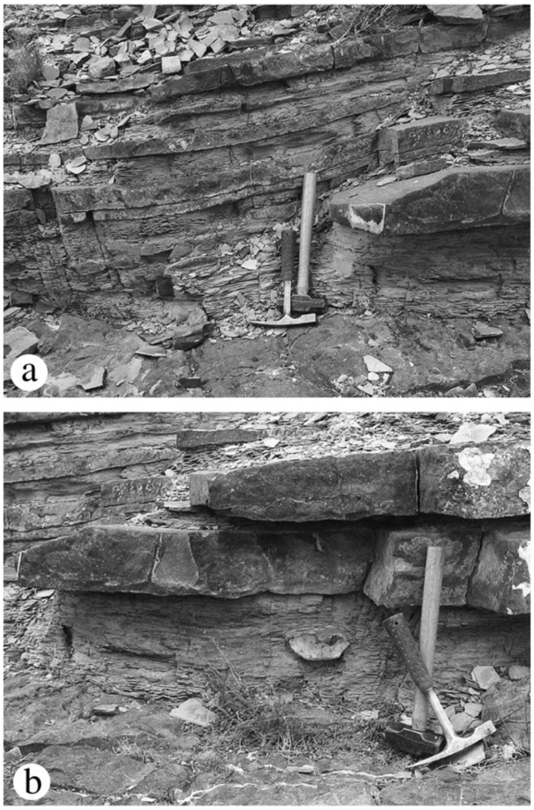


Fig. 9. Calcareous shale and thin limestone facies. a) lenticular and concretionary oolitic/skeletal grainstones alternating with calcareous shale. b) enlargement of view showing lenticular nature of oolitic bed and carbonate concretion; hammers for scale.

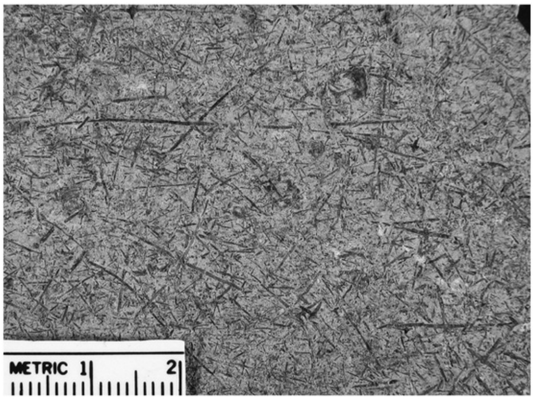


Fig. 10. Thin (<1 cm) condensed bed of sponge spicules from top of upper Wheeler T-0 limestone. East flank of Sawtooth Ridge, Drum Mountains.

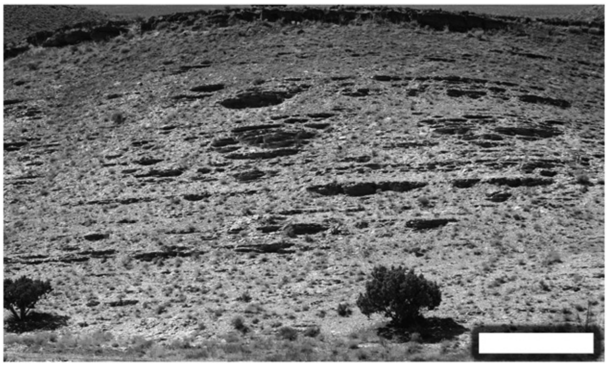


Fig. 12. Outcrop of calcareous gray shale facies Wheeler Shale. Drum Mountains, Millard County, Utah. Note fine bedding and rhythmic variation in resistance to bedding, scale-bar is 5 m long.

new soft-bodied metazoan (Robison, 1991; Briggs et al., 2005). These conservation *lagerstätten* are preferentially associated with dark, fissile shales with high-gamma ray counts (Fig. 15; Halgedahl et al., 2009).

5.5.2. Interpretation

Black, fissile, paper shales represent deepest water, dysoxic to anoxic conditions starved of carbonate input during the early HST (in contrast to earlier interpretations as transgressive deposits by Aitken, 1978; Elrick and Snider, 2002). The paucity of calcareous material suggests strong flooding of the carbonate banks and relatively little wash-off of carbonate sediment (cf. Elrick and Snider, 2002). Such shales typically lack trace or body fossils, with the exception of carbonized algae (Tables 4, 8); the latter are typically discoidal to beaded forms that may record planktonic algae (Fig. 14b). The absence of agnostoid triobite remains in many such beds (see Table 8) is at odds with the interpretation of these trilobites as truly pelagic (Bergström, 1973; Gaines and Droser, 2003, 2005). That is, they do appear to have a facies controlled distribution. The rare occurrences of diminutive agnostoids on a few bedding planes, further suggests that these represent stressed conditions and that the trilobites were stunted or underwent juvenile mortality in marginal, benthic conditions.

Conservation *lagerstätten*, featuring abundant algae and less common soft-bodied animals, occur primarily in these sparsely fossiliferous shales. It is somewhat unclear whether these remains represent allochthonous carcasses swept into anoxic settings or tolerant, dysoxic-adapted, benthic and nektobenthic taxa that were occasionally killed and buried rapidly during obrution events. However, evidence for low energy, autochthonous burial in the slightly more proximal *Elrathia* facies (see below), as well as intact preservation of delicate benthic sponges (*Choya*) argue against an allochthonous import of carcasses of

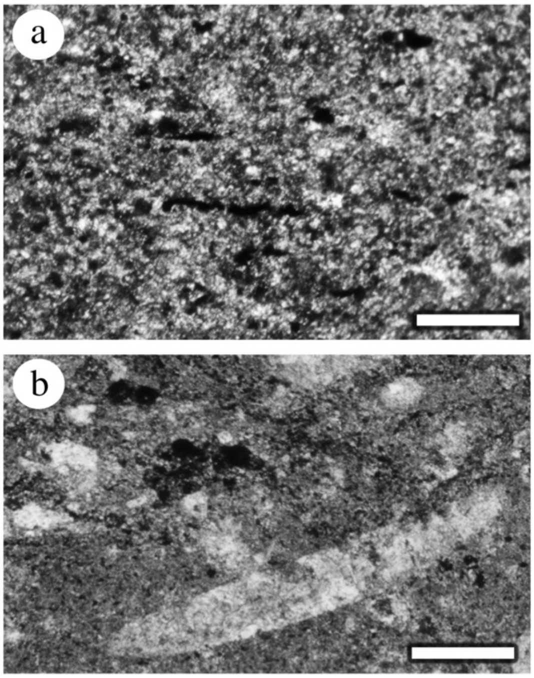


Fig. 11. Photomicrographs of Wheeler Formation thin-sections. (a) "purple" shale with discontinuous stringers of opaque pyrite, scale-bar is 0.25 mm. (b) sponge spicule-bearing lag, scale-bar is 1 mm.

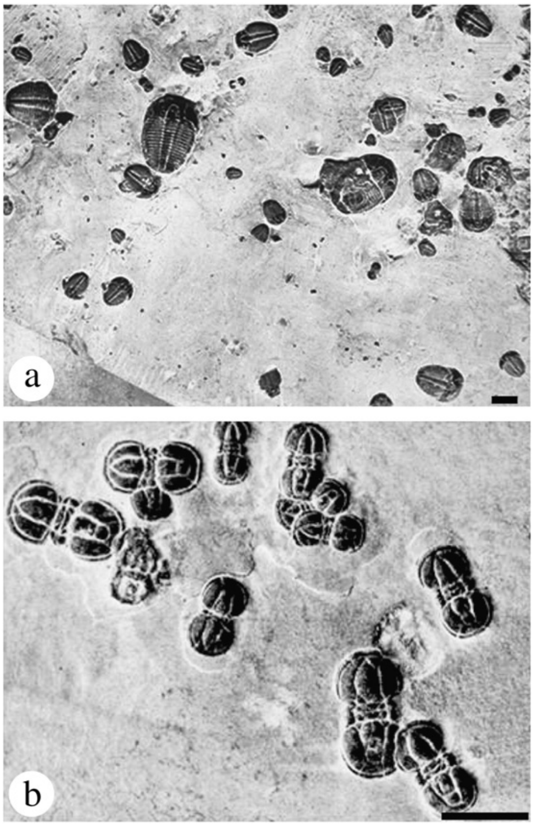


Fig. 13. Typical fossils of Wheeler gray, calcareous shale facies. (a) articulated multi-element bodies and molts of *Elrathia kingii*, scale-bar is 1 cm. (b) articulated specimens of *Peronopsis interstrictus*; Wheeler Shale, Wheeler Amphitheater, central House Range, Millard County, Utah; scale bar is 5 mm.

soft-bodied animals into these environments. The combination of lower dysoxic–anoxic conditions, abundant organic detritus, and relatively rapid episodic influx of detrital sediment favored repeated burial and preservation of organic remains, primarily algae, but in rare instances, including soft-bodied animal remains. The black shales grade vertically, both above and below, into dark gray to olive clay shales and calcareous shales that range from sparsely to highly fossiliferous suggesting fluctuating conditions.

5.6. Rhythmically bedded calcisiltites and shales

5.6.1. Description

Platy, calcareous shale beds commonly grade upward into interbedded yellow-orange weathering shale and thin (3–7 cm), medium gray (N5), pale-gray weathering calcisiltites (Fig. 16; Table 1). Limestones consist of pelloidal grains surrounded by recrystallized microspar cements. The beds feature planar to slightly wavy laminations composed of micro-graded layers typically <1 mm in thickness. The beds are graded with a bimodal grain size distribution (Rogers, 1984). The limestones are argillaceous, with 5–25% illite clay and quartz silt for Marjum Formation samples; the term calcisiltite is appropriate as a majority of grains are pellets or peloids in the medium to coarse silt size (<50 µm) fraction (Elrick and Snider, 2002, p. 1024–1025); Rogers (1984, p. 110) reports 60% fine grained carbonate, 18% quartz silt and 10% clay for calcisiltites in the Wheeler Formation at Swasey Springs. Intervening calcareous shales or very argillaceous limestones contain 10 to 70% illite to chlorite clay and minor quartz silt (Elrick and Snider, 2002, p. 1025).

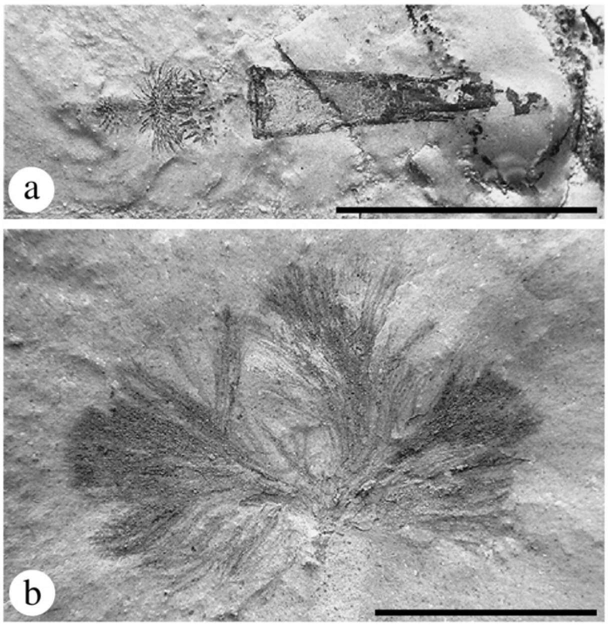


Fig. 15. Fossils of soft-bodied and lightly sclerotized organisms. Upper Wheeler; shale above T-5; knoll 2 km SE of Sawooth Ridge; Drum Mountains, Millard County, Utah. (a) *Selkirkia*; tube-dwelling annelids; (b) *Marpolia* sp.; possible green alga in laminated mudstone, scale-bar is 1 cm. Photos courtesy of S. Halgedahl and R. Jarrard.

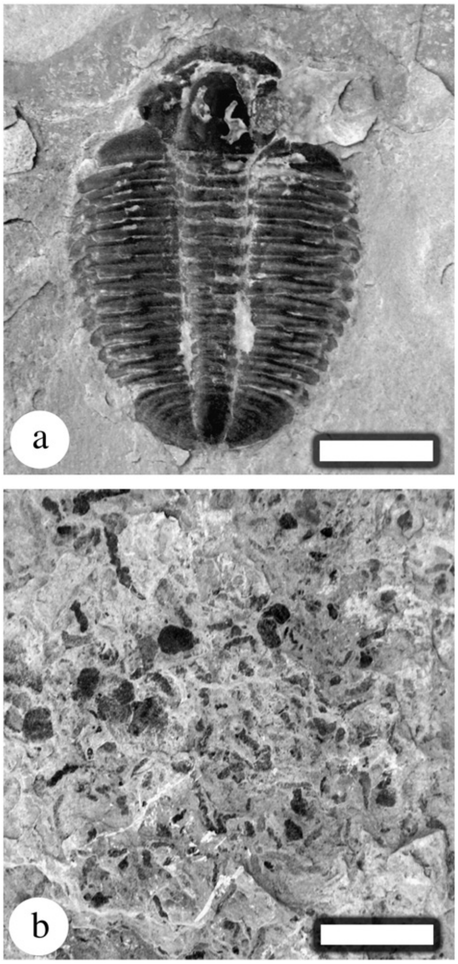


Fig. 14. Fossils of dark gray to black shale facies, upper Wheeler Formation: (a) articulated molt of *Elrathia*; note absence of free cheeks; bar scale is 1 cm. (b) carbonized algal fossils; bar scale is 0.5 cm. Drum Mountains, Millard County, Utah.

Basal surfaces of calcisiltites include very thin lags of skeletal debris or in some instances ooids. Soles of the beds are sharp and may include tool marks and minor flutes. In some sections these laminated calcisiltite beds have small-scale soft sediment deformation, interpreted as minor slumps by Rogers (1984) who recorded rather consistent overturn directions toward S 25°W and inferred a gently

Table 8
Survey of upper Wheeler Shale (*P. atavus* Zone) agnostoid beds; Marjum Pass, Millard County, Utah; counts of ~2×0.5 m strips, spaced ~1 m apart.

Cycle	*N*	Artic.	%	Convex-up (Articulated)	%	Comments
1	1	0	0	–	–	hashy, very abundant spicules
	11	1	9	1	100	hashy, spicules
	20	5	25	5	100	
	12	4	33	4	100	algal hash
	4	3	75	1	33	algal fragments
2	0	–	–	–	–	barren/small fragments
	7	2	29	2	100	
	5	1	20	1	100	
	3	3	100	2	66	mostly barren
	16	8	50	7	87	abundant algal blobs
3	15	9	56	7	78	hashy
	7	5	71	4	80	algal fragments
	12	8	67	7	87	
4	28	21	75	7	33	
	14	8	57	8	100	
	22	14	63	12	86	algal hash
5	44	14	31	12	86	
	19	8	42	8	100	carbonaceous
	21	16	76	10	62	algal blobs; *Acrothele*
6	12	8	66	7	86	
	13	7	61	7	100	
	23	17	73	14	82	algal blobs
7	34	22	65	22	100	
	15	11	73	10	90	
Total	358	195	54	158	81	

N = number of agnostoids counted; Artic. = number of articulated specimens; % is percentage of articulated; convex-up = number of articulated specimens in convex upward position; % is the percentage of convex-up individuals.

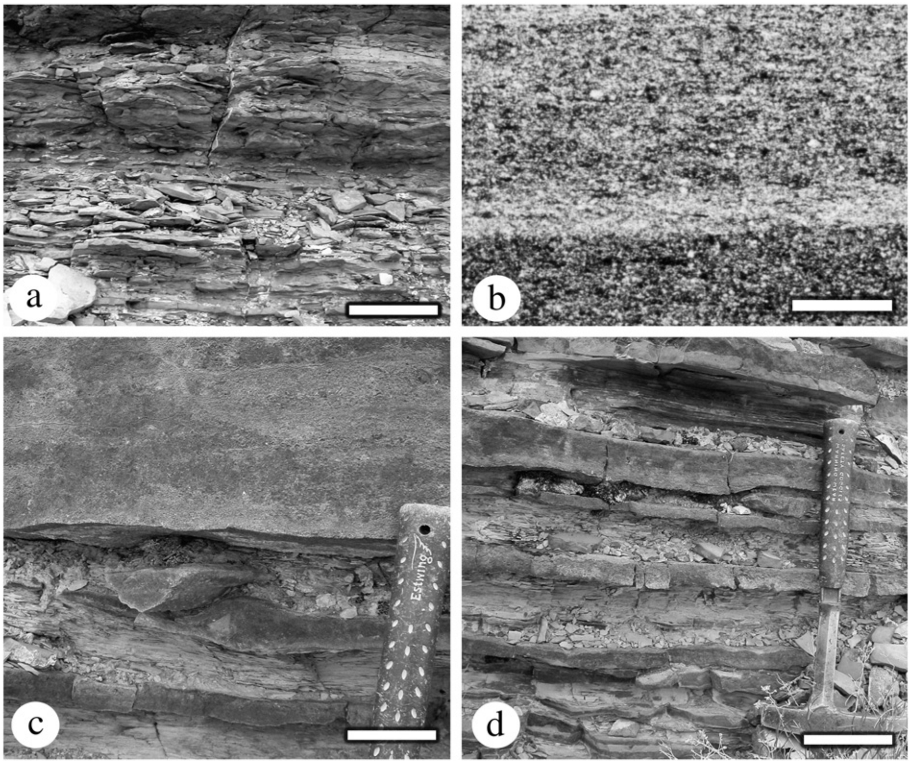


Fig. 16. Rhythmically bedded calcisiltite-shale facies. a–c exposures on east flank of Sawtooth Ridge, Drum Mountains. (a) package of thin-bedded calcisiltites, showing sharp contacts with interbedded shales and rhythmic character; upper Wheeler; bar scale 20 cm. (b) photomicrograph of finely laminated calcisiltite, scale-bar is 1 mm. (c) calcisiltites and calcarenites; note gutter cast, beneath sharp base of T-3 oolitic limestone bed; bar scale 5 cm. (d) thin platy limestones alternating with calcareous shale; 3 m below top of Wheeler Formation; bar scale 10 cm; low cuesta 2 km SE of Sawtooth Ridge, Drum Mountains, Millard County, Utah.

SW dipping ramp. Larger scale deformation features (Grannis, 1982) in the base of his middle Wheeler division of the Drum Mountains, have been ascribed to submarine slumping and sliding down steepened paleoslope.

The calcisiltite beds are sparsely fossiliferous and never yield fossils of soft-bodied organisms, but do preserve a slightly more diverse assemblage, including acrotretid inarticulate brachiopods (*Acrothele*), rare orthid brachiopods, diverse polymerid trilobites, and agnostoids and eocrinoid echinoderms (*Gogia*; Fig. 17). Specimens of the latter have been obtained from basal surfaces of laminated calcisiltite beds.

5.6.2. Interpretation

Rhythmic calcisiltite-shale facies preserve evidence for rapid, episodic deposition of detrital carbonate into deeper ramp settings. Tool marks, scours, and minor ripples indicate deposition by either distal turbidity currents or storm generated gradient currents (Rogers, 1984; Elrick and Snider, 2002). We agree with Elrick and Snider (2002) that the rhythmite facies formed preferentially during stable highstand to initially falling sea level (HST). However, in contrast to their inference that individual micro-graded lamina within the rhythmite beds represent discrete events; we view each calcisiltite bed as the deposit of a single storm or turbidity current event. Evidence for this includes overall grading, sharp scour marks on bases of beds and rarely, fossils that protrude through the layers. The individual laminae may represent a pulsed flow as is typical of both gradient and turbidity currents.

The sparsely fossiliferous to barren character of many beds in this facies can be attributed to a combination of rapid sedimentation, hence dilution, together with the inimical effects of high turbidity and loose, unstable substrates. However, obrution *lagerstätten* of articulated trilobites and eocrinoids were preferentially preserved by episodic mud tempestites/turbidites on more oxic seafloors during the later highstand (see Powell et al., 2003). These sediments record late HST to falling stage (FSST) carbonate shedding. The high sediment influx typical of FSSTs resulted in sparsely fossiliferous strata. However, in rare cases, well-articulated remains of eocrinoids and trilobites occur on the undersides of beds (Fig. 17). Evidently, these organisms were caught up in sediment flows, probably dilute turbidity flows and buried very rapidly. They need not have been transported any great distance. The fact that certain polymerid trilobites and eocrinoids characterize these facies and are not associated with other, deeper water organisms, such as agnostoids, suggests that they are autochthonous and not imported as carcasses into an exotic environment. Abundant burrowing in these facies indicates oxic bottom water with an autochthonous benthic infauna.

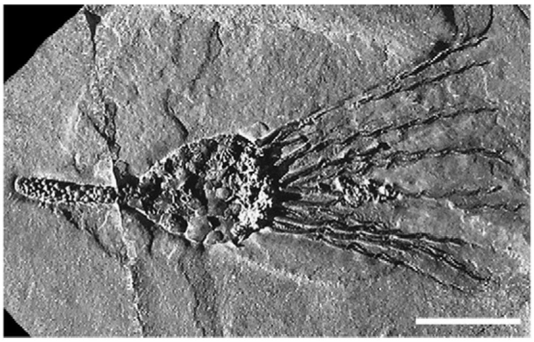


Fig. 17. Articulated specimen of the eocrinoid *Gogia spiralis*; bar scale ~1 cm; upper Wheeler Formation, Wheeler Amphitheater, Millard County, Utah. Courtesy of S. Halgedahl and R. Jarrard.

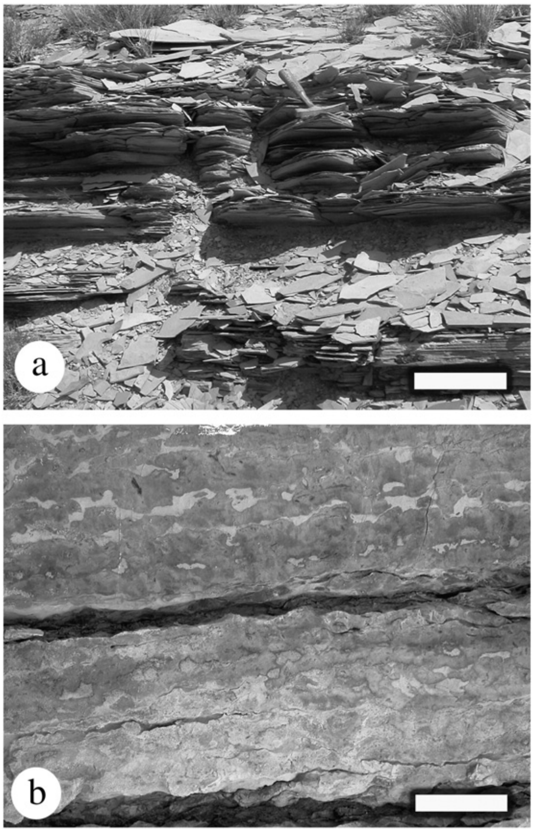


Fig. 18. Platy calcareous shale and bioturbated calcisiltite facies. (a) platy calcareous shales. (b) heavily bioturbated calcisiltites at top of Wheeler Formation; low cuesta 2 km SE of Sawtooth Ridge, Drum Mountains, Millard County, Utah.

5.7. Bioturbated calcisiltites/calcarenites

5.7.1. Description

The rhythmites pass upward into thin (1–5 cm) burrow mottled wavy to nodular bedded calcisiltites and fine grained calcarenites with lenticular pack- to grainstones (Fig. 18; Table 1). The latter are comprised of oolitic, pelletal, and skeletal grains (trilobite fragments, echinoderm debris, orthid brachiopods or stenothecids. Beds show sharp bases with scour features and in a few instances the skeletal and ooid grains are concentrated in small-scale gutter casts (Fig. 17c). Fossil material is typically disarticulated, fragmented and concentrated at the bases of beds. Beds finer than calcarenites are typically burrowed (ichnofabric index 2 to 4). Burrows are infilled with buff weathering dolomitic silts, which contrast with the pale to medium gray color of the calcisiltites and fine calcarenites (Fig. 18b). Burrowed beds are rather closely stacked with only argillaceous partings separating them.

Packages of burrowed calcisiltites and calcarenites are sharply set off from underlying shales and rhythmically bedded calcilsilites at flat to slightly undulatory boundaries. The tops of these intervals are sharply defined at the bases of the compact calcarenitic limestones. These are coarse, sandy textured, compact pack- to grainstones, with abundant fossil fragments including abundant sponge spicules, large peloids, and scattered ooids.

5.7.2. Interpretation

The bioturbation of these beds indicates fully oxygenated bottom water and perhaps relatively lowered rates of sedimentation and/or bypass of fine-grained sediments. The presence of a sharp basal contact to some bundles of burrowed calcisiltite to calcarenite indicates frequent touch-down of storm waves in a still relatively low sedimentation setting. We interpret such surfaces as forced regression surfaces. Bioturbated silty limestones and calcarenites would then record falling stage deposits, accumulated during a more rapid phase of sea level drop. The presence of gutter casts and graded beds in some of the shallower portions of this facies strongly suggests storm wave touch down on the seafloor. The FSST deposits are terminated by a sharply erosive sequence boundary recording maximum lowstand.

More compact, slightly coarser fine-grained calcarenites are interpreted as reworked lag deposits, analogous to, but slightly deeper than, compact oolitic limestones. These beds are interpreted as initial transgressive lag deposits.

6. Cyclicity in the Wheeler and Marjum formations

The Middle Cambrian interval of the Great Basin is divisible into sedimentary cycles at three scales (Schneider, 2000), each with similar motifs. The largest cycles are of formational scale, 30 to 100 m thick, and interpreted as 3rd order composite depositional sequences or “grand cycles” (Fig. 19). Cycles of 2 to 20 m thickness, generally comprised of several meter-scale cycles, display a typical sequence-like pattern (see

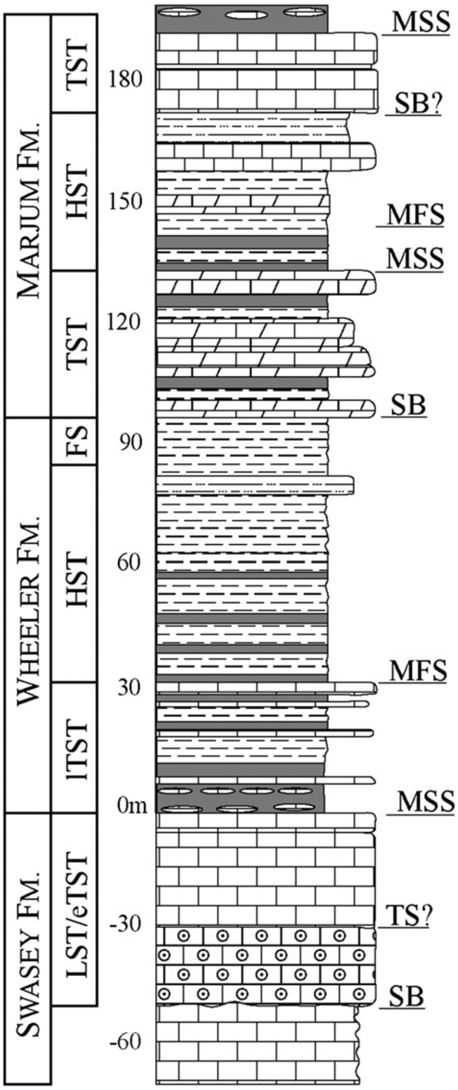


Fig. 19. Third-order sequence stratigraphic interpretation of Middle Cambrian Swasey–Wheeler-lower Marjum succession of the central House Range, Millard County, Utah. Abbreviations: SB: sequence boundary; MFS: maximum flooding surface; MSS: maximum sediment starvation surface. Systems tracts (STs): LST: lowstand systems tract; eTST early transgressive; lTST: late transgressive; HST: highstand; FSST: falling stage.

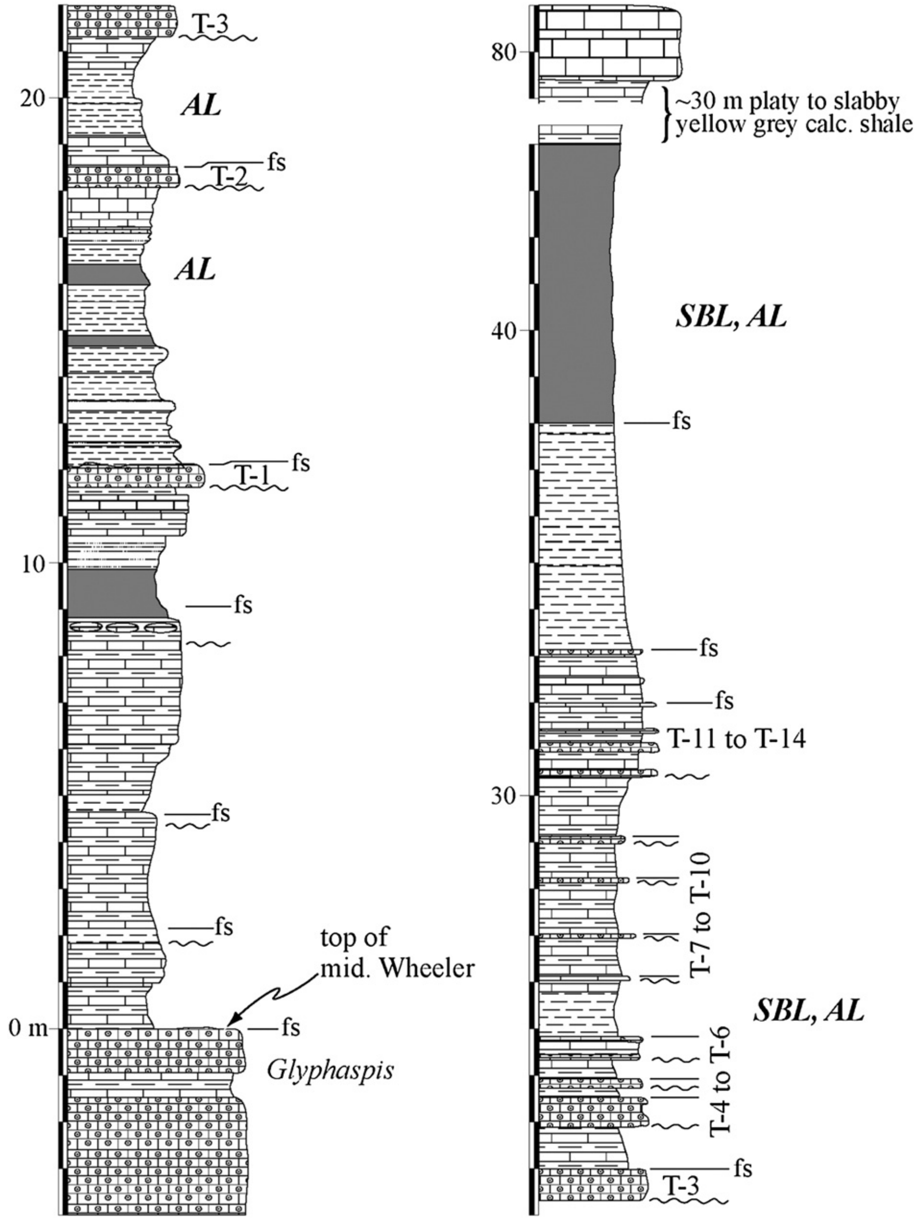


Fig. 20. Upper member of Wheeler Formation at Sawtooth Ridge in the Drum Mountains, Millard County, Utah, showing 1–5 m cycles discussed in this paper. Major condensed limestones noted in the text are designated T-1 to T-5; i.e., condensed transgressive lags. Abbreviations: fs = flooding surface; AL = algal lagerstätten interval; SBL = soft-bodied lagerstätten interval. Refer to Fig. 5 for key to lithological symbols.

below) and are interpreted as high frequency (4th to 5th-order) depositional sequences (Figs. 18–22). These are the primary focus of this study. At a smallest scale, are alternations of shaly and carbonate dominated strata, ranging from 30 to 200 cm, approximately meter-scale. Cycles, whether at a meter, decameter, or larger scale, start with carbonate-dominated lowstand to transgressive systems tract (TST), followed by a thicker, upward-shallowing, shale rich highstand systems tract (HST), and a carbonate dominated regressive, or falling stage systems tract (FSST; Figs. 19–21).

6.1. Grand cycles: third order sequences

Widespread large-scale ("third order"; ~1 to 5 million year) cycles occur in the outer detrital belt of the Middle Cambrian of Cordilleran Laurentia (Aitken, 1978). As defined by Aitkin, "grand cycles" comprise thick shale-rich intervals inferred to represent transgressive portions and limestone rich intervals considered to reflect regressions and associated influx of detrital carbonates into offshore areas. Such grand cycles have been correlated between the Great Basin and the southern Appalachians and this favors a eustatic origin (Markello and Read, 1981; Bond et al., 1988). They are comparable in temporal scale to third order depositional sequences, which have been recognized elsewhere by seismic stratigraphers, in terms of thickness and duration (Van Wagoner et al., 1990; Vail et al., 1991; Coe, 2003). However, the boundaries of grand cycles are approximately equivalent to flooding surfaces of sequences and sequence boundaries lie within the upper parts of grand cycles.

The upper Swasey through lower Marjum interval comprises portions of two depositional sequences (Schneider, 2000; Langenburg, 2003). The estimated one to three million-year duration of these sequences is in line with the general time frame presently used for third-order depositional sequences (Fig. 19).

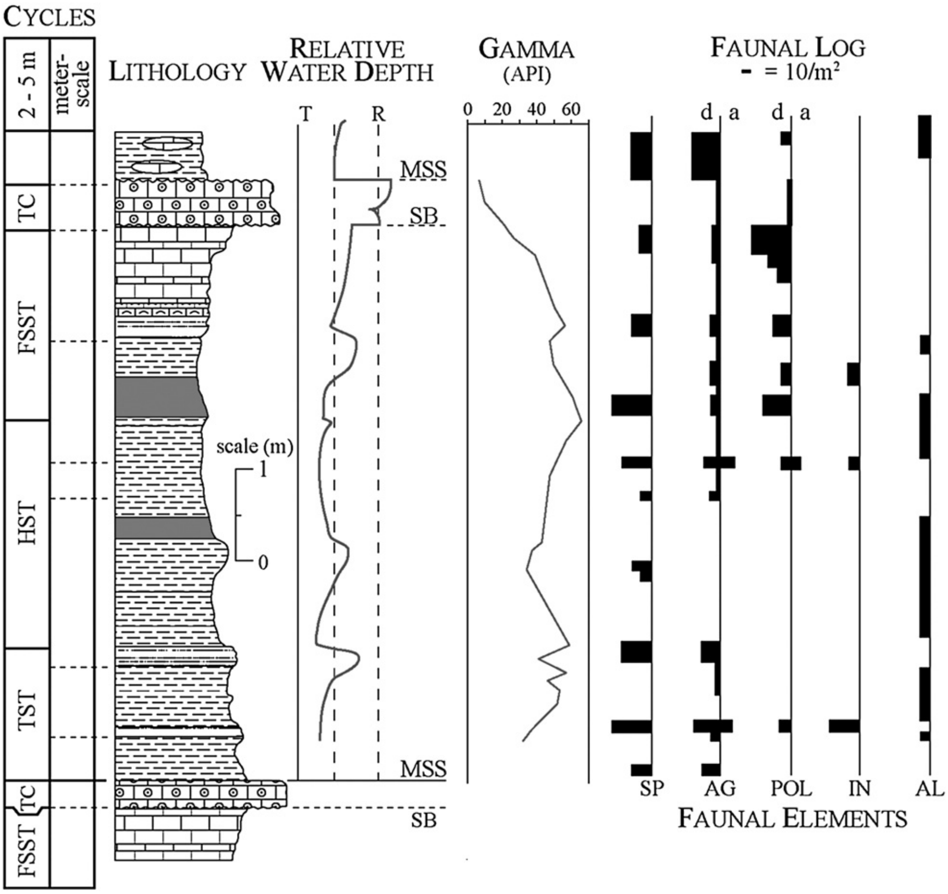


Fig. 21. Detailed log of upper Wheeler cycle T-1 to T-2, East flank of Sawtooth Ridge, Drum Mountains, Millard County, Utah, showing 4th order sequence stratigraphic interpretation, gamma ray profiles, as a proxy for clay-carbonate ratios, and fossil distribution and preservation modes. Abbreviations – Sequence Stratigraphy: FSST = falling stage systems tract, FS: flooding surface, MSS = maximum starvation surface, SB = sequence boundary, SSB = sub-sequence boundary, TC = transgressive condensed beds. Faunal Elements: SP = sponge spicules, AG = agnostoid trilobites, POL = polymerid trilobites, IN = inarticulate brachiopods, mainly acrotretids, AL = algae. Taphonomy: d = disarticulated, a = articulated; note bar widths indicate abundance. Refer to Fig. 5 for key to lithological symbols.

The basal sequence boundary of the Wheeler third order sequence occurs within the Swasey Formation. A subtle, but irregular erosion surface, interpreted as a lowstand erosion surface separates thin platy dark gray limestones from massive, 18–20 m, oolitic to oncolitic pack and grainstones of the informal middle member of the Swasey Formation (Sundberg, 1994; Langenburg, 2003). The base of the upper member represents the maximum basinal displacement of shallow oolitic facies and may record a lowstand deposit (LST) or earliest transgressive systems tract (TST; Fig. 19). The upper portion of the Swasey, 29 m thick in the Drum Mountains, clearly was deposited in progressively deeper water and records the initial portion of a transgressive systems tract (TST; Fig. 19). The uppermost 1 to 3 m of the Swasey is a bioclastic grainstone with a diverse, though fragmentary, trilobite fauna, referred to as the *Glyphaspis* fauna (of the lower *Altiocculus* Subzone; Randolph, 1973; Sundberg, 1994); this bed may record a condensed interval associated with platform drowning (Rees, 1986). A corroded and mineralized hardground at the top of the Swasey has been interpreted as a major flooding surface or drowning unconformity (Fig. 19; Palmer, 1971; Robison, 1964; Grannis, 1982; Rees, 1986). It may correlate with a widespread Middle Cambrian sea level rise (Landing, 2007). However, in the case of the Wheeler Shale, it is evident that the strong deepening was partly the result of abrupt collapse of the carbonate bank along basement faults, forming the House Range Embayment (Rees, 1986). In either case, strong deepening led to condensation marked by trilobite debris, and black platy limestones with carbonate concretions in the lowest Wheeler Formation. This 2–5 m interval reflects a time of maximum sediment starvation and condensation throughout the area and an abrupt passage from shallow water (shoreface to shoal) carbonates into deeper ramp agnostoid-bearing platy dark limestone and calcareous shale facies. At the scale of the third order sequence, the lower Wheeler interval is interpreted as the later transgressive systems tract, whereas the remainder of the formation reflects highstand to falling stage (regressive) systems tracts (Langenburg, 2003). However, at higher resolution this is clearly an oversimplification. At all sections, except for the Drum Mountains, the Wheeler exhibits a more complex pattern of shallowing in the lower third followed by development of a complex series of condensed limestone beds and finally deepening into monotonous dark, calcareous shale facies. In the Drum Mountains a thick succession of cliff-forming rhythmite limestone and massive oolitic burrowed wackestone and grainstone, about 70 m thick, intervenes in the middle Wheeler (Grannis, 1982; Schneider, 2000; Langenburg, 2003; Halgedahl et al., 2009). It is overlain by a meter-thick skeletal grainstone that contains a rich *Glyphaspis* fauna that occupies an analogous position, below an interval of strong deepening to agnostoid facies, and closely resembles the upper Swasey *Glyphaspis* bed in all other sections. The anomalous middle Wheeler unit, which divides the formation into two major depositional sequences at the Drum Mountains, is still poorly understand and is the subject of ongoing study (Halgedahl et al., 2009).

The top of the upper Wheeler Formation interval and also the upper boundary of the Swasey–Wheeler third order depositional sequence is marked by a sharp change to massive, burrow-mottled to oolitic carbonates of the basal Marjum Formation (Fig. 19). The abrupt facies dislocation at the base of the Marjum–Pierson Cove Formation indicates a major drop in relative sea level and increased input or buildup of pelletal bioturbated carbonate. The interval is therefore interpreted as a major (3rd order) sequence boundary that terminates the Swasey–Wheeler sequence. The Marjum itself constitutes at least one (and possibly more than one) third order depositional sequence. As noted above, the basal quarter of the Marjum is typically comprised of a set of shallowing-upward or progradational small-scale sequences, followed by a retrogradational set of three to four that culminate in the deep water deposition of the "Trilobite quarry" shales. The flooding surface of the third minor sequence of the Marjum–Pierson Cove marks a change from the progradational patterns below (LST or early TST), culminating with oolitic or stromatolitic limestone and a retrogradational pattern through the next two to three 4th order sequences.

6.2. Intermediate- and small-scale sequences

The upper Swasey–Wheeler and lower Marjum third-order depositional sequences are composite sequences, comprised of about 16 cycles ranging in thickness from 2 to over 30 m, interpreted as high frequency sequences (Figs. 20–25). The cycles we recognize are comparable in scale to those recognized by Langenburg (2003); and comprise two major portions, which she referred to as the basal, typically shale prone portion, and upper, typically more limestone-rich "cap" of each cycle (Fig. 20). Gamma ray profiles show that the most clay-rich portion of the cycles lies near the middle of the cycle (Fig. 21); we interpret this interval as recording highstand conditions. We define these cycles as beginning with a compact, condensed bed that typically overlies the

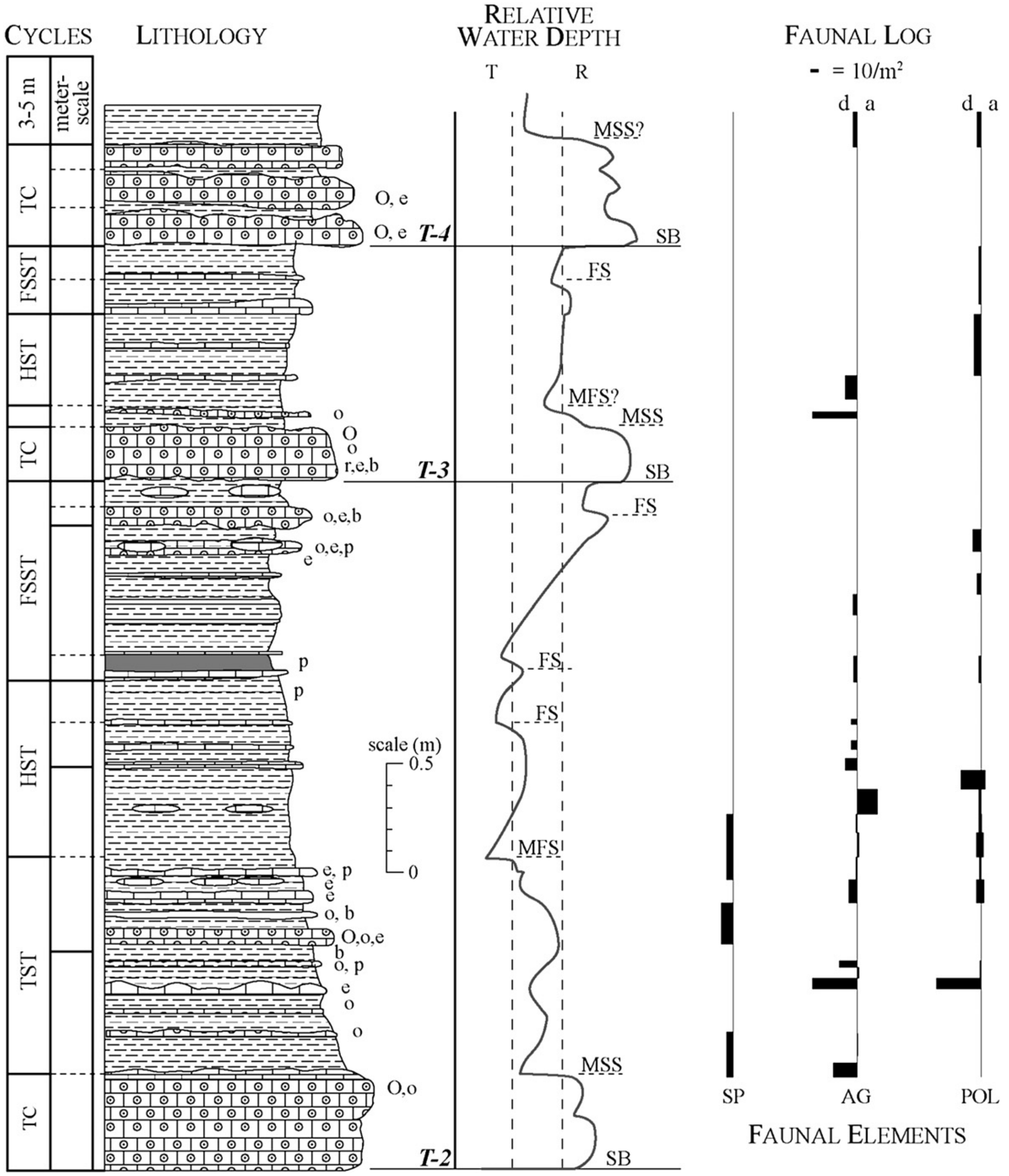


Fig. 22. Detailed log of two proximal ramp cycles; upper Wheeler cycle T-2 to T-3, and T-3 to T-4. East flank of Sawtooth Ridge, Drum Mountains, Millard County, Utah Abbreviations as in Fig. 21. Lettered symbols include: b = large burrows; c = cone-in-cone calcite; e = echinoderm debris; O = oncolites; o = ooids; p = phosphatic nodules; r = rip-upclasts.

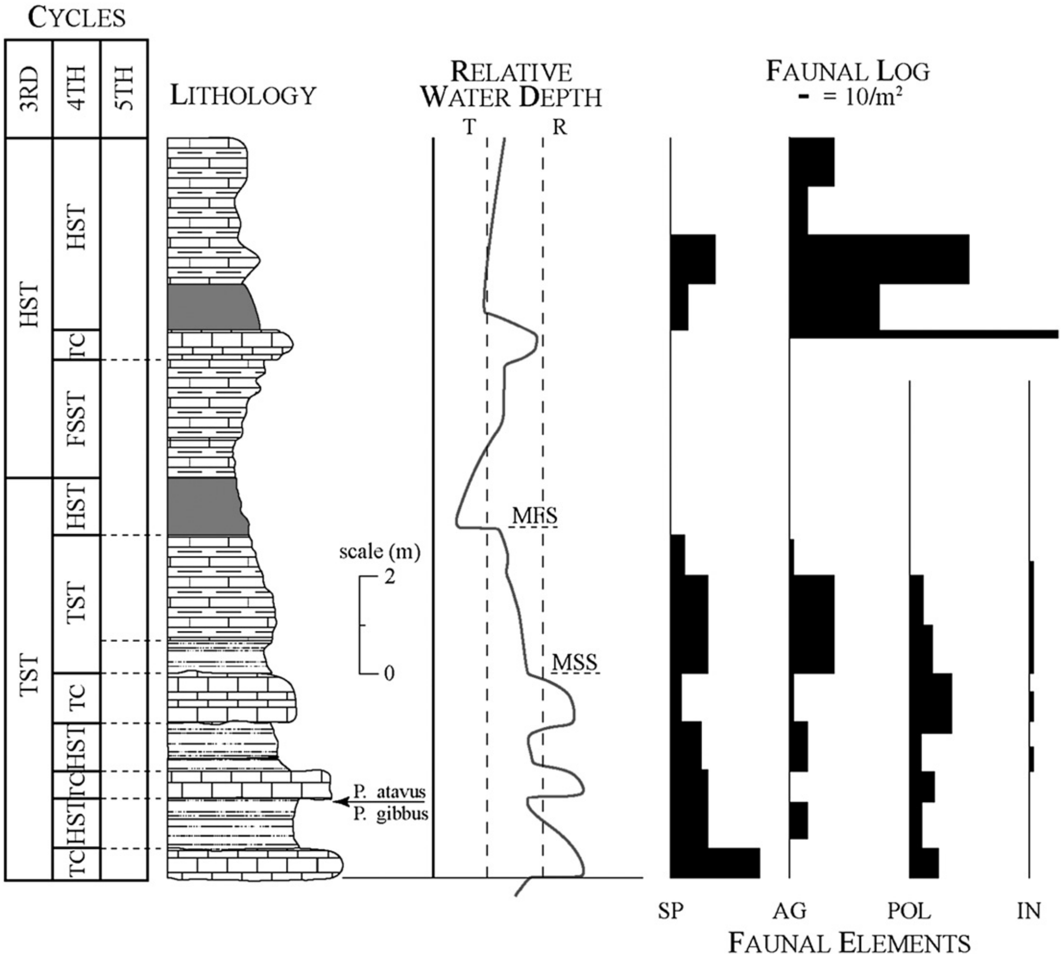


Fig. 23. Log of representative medial to distal ramp cycles, showing sequence interpretation, lithology, and common fossil distribution; lower Wheeler Formation, 50 to 90 m above Swasey Limestone. Stratotype Ridge, Drum Mountains, Millard County, Utah. Abbreviations, as in Fig. 21.

shallowest portion of the underlying cycle; this bed underlies the thicker, shaly portion of each cycle (Figs. 20–22). These intermediate or 4th order cycles have a sequence-like motif, in that they begin with an abrupt facies dislocation at which underlying calcisiltite-rich, apparently shallowing upward successions, are sharply overlain by shallower, condensed intervals that may show erosive bases and flooding surfaces at their tops. Condensed pack- and grainstone beds, pass upward, typically through a thin condensed zone into a relatively thick interval of dark shale; at one scale this represents simply a basal, particularly thick "meter-scale cycle" (Figs. 20–22). The upper or cap interval of each intermediate scale cycle shows a clustering of thin, lenticular limestones that define bases of smaller-scale cycles. Comparable, cyclic packages have been termed "parasequences" (cf. Elrick and Snider, 2002). However, they are divisible into even smaller shallowing-upward bundles, herein termed meter-scale cycles (Figs. 21, 22).

Meter-scale cycles are more comparable to parasequences, in that most of their thickness comprises a subtly shallowing-upward, shale to silty carbonate package; however, they, too, exhibit a sequence-like motif that is similar to that of the larger 4th order cycles in which they are packaged. They are most readily recognized in proximal ramp successions. As defined herein, each meter-scale cycle commences with condensed bed, 1 to 50 cm thick, typically enriched in fragmentary fossils, ooids, oncoids, peloids, or other sand-to granule-sized grains (Fig. 22; Table 2). This bed displays a relatively sharp base and top. The other portion of the meter-scale cycle consists of shale, thin calcisiltites and/or thin, lenticular skeletal or ooid beds and stringers.

In the following sections we examine the motifs of meter-scale and intermediate scale cycles in proximal, medial, and distal ramp successions of the Wheeler and lower Marjum/Pierson Cove formations. Shallow shelf and peritidal cycles occur in the Pierson Cove Formation (=Marjum Fm.) at the Drum Mountains section, but these are beyond the scope of the present study.

6.2.1. Proximal ramp cycles

Proximal ramp successions are represented by the upper member of the Wheeler at the Drum Mountains (Figs. 20–22). The lower third of the upper member of the Wheeler Formation in the Drum Mountains, approximately 35 m thick, was studied to provide a detailed example of high-resolution sequence stratigraphy in a proximal ramp succession (Figs. 20–22; Tables 2, 3, 5). It includes six medium-scale (4th order) cycles, that range from 2 to 8 m in thickness (mean approximately 5 m); these are further subdivided into 0.2 to 3 m-thick smaller cycles. The upper five medium-scale cycles, which total about 20.3 m in thickness, possess a total of 25 m-scale cycles, four to six for each larger cycle; these range in thickness from 25 to 150 cm with a mean thickness of about 80 cm.

Meter scale cycles commence with 20–50 cm thick compact ledge-forming, pelletal, oolitic to oncolitic carbonate intervals (Figs. 21, 22). This interval is followed by a succession of medium to dark gray shale that passes upward into interbedded thin, laminated to cross-bedded, calcisiltites and this in turn is sharply overlain by the compact oolitic to skeletal grainstone at the base of the next meter-scale cycle. At Sawtooth Ridge in the Drum Mountains, 20 of the 25 m-scale cycles commence with oolitic pack- to grainstone beds. About half of these show abundant skeletal components, including echinoderm grains, trilobite fragments, and brachiopods (Figs. 6, 7; Table 2).

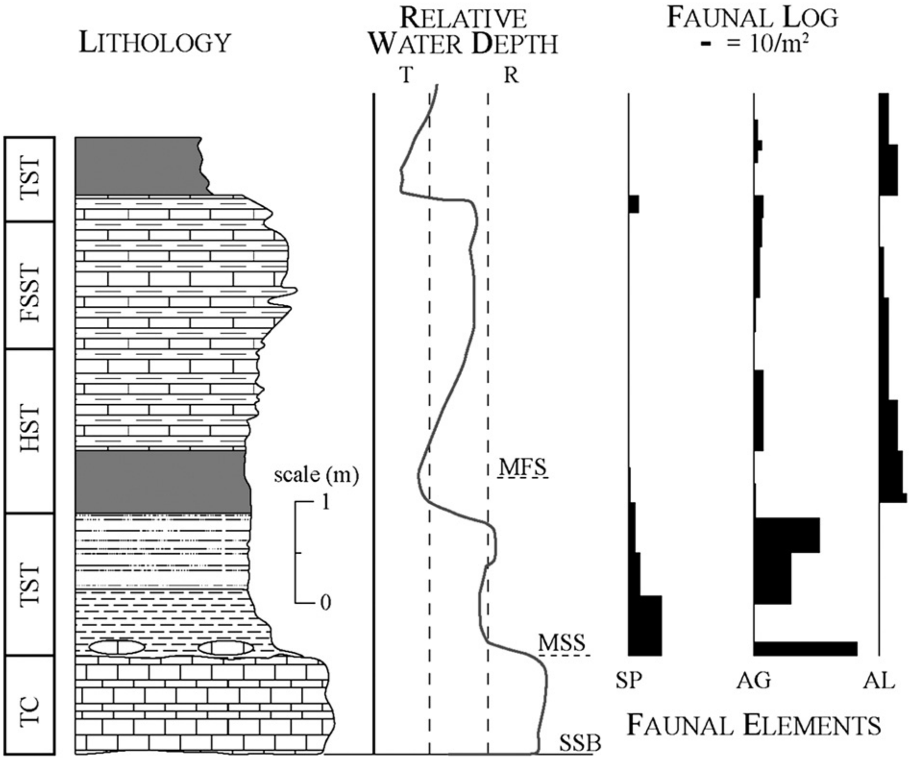


Fig. 24. Log of representative medial ramp cycle, showing sequence interpretation, lithology, grain types, and common fossil distribution; lower Marjum Formation. Marjum Pass, House Range, Millard County, Utah. Abbreviations as in Fig. 21.

Each 4th order cycle commences with a relatively thick and shale prone meter-scale cycle (Figs. 20–22). The base of this thick cycle is a typically distinctive, often a slightly thicker, grainstone bed containing oncolites as well as ooids and with a distinct firm- or hardground on its upper surface (Figs. 7, 21, 22).

Beds above this basal ledge include interbedded shales and lenticular limestones that are typically oolitic to skeletal pack- and grainstones with echinoderm debris as well as disarticulated and fragmented trilobites, especially agnostoids (Fig. 20; Table 3). Intervening shales are sparsely fossiliferous, but may contain articulated small trilobites. Concentration of skeletal material is evident in the bases of most cycles.

The overlying early highstand zone occurs as olive to black, highly fissile to papery shales. These weakly calcareous, clay shales are interpreted to represent the deepest water conditions of the 4th order sequence (Figs. 21, 22). Fossil concentration is less than in underlying beds, but articulated trilobites, representing obrution deposits are typical (Figs. 13, 14). Higher portions of the sequence are composed of calcareous, platy shales and thin micritic, argillaceous limestones. They are sharply overlain by rhythmically interbedded shales and thin tabular to nodular micritic limestones formed during rapid sea level fall and progradation of allodapic carbonate (cf. Elrick and Snider, 2002). The higher or "cap" portion of the 4th order sequence, consists of interbedded shales and calcisiltites with minor oolitic or skeletal limestone beds, comprising two or more meter-scale cycles (Fig. 22).

6.2.2. Medial ramp cycles

Medial ramp cycles are well represented by the lower Wheeler Formation in nearly all locations (Fig. 23; Table 6), the lower 4th order sequences of the upper Wheeler Formation in the Drum Mountains (Table 6) and in the lower Marjum Formation in the House Range (Fig. 24; Tables 6, 7). They range from 3 to 11.5 m in thickness, averaging 6.7 m. In some cases these intervals are also divisible into meter scale cycles.

Meter scale cycles consist of a basal ledge-forming, dark gray, sandy textured, argillaceous pelletal grainstone or calcisilitite; their upper surfaces may show an abundance of comminuted agnostoid and/or polymerid trilobite sclerites or sponge spicules (Fig. 23; Tables 6, 7). These beds are overlain by thin, dark gray, agnostoid-bearing, limestones that may grade abruptly into a thin interval, up to half a meter, of medium gray to pale lavender, typically sponge spicule-rich, siliceous mudstone representing a maximum flooding interval (Figs. 23, 24; Tables 6, 7). In some cycles, only the lavender spicule rich beds may be present above an interval of thicker calcisiltites, marking the condensed base of the next meter-scale cycle.

This unit is followed by laminated, reddish to purplish, papery shale, black, fissile shale, olive gray shale and alternating calcisiltite. These dark shales may be barren or contain abundant carbonized algal debris. A series of thicker, graded, dark gray pelletal grainstones with minor trilobite, alternating with thinner, pale gray laminated calcisiltites and shales caps the larger cycles (Figs. 23, 24).

6.2.3. Distal cycles

The upper portion of the Wheeler Formation in the Drum Mountains and the majority of the formation in distal sections, such as Marjum Pass, consist largely of yellowish weathering, platy, calcareous shale that may appear barren and monotonous. However, close scrutiny of these intervals shows the presence of subtle meter to decameter scale cycles (Fig. 25; Tables 4, 8). In weathered sections meter-scale cycles may be recognizable as subtle alternations of recessive, dark gray to black, fissile shale and slightly more resistant, platy, medium gray calcareous shale. The latter may contain inarticulate brachiopods and articulated agnostoid and, rarely, polymerid trilobites (Table 8). These rhythmic alternations may be bundled into larger intervals capped by thin calcisiltites.

At Marjum Pass eight distal cycles were recognized in the Wheeler Formation by Langenburg (2003); these range from 5 to 25 m in thickness with a mean thickness of about 15 m. Each cycle has a basal interval comprising a thicker, compact, typically orange weathering (pyritic?) calcisiltite, overlain by black, fissile shale (see Figs. 12, 18). The cycle caps are typically thinner intervals of alternating laminated ribbon calcisiltite and shale, showing subtle bundling. No major

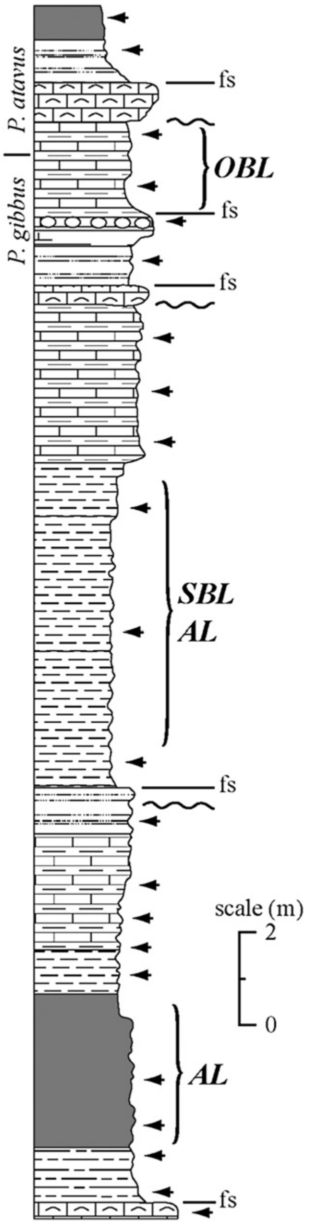


Fig. 25. Stratigraphic column of sampled portion of the lower Wheeler Shale at Marjum Pass showing positions of samples noted in Table 4 at arrows.

skeletal or oolitic/oncolitic limestone beds are present, although bedding planes of trilobite debris may occur near the boundaries between calcisiltite bundles and fissile shales. In upper portions the ribbon calcisiltites become thicker and more tightly stacked and may pass upward into bioturbated, somewhat nodular limestone.

The upper 40–50 m of the Wheeler Shale in the Drum Mountains was treated as the base of a single cycle by Langenburg (2003). As noted, her inferred sea level curve shows these beds as shallower than underlying oolitic limestone. However, the base of this package comprises the most fissile shales with highest gamma ray values (Halgedahl et al., 2009). Moreover, the lower shales are very rich in agnostid trilobites, *Elrathia*, and even soft-bodied lagerstätten, indicating similar biofacies to those interpreted as deep water facies at Marjum Pass (Tables 4, 8). Observations of weathered outcrops of this interval reveal a pattern of alternating recessive calcareous shales (<75% carbonate) and more ledgy weathering, platy limestone bundles (86–88 weight percent carbonate; Langenburg, 2003); the latter range from, <10 cm to about 100 cm (mean = 35 cm; $n = 18$).

Larger, 5 to 10-m scale, cycles are also evident as minor oscillations in the gamma ray profiles (Halgedahl et al., 2009; R. Jarrard unpublished data). Eight such cycles can be recognized both in outcrop and from spectral gamma ray analysis for the upper 30 m of the Wheeler Formation in the Drum Mountains, and each of these is identifiable as an upward thinning pattern of three to four meter-scale bundles (that actually range from 3 m to <1 m upward). The lower minor cycles are capped by thin (~10 cm) ledges, while the thinnest, upper one is capped by a more prominent 50 to 100 cm ledge. Although this is too small a sample to test rigorously for hierarchical cyclicity, we suspect that the bundling pattern records modulation of smaller precessional cycles within larger 100 kyr cycles. Overall, these cycles show a progradational pattern typical of highstand to falling stage systems tracts, with capping calcareous beds becoming thicker upward.

7. Model for genesis of high order cycles

Any model proposed to explain the recurrent meter to decameter scale cycles in the Middle Cambrian must account for the following recurring phenomena: A) a repeated motif of facies starting with a sharp based compact peloidal, skeletal, oolitic/oncolitic or intraclastic limestone; B) the sharp corroded tops of these limestone beds; C) the common occurrence of skeletal hash and sponge spicule beds above the condensed limestones; D) the black and dark gray fissile shales with *lagerstätten*; E) the bed thickening and increasingly burrowed successions at cycle tops.

Schneider (2000) postulated that small-scale cycles in the Wheeler and Pierson Cove formations of the Drum Mountains reflected repeated pulses of subsidence in the House Range embayment. However, the regularity and traceability of these cycles, at least within the Drum Mountains suggests otherwise. Middle Cambrian peritidal facies laterally equivalent to the Wheeler and Marjum formations, display 3 to 5 m cycles that have been ascribed to Milankovitch band eustatic fluctuations composed of approximately 15 kyr precessional and 127 kyr eccentricity cycles (Kepper, 1972, 1976; Bond et al., 1991). Comparable scales of cyclicity have also been recognized in offshore outer ramp to basinal facies of the Middle Cambrian (Montañez and Osleger, 1993; Montañez et al., 1996; Elrick and Snider, 2002) and interpreted as high frequency sea-level oscillations. Moreover, spectral analyses of these cycles demonstrate a hierarchical pattern of probable Milankovitch driven eustatic cycles of several meters magnitude (Bond et al., 1991). We infer that this same driving mechanism of high frequency cyclicity may also apply in the mid to deeper ramp facies of the Wheeler and Marjum formations.

On the other hand, there is little doubt that the initial deepening in the Wheeler Formation was greatly accentuated by subsidence of the House Range Embayment. A subtle facies shift to slightly more offshore facies occurs in the pure carbonate facies of the surrounding shelf where the Eye of the Needle Limestone suggests slightly deeper conditions than the underlying Swasey Limestone and overlying Pierson Cove Formation. Nonetheless, the Wheeler shows much deeper water facies. Moreover, the sharp flooding surfaces that characterize Wheeler cycles may reflect the strong drowning effect of sea level rise coupled with strong subsidence.

7.1. Sequence stratigraphic model

In our interpretation, the thin, compact limestones record lowstand to initial sea level rise following a lowering of base level and storm wave scouring of the seafloor. The occurrence of reworked ooids, skeletal fragments and intraclasts in the compact limestone beds of the proximal Wheeler Formation of the Drum Mountains and the Marjum Formation of the House Range suggests that they represent winnowed and reworked basal transgressive lags. The ooids and perhaps also the oncoids were input into the mid ramp depositional setting from shallow shoals during severe storms, as evidenced by discrete sharply bounded and vaguely graded beds encased in shales, the presence of small gutter fills, rip-up clasts, and subtle hummocky cross stratification in some beds. In the absence of other sediment input, as well as winnowing and bypass of fines, they accumulated to form lag sand blankets. In more distal settings, sandy, pelletal limestones occur in analogous position to the oolitic–oncolitic deposits. These sandy textured beds reflect winnowing of allodapic carbonates during sea-level drops (Elrick and Snider, 2002), or initial transgression.

Oolitic shoals were preferentially established during early transgressive phases in shallow, but rather clear water conditions (see also Markello and Read, 1981). Moreover, their abundant occurrence suggests that the shallow shelf may have developed under semi-arid, slightly hypersaline conditions typical of the subtropical latitudes of the Cambrian northern Laurentian platform.

The sharp, mineralized, runneled, and corrosion/erosion pocked upper surfaces of the limestones formed during periods of near total sediment starvation associated with drowning of the carbonate platform and near-shore sequestration of siliciclastics in their source areas. Hence, rather than being sequence boundaries we infer that these represent surfaces of maximum sediment starvation associated with accelerated base level rise. These surfaces are sharply overlain by silts and clay shales formed during deepening.

Maximum flooding zones are marked, in some cases, by condensed fossil fragmental and, in somewhat deeper water, by spicular siliceous mudstones. Under low sedimentation, but still oxic and relatively deep water, conditions sponges appear to have thrived and their spicular skeletons accumulated to form a major component of the sediment. During ensuing early highstand the shallow carbonate platform had retrograded up-ramp and major portions of the shelf may have been flooded leading to minimal supply of detrital carbonate. At this point in the cycle siliciclastics were input into the House Range Embayment and surrounding shelf areas, in greater quantity, perhaps associated with increased humidity and fluvial input. As noted above, there is no evidence that these siliciclastics were derived from the inner detrital belt, at least not nearby. Either these muds were supplied from sources further north (present directions), as suggested by Elrick and Snider (2002), or from offshore terranes. Associated stratification of the water column promoted development of dysoxic to anoxic facies on the deeper ramp and basin. Under such conditions, dark shales accumulated and occasional burial events entombed organics and fossils. Relatively low sedimentation enabled organic matter to be somewhat concentrated. The combination of anoxia (at least in the upper sediments) and pulses of clay deposition favored soft-bodied organism preservation. Black, weakly calcareous shales are most pronounced in the 4th order cycles that occur in the late TST to early HST of the 3rd order sequences; for example, in the lower third of the Wheeler Shale.

A greater carbonate content, relative to black to olive clay shales, occurs in calcareous dark shale facies in higher parts of sequences and suggests a increased influx of detrital carbonate during highstand conditions. Decreasing accommodation in shelf environments favored progradation of the carbonate platform down ramp and allowed the input of increasing amounts of fine silt-sand sized detrital carbonate, i.e. highstand shedding. This was also associated with deepening of the oxycline, such that low-oxygen adapted organisms, such as *Elrathia*, could colonize the seafloor. Dilution and instability of soft, rapidly deposited substrates, contributed to an upward decrease in the abundance of benthic organisms even as benthic oxygen conditions improved. The increasing supply of detrital siliciclastics and carbonate sediments also meant more frequent obrution deposits although these are not as recognizable as in deeper parts of the cycle owing to dilution of organism remains.

Ultimately, seafloor deposition was interrupted by periods of increased erosion and bypass during falling stage to lowstand. Storm wave scouring produced sharply erosive surfaces typically with well incised burrows marking temporary firmgrounds.

7.2. Comparison with other Paleozoic cycles and taphofacies

Cambrian cycles resemble in many ways those of later time such as those of the Upper Ordovician Kope and Collingwood formations (Brett et al., 2003, 2006, 2008) and even, to a degree, Jurassic cycles in the Blue Lias of Great Britain (Allison et al., in press). They are similar in thickness and motif. In all cases there appears to be a coupling of a sea-level fluctuation with changing patterns of sedimentation, and a cyclic change in bottom water oxygenation. However, Cambrian cycles differ very much in the composition of the condensed limestones (ooids, trilobite and sponge fragments, as opposed to brachiopod/mollusk shells, bryozoans and crinoid debris). There is also a greater presence of flat-pebble intraclasts (see Sepkoski et al., 1991).

Perhaps most importantly, although all cycles may feature dark, organic-rich shales in the middle, early HST portions, only those of the Early to Middle Cambrian feature much soft-bodied preservation in this facies and they show this with every cycle to varying degrees. A number of hypotheses have attempted to explain the Cambrian *lagerstätten* window, including: an absence of dysoxic infauna (Allison and Briggs, 1993; but see Aronson, 1992, 1993; and Pickerill, 1994; Orr et al., 2003), reactive clays (Butterfield, 1995; Orr et al., 1998), early carbonate cementing and porosity reduction (Gaines and Droser, 2005), and unusual chemical conditions that inhibited decay (Petrovich, 2001; but see Powell, 2003 for counter arguments). Many of these mechanisms, however, should not be unique to the Cambrian.

This window may most closely correspond to the near absence of burrowing organisms in dysoxic facies (Allison and Briggs, 1991, 1993; Orr et al., 2003; Powell et al., 2003). Middle Paleozoic and even Late Ordovician cycles show abundant small *Chondrites* and *Planolites* in dark organic-rich facies. These are virtually lacking in the Cambrian cycles we have examined, although small burrows were reported from beds intercalated with barren layers yielding soft-bodied organisms (Gaines and Droser, 2005). We suggest that at this early time in development of the benthic ecosystem, larger infaunal organisms had not yet evolved the capacities to survive in low oxygen, hydrogen sulfide rich systems (see also Orr et al., 2003). As such, true exaerobic settings (sensu Savrda and Bottjer, 1987), may have been much more widespread than in later times. Benthic epifaunal organisms survived in dysoxic environments in the absence of a burrowing infauna. In contrast during Ordovician and later geologic time small shallow burrowing organisms, such as nuculid bivalves and producers of *Chondrites* traces, became among the most tolerant of low benthic oxygen levels and thus may have been among the first colonizers on dysoxic seafloors.

If burrowers were largely absent in dysoxic seafloors then little oxygen would have been introduced into the upper sediments and, once buried, organism remains, even lightly sclerotized or soft parts would not be disrupted. Hence, scenarios calling for major importation of allochthonous remains may be unnecessary. The existence of a fluctuating benthic oxygen regime enabled temporary seafloor colonization of tolerant benthic organisms (Gaines and Droser, 2003, 2005); this, coupled with episodic burial of more or less autochthonous epifaunas or nektobenthic forms may partially account for soft bodied preservation in the more distal settings (cf. Orr et al., 2003; Powell et al., 2003). Nonetheless, we agree with Gaines and Droser (2005) that additional mechanisms may also be at play in soft-bodied organism preservation, including deflocculation of clays and early diagenetic carbonate sealing.

In environments with increased oxygenation and some burrowing, excellent preservation of articulated remains could still take place, but the occurrence of soft-bodied organisms would be reduced. Burial in relatively impermeable fine clay rich sediment may have been a further factor of key importance to the preservation of organism bodies near the peak highstands as suggested by the coincidence of soft bodied organisms with high K-gamma ray "hot zones" (Halgedahl et al., 2009). The concatenation of rapid clay burial pulses with low oxygen, and an absent dysoxic benthic infauna may in the end provide the key ingredients to explain the Early to Middle Cambrian *lagerstätten* window.

8. Conclusions

A) Distinctive taphofacies, including soft-bodied lagerstätten, occur predictably in 10 m scale sequences in the Middle Cambrian Wheeler and Marjum Formations.

B) Compact oolitic and oncolitic and sandy peloidal carbonate beds formed during initial transgressions following shallowing episodes. Mounded cyanobacterial buildups are associated with periods of rising sea level at the tops of some early TSTs; otherwise fossils are scarce and poorly preserved in the early TST.

C) Skeletal concentratins are represented by spicular and fragmental trilobite hash beds and associated with the sediment-starved conditions of the later TST.

D) Conservation *lagerstätten*, featuring abundant algae and soft-bodied animals, occur primarily in the sparsely fossiliferous HST portions of cycles.

E) Obrution *lagerstätten* of articulated trilobites and eocrinoids were preferentially preserved by episodic mud tempestites/turbidites on oxic seafloors of the HST to FSST.

F) The integration of sequence stratigraphy, sedimentology and taphonomy is leading to integrated models that may not only explain the distribution of various fossil groups and modes of preservation, but also may permit prediction of likely portions of sedimentary cycles in which to prospect for extraordinarily preserved biotas in Cambrian silicilcastic/carbonate successions.

Acknowledgements

We gratefully acknowledge the assistance and insights provided by Susan Halgedahl and Rich Jarrard of the University of Utah, Salt Lake City. Rich kindly provided spectral gamma ray data for the T1–T2 cycle in the Drum Mountains. Discussions of various aspects of Cambrian stratigraphy, paleontology, and depositional environments with Loren Babcock, Robert Gaines, Allison (Pete) Palmer, and Ed Landing helped clarify our ideas. Gordon Baird aided in early phases of fieldwork and Melissa McMullen helped substantially in later field sampling. Initial field work was funded by a NATO grant to PAA and CB.

References

Aitken, J.D., 1978. Revised models for depositional grand cycles, Cambrian of the southern Rocky Mountains. Canadian Bulletin of Petroleum Geology 26, 512–542.

Aitken, J.D., 1997. Stratigraphy of the Middle Cambrian platform succession, southern Rocky Mountains. Geological Survey of Canada, Bulletin 396 322 pp.

Allison, P.A., 1986. Soft-bodied animals in the fossil record, the role of decay upon fragmentation during transport. Geology 14, 979–981.

Allison, P.A., 1988a. The decay and mineralization of proteinaceous macrofossils. Paleobiology 14, 139–154.

Allison, P.A., 1988b. *Konservat -Lagerstätten*: cause and classification. Paleobiology 14, 331–344.

Allison, P.A., Briggs, D.E.G., 1991. Preservation of soft-tissues. In: Allison, P.A., Briggs, D.E.G. (Eds.), Taphonomy: releasing the data locked in the fossil record. Plenum Press, New York, pp. 26–71.

Allison, P.A., Briggs, D.E.G., 1993. Exceptional fossil record: distribution of soft tissue preservation rough the Phanerozoic. Geology 21, 605–608.

Allison, P.A., Brett, C.E., 1995. *In-situ* benthos and paleo-oxygenation within the Burgess Shale. Geology 26, 1079–1082.

Allison, P.A., Brett, C.E., Paul, C.R.C., Bilton, J., in press. Taphonomy of ammonite Konzentrat Lagerstätten in the early Blue Lias Formation of Dorset, UK. Journal of the Geological Society of London.

Aronson, R.B., 1992. Decline of the Burgess Shale fauna: ecologic or taphonomic restriction? Lethaia 25, 225–229.

Aronson, R.B., 1993. Burgess Shale-type biotas were not just burrowed away: reply. Lethaia 26, 185.

Babcock, L.E., Peng, S., Geyer, G., Shergold, J.H., 2005. Changing perspectives on Cambrian chonostratigraphy and progress towards subdivision of the Cambrian system. Geosciences Journal (Seoul) 9, 101–106.

Bergström, J., 1973. Organization, life, and systematics of trilobites. Fossils and Strata 2, 1–69.

Bond, G.C., Kominz, M.A., Grotzinger, J.P., 1988. Cambro-Ordovician eustasy: evidence from geophysical modeling of subsidence in Cordilleran and Appalachian passive margins. In: Kleispaahn, K.L., Paola, C. (Eds.), New Perspectives in Basin analysis. Springer Verlag, New York, pp. 129–160.

Bond, G.C., Kominz, M.A., Beavan, J., 1991. Evidence for orbital forcing of Middle Cambrian peritidal cycles: Wah Wah Range, south-central Utah. In: Franseen, E.K., Watney, W.I., Kendall, C.G. St.C., Ross, W. (Eds.), Sedimentology Modeling: Computer Simulations and Methods for Improved Parameter Definition. Kansas Geological Survey Bulletin, vol. 233, pp. 293–317.

Bowring, S.A., Erwin, D.H., 1998. A new look at evolutionary rates in deep time: uniting paleontology and high-precision geochronology. GSA Today 8, 1–8.

Brady, M.J., Koepnick, R.B., 1979. A Middle Cambrian platform-to-basin transition, House Range, west central Utah. Brigham Young University Geological Studies 26, 1–17.

Brett, C.E., 1995. Sequence stratigraphy, biostratigraphy, and taphonomy in shallow marine environments. Palaios 10, 597–616.

Brett, C.E., 1998. Sequence stratigraphy, paleoecology, and evolution: biotic clues and responses to sea-level fluctuations. Palaios 13, 241–262.

Brett, C.E., Algeo, T.J., McLaughlin, P.I., 2003. The use of event beds and sedimentary cycles in high-resolution stratigraphic correlation of lithologically repetitive successions: the Upper Ordovician Kope Formation of Northern Kentucky and Southern Ohio. In: Harries, P., Geary, D. (Eds.), High-Resolution Stratigraphic Approaches to Paleobiology. Kluwer Academic/Plenum Press, Boston, pp. 315–351.

Brett, C.E., Allison, P.A., Tsujita, C.J., Soldani, D., Moffat, H., 2006. Sedimentology, taphonomy, and paleoecology of meter-scale cycles from the Upper Ordovician of Ontario. Palaios 21, 530–547.

Brett, C.E., Kirchner, B.T., Tsujita, C.J., Dattilo, B.F., 2008. Depositional dynamics recorded in mixed siliciclastic-carbonate marine successions: Insights from the Upper Ordovician Kope Formation of Ohio and Kentucky, USA. In: Pratt, B.R., Holmden, C. (Eds.), Dynamics of Epeiric Seas. Geological Association of Canada, Special Paper, 48, 73–102.

Briggs, D.E.G., 2003. The role of decay and mineralization in the preservation of soft-bodied fossils. Annual Review of Earth and Planetary Sciences 31, 275–301.

Briggs, D.E.G., Robison, R.A., 1984. Exceptionally Preserved Non-trilobite Arthropods and *Anomalocaris* from the Middle Cambrian of Utah. University of Kansas Paleontological Contributions, no. 111. University of Kansas Paleontological Institute, Lawrence.

Briggs, D.E.G., Lieberman, B.S., Halgedahl, S.L., Jarrard, R.D., 2005. A new metazoan from the Middle Cambrian of Utah and the nature of the Vetulicolia. Palaeontology 48, 681–686.

Bright, R.C., 1959. A paleoecologic and biometric study of the Middle Cambrian trilobite *Elrathia kingi* (Meek) [Utah]. Journal of Paleontology 33, 83–98.

Butterfield, N.J., 1990. Organic preservation of non-mineralizing organisms and the taphonomy of the Burgess Shale. Paleobiology 16, 272–286.

Butterfield, N.J., 1995. Secular distribution of Burgess Shale-type preservation. Lethaia 28, 1–13.

Caron, J.B., Jackson, D.A., 2006. Taphonomy of the greater Phyllopod Bed community, Burgess Shale. Palaios 21, 451–465.

Coe, A.L. (Ed.), 2003. The Sedimentary Record of Sea-level Change. Cambridge University Press, Cambridge, UK. 288 pp.

Conway Morris, S., Robison, R.A., 1986. Middle Cambrian priapulids and other soft-bodied fossils from Utah and Spain. University of Kansas Paleontological Contributions. Paper 117, 1–22.

Conway Morris, S., Robison, R.A., 1988. More soft-bodied animals and algae from the Middle Cambrian of Utah and British Columbia. University of Kansas Paleontological Contributions. Paper 122, 1–48.

Crittenden Jr., M.D., Straczek, J.A., Roberts, R.J., 1961. Manganese deposits in the Drum Mountains, Millard and Millard County, Utah. United States Geological Survey Bulletin 1082-H, 493–544.

Dommer, M.L., 1980. The geology of the Drum Mountains, Millard and Millard Counties, Utah. Brigham Young University Geology Studies 27 (3), 55–72.

Droser, M.L., Bottjer, D.J., 1988. Trends in depth and extent of bioturbationin carbonate carbonate marine environments. Geology 16, 233–236.

Elrick, M., Snider, A.C., 2002. Deep-water stratigraphic cyclicity and carbonate mud mound development in the Middle Cambrian Marjum Formation, House Range, Utah, USA. Sedimentology 49, 1021–1047.

Gaines, R.R., Droser, M.I., 2003. Paleoecology of the familiar trilobite *Elrathia kingii*: an early exaerobic zone inhabitant. Geology 31, 941–944.

Gaines, R.R., Droser, M.L., 2005. New approaches to understanding the mechanics of Burgess Shale-type deposits: from the micron scale to the global picture. Sedimentary Record 3, 4–8.

Gaines, R.R., Kennedy, M.J., Droser, M.L., 2005. A new hypothesis for organic preservation of Burgess Shale taxa in the Middle Cambrian Wheeler Formation, House Range, Utah. Palaeogeography, Palaeoclimatology, Palaeoecology 220, 193–205.

Gradstein, F.M., Ogg, J.G., Smith, A.G., et al., 2004. A Geologic Time Scale 2004. Geological Survey of Canada Report 86, Ottawa, Ontario. 1 pp.

Grannis, J.L. 1982, Sedimentology of the Wheeler Formation, Drum Mountains, Utah. Unpublished MS Thesis, University of Kansas, Lawrence, Kansas.

Halgedahl, S., Jarard, R., Brett, C.E., Allison, P.A., 2009. Geophysical and geological signatures of relative sea level change in the upper Wheeler Formation, Drum Mountains, West-central Utah: a perspective into exceptional preservation of fossils. Palaeogeography, Palaeoclimatology, Palaeoecology 277, 34–56.

Hintze, L.F., Robison, R.A., 1975. Middle Cambrian stratigraphy of the House, Wah Wah, and adjacent ranges in western Utah. Geological Society of America 86, 881–891.

Hintze, L.F., Davis, F.D., 2002. Geologic map of Delta Quadrangle, Lynndyl Quadrangle, Millard, Millard, Sanpete, and Sevier Counties, Utah, UGS Map 184 Utah Geological Survey, Utah Department of Natural Resources.

Kepper, J.C., 1972. Paleoenvironmental patterns in the Middle to lower Upper Cambrian interval in eastern Great Basin. American Association of Petroleum Geologists Bulletin 58, 503–527.

Kepper, J.C., 1976. Stratigraphic relationships and depositional facies in a portion of the Middle Cambrian of the Basin and Range. Brigham Young University Geological Studies 23, 75–91.

Landing, E., 2007. Ediacaran–Ordovician of east Laurentia geologic setting and controls on deposition along the New York Promontory. In: Landing, E. (Ed.), Ediacaran–Ordovician of east Laurentia. S. W. Ford Memorial Volume. New York State Museum Bulletin, vol. 510, pp. 5–24. 93 pp., 30 figs.

Langenburg, E.S., 2003. The Middle Cambrian Wheeler Formation: sequence stratigraphy and geochemistry across a ramp-to-basin transition. Utah State University, Logan, Utah, unpub. M.S. thesis, (120 pp).

Markello, J.R., Read, J.F., 1981. Carbonate ramp-to-deeper shale shelf transitions of an Upper Cambrian intrashelf basin: Nolichucky Formation southwest Virginia Appalachians. Sedimentology 28, 573–597.

Montañez, L.P., Osleger, D.A., 1993. Parasequence stacking patterns, third order accommodation events and sequence stratigraphy of Middle to Upper Cambbrian platform carbonates, Bonanza King Formation, southern Great Basin. In: Loucks, B., Sarg, J.F. (Eds.), American Association of Petroleum Geologists Memoir, vol. 57, pp. 305–326.

Montañez, L.P., Banner, J.L., Osleger, D.A., Borg, L.E., Bosserman, P.J., 1996. Integrated Sr isotope stratigraphy and relative sea-level history in Middle Cambrian platform carbonates. Geology 24, 917–920.

Orr, P.J., Briggs, D.E.G., Kearns, S.L., 1998. Cambrian Burgess Shale animals replicated in clay minerals. Science 281, 1173–1175.

Orr, P.J., Benton, M.J., Briggs, D.E.G., 2003. Post-Cambrian closure of the deep-water slope-basin taphonomic window. Geology 31, 769–772.

Oschmann, W., 1991. Anaerobic-poikilaerobic-aerobic: a new facies zonation for modern and ancient redox facies. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Statigraphy. Springer-Verlag, Berlin, pp. 565–571.

Palmer, A.R., 1960. Some aspects of the Upper Cambrian stratigraphy of White Pine County, Nevada, and vicinity. Intermountain Association of Petroleum Geologists. Eleventh Annual Field Conference, pp. 53–58.

Palmer, A.R., 1971. The Cambrian of the Great basin and adjacent areas, western United States. In: Holland, C.H. (Ed.), Cambrian of the New World. Wiley Interscience, New York, pp. 1–78.

Petrovich, R., 2001. Mechanisms of fossilization of the soft-bodied and lightly armored faunas of the Burgess shale and of some other classical localities. American Journal of Science 301, 683–726.

Pickerill, R.K., 1994. Exceptional fossil record: distribution of soft-tissue preservation through the Phanerozoic: discussion. Geology 22, 183–184.

Powell, W.G., 2003. Greenschist-facies metamorphism of the Burgess Shale and its implications for models of fossil formation and preservation. Canadian Journal of Earth Sciences 40, 13–25.

Powell, W.G., Johnston, P.A., Collom, C.J., 2003. Geochemical evidence for oxygenated bottom waters during deposition of fossiliferous strata of the Burgess Shale Formation. Palaeogeography, Palaeoclimatology, Palaeoecology 201, 249–268.

Randolph, R.L., 1973. Paleontology of the Swasey Limestone, Drum Mountains, west-central Utah. Unpublished MS Thesis, University of Utah, Salt Lake City, 73 pp.

Rees, M., 1986. A fault-controlled trough through a carbonate platform: the Middle Cambrian House Range embayment. Geological Society of America Bulletin 97, 1057–1069.

Rees, M., Robison, R.A., 1989. Days 5 and 6: Cambrian stratigraphy and paleoecology of the central House Range and Drum Mountains, Utah. In: Taylor, M.E. (Ed.), Cambrian and Early Ordovician Stratigraphy and Paleontology of the Basin and Range Province. IGC Field Trip Guidebook T125. American Geophysical Union, Washington, DC, pp. 59–72.

Robison, R.A., 1964. Upper Middle Cambrian stratigraphy of western Utah. Geological Society of America Bulletin 75, 995–1010.

Robison, R.A., 1976. Middle Cambrian biostratigraphy of the Great Basin. Brigham Young University Studies in Geology 23, 93–109.

Robison, R.A., 1982. Some Middle Cambrian agnostoids from the from western North America. Journal of Paleontology 56, 132–160.

Robison, R.A., 1984a. New occurrences of the unusual trilobite *Naraoia* from the Cambrian of Idaho and Utah. University of Kansas Paleontological Contributions. Paper 112, 1–8.

Robison, R.A., 1984b. Cambrian Agnostida from North America and Greenland: Part 1. Ptychagnostidae. University of Kansas Paleontological Contributions 109, 1–59.

Robison, R.A., 1991. Middle Cambrian biotic diversity: examples from four Utah *Lagerstätten*. In: A.M. Simonetta, M., Conway Morris, S. (Eds.), The Early Evolution of Metazoa and the Significance of Problematic Taxa. Cambridge University Press, Cambridge, pp. 77–98.

Rogers, J.C., 1984. Depositional environments and paleoecology of two quarry sites in the Middle Cambrian Marjum and Wheeler Formations, House Range, Utah. Brigham Young University Geology Studies 31, 97–115.

Savrda, C.E., Bottjer, D.J., 1987. The exarobic zone, a new oxygen-deficient marine biofacies. Nature 327, 54–56.

Schneider, L.P., 2000. The sequence stratigraphy of the Middle Cambrian Wheeler Formation in the Drum Mountains of west central Utah. Utah State University, Logan, Utah, unpub. M.S. thesis, 82 pp.

Scotese, C.R., 1997. PALEOMAP Paleogeographic Atlas. PALEOMAP Progress Report 20. Department of Geology, University of Texas, Arlington.

Seilacher, A., 2001. Concretion morphologies reflecting diagenetic and epigenetic pathways. Sedimentary Geology 243, 41–57.

Seilacher, A., Reif, W.E., Westphal, F., 1986. Sedimentological, ecological and temporal patterns of fossil Lagerstätten. Philosophical Transactions of the Royal Society of London B311, 5–23.

Sepkoski Jr., J.J., Bambach, R.K., Droser, M.L., 1991. Secular changes in Phanerozoic event bedding and the biological overprint. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Statigraphy. Springer-Verlag, Berlin, pp. 298–312.

Sundberg, F.A., 1994. Corynexochida and Ptychopariida (Trilobita, Arthropoda) of the *Ehmaniella* Biozone, Middle Cambrian), Utah and Nevada. Natural History Museum of Los Angeles County, Contributions in Science 446, 1–137.

Vorwald, 1983. Paleontology and paleoecology of the upper Wheeler Formation (late Middle Cambrian), Drum Mountains, west-central Utah. Unpublished MS Thesis, University of Kansas, 117 pp.

Walcott, C.D., 1908. Cambrian geology and paleontology, pt.1. Nomenclature for some Cambrian Cordilleran formations. Smithsonian Miscellaneous Collections 53, 1–12.

Westfield, I.T., Liddell, W.D., Brett, C.E., 2005. Cambrian microbial communities along a bathymetric gradient. Geological Society of America Abstracts with Programs 37 (7), 340.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., Pérèz-Cruz, C., 1991. The stratigraphic signatures of tectonics, eustasy and sedimentation: an overview. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Stratigraphy. Springer, New York, pp. 617–659.

Van Wagoner, J.C., Mitchum, K., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops. American Association of Petroleum Geologists Methods in Exploration Series, No. 7, Tulsa. 55 pp.

Young, G.C., Laurie, R.R., 1996. An Australian Phanerozoic Timescale. Oxford University Press, Melbourne, Australia.