Paleoecology of the Middle Jurassic Carmel Formation, Utah

by

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Cover Photo:
https://commons.wikimedia.org/wiki/File:CarmelGunlock2.jpg
The Carmel Formation near Gunlock, Utah. Photo taken by Mark Wilson.

ABSTRACT

The shallow marine fossil fauna of the Middle Jurassic Carmel Formation is unusually low diversity compared to other Middle Jurassic faunas. The cause of this low diversity is not fully established, but may be a combination of stressed environmental conditions, geographic isolation, and selection for generalist species. The Carmel Formation is located in southern and eastern Utah and was deposited in the southernmost tip of a shallow epicontinental seaway, which connected to the ocean through a single high-latitude entrance in the north. Carmel deposits in southwest Utah were deposited in subtidal to supratidal facies along the coastline of the seaway and are fossiliferous, especially in more offshore facies. The paleoclimate of the region was hot and arid, producing evaporite-dominated and hypersaline conditions onshore.

Bivalve fossils predominate throughout the seaway and in the Carmel Formation, and the majority of bivalve fossils belong to only a handful of species, especially the encrusting oyster *Liostrea strigilecula*. Gastropod, crinoid, and trace fossils show similar trends to low diversity, but bryozoan fossils and cryptic encrusting communities do not. Paleoecologically unusual assemblages like free-rolling oyster accumulations and abnormally young crinoidal limestones also occur in the seaway, possible related to the same restricted conditions.

Despite its unique paleoecological features, the Carmel Formation is still not thoroughly studied. The effects of taphonomy and sampling intensity on observed diversity have not been reported in detail, and only initial in-depth descriptions have been published on the unusual fossil assemblages of the Carmel.

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INTRODUCTION

The Middle Jurassic Carmel Formation of Utah is a mixed carbonate, siliciclastic, and evaporite formation deposited in a shallow inland sea (Imlay 1980). Previous work on the fossils of the Carmel has found unusually low diversity when compared to other Middle Jurassic deposits, especially the well-studied Middle Jurassic of Europe (e.g. Imlay 1964, Sohl 1965, Tang 1996, de Gibert and Ekdale 1999). This low diversity extends from the dominance of a handful of bivalve species throughout the formation to low beta diversity between sites and abnormally low species richness within many invertebrate groups. Geographic barriers to colonization, selection for generalist species, and stressed paleoenvironmental conditions have all been suggested as possible causes of low diversity (Tang and Bottjer 1996, de Gibert and Ekdale 2002).

The Carmel Formation also contains paleoecologically unusual fossil assemblages. Ostreoliths, free-rolling spheroidal accumulations of colonial oysters, have only been found in the Carmel, the laterally equivalent Twin Creek Limestone (Wilson et al. 1998), and the Upper Jurassic of Poland (Zaton and Machalski 2013). An encrinite, or crinoidal limestone, is found in the Carmel Formation and is among the youngest in the geologic record (Tang et al. 2000).

Despite this, the Carmel Formation is still not well studied, and little paleoecological work in the formation has been published since 2000. No new research has been published on the unusual fossil assemblages of the Carmel since their respective detailed descriptions by Wilson et al. (1998) and Tang et al. (2000). However, research outside the Carmel Formation continues to build on studies from the Carmel. Ostreoliths, first described as unique to the Carmel, have since been discovered in the Upper Jurassic of Poland (Zaton and Machalski 2013). The work of Tang et al. (2000) on the encrinite found in the Carmel was included in a review of Middle Jurassic encrinites in North America as compared to those of Europe (Hunter and Zonneveld 2008). Recent work in the Sundance Formation, deposited in the same seaway as the Carmel, has revisited quantitative paleoecology in the Carmel from the 1990s (Tang 1996, Tang and Bottjer 1996, Tang and Bottjer 1997) using modern techniques like cluster analysis and nonmetric multidimensional scaling (Danise and Holland 2017). New work in the Carmel Formation will both aid and benefit from these studies in putting the paleoecology of the Carmel in its global context.

PALEOGEOGRAPHIC SETTING

In the Middle Jurassic, a shallow inland sea intermittently covered what is now the western interior region of the United States and Canada (Imlay 1980). The seaway formed in a retro-arc foreland basin associated with subduction along the Pacific coast of North America and was bounded on the west by the Cordilleran volcanic arc (Nielson 1990, Danise and Holland 2017). The seaway connected to the Pacific Ocean through a single entrance in the north (Fig. 1). Rapid transgressions and regressions of the seaway across large areas throughout the Middle Jurassic indicate that the seaway was shallow and the basin floor relatively level, so slight changes in relative or eustatic sea level produced large changes in area (Imlay 1980).

The Carmel Formation of southern and eastern Utah was deposited in the distal southern end of the seaway (Imlay 1980). In southwest Utah, the Carmel was deposited along the coastline of the seaway and shows several higher-order transgressions and regressions between subtidal to supratidal facies (Taylor 1981, Nielson 1990). At the time the Carmel was deposited, this region was about 20°N paleolatitude (Nielson 1990). The climate was arid and dry, and ergs were present near the shore of the seaway. The seaway deepened to the northwest in the region (Fig. 2; Imlay 1964).

Sequence Stratigraphic Interpretations

Tang (1996) describes six depositional sequences across the Jurassic inland seaway (Fig. 3). The sequences are bounded by the regional unconformities J1, J2, an unnamed unconformity best developed in the southern end of the seaway, J3, J4, and J5. Tang (1996) refers to these sequences as numbered units.

More recently, Danise and Holland (2017) recognize eight depositional sequences in a portion of the seaway, the Sundance Formation of Wyoming. They recognize two additional regional unconformities (J1a and J1b) between J1 and J2, dividing Unit 1 of Tang (1996) into three sequences. They also recognize an unconformity J2a between J2 and J3, but it is unclear if this corresponds to the unnamed unconformity of Tang (1996). Danise and Holland (2017) refer to these sequences by their underlying unconformity.

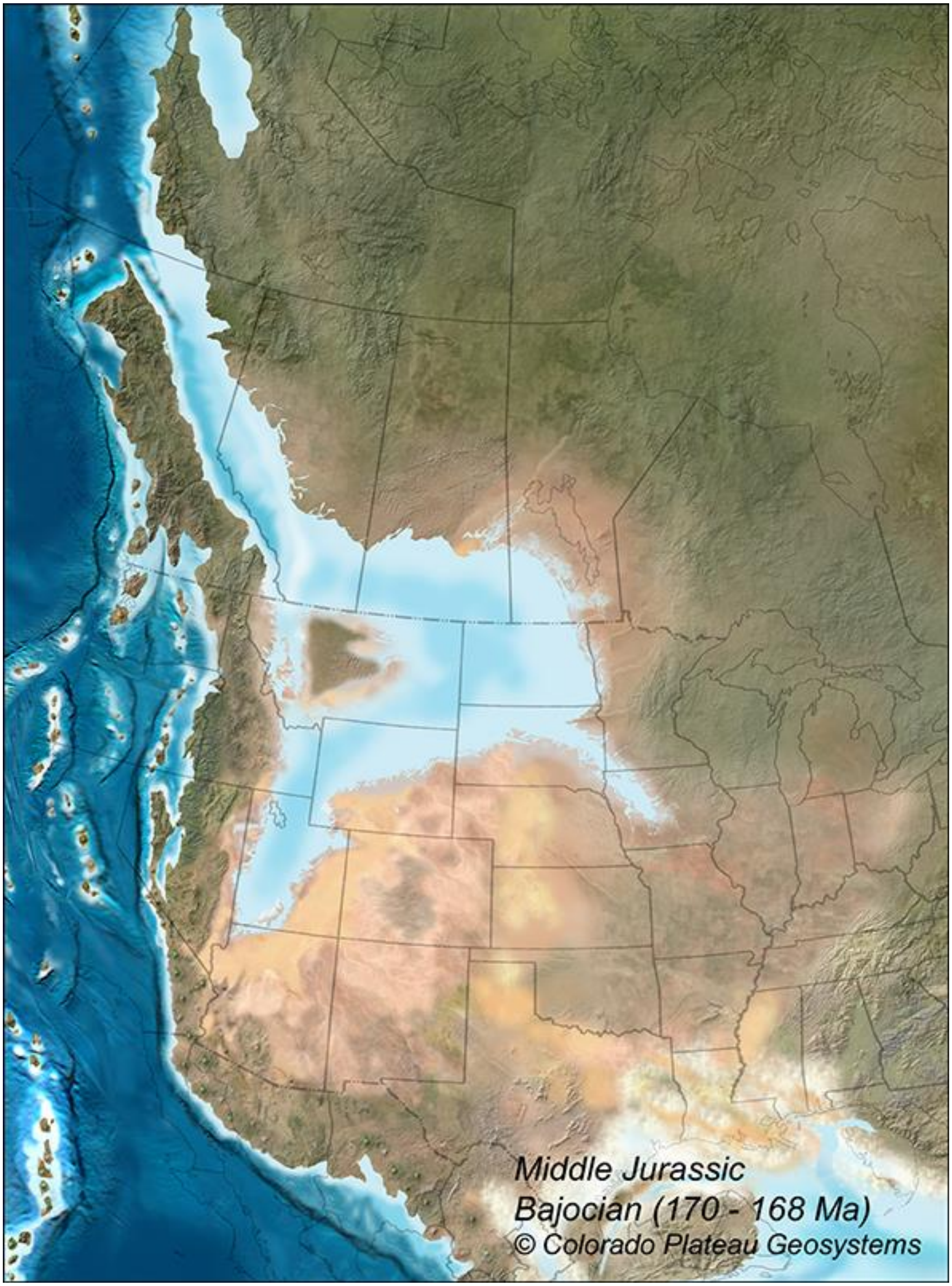

Figure 1. Bajocian geography of the western United States, showing the shallow epicontinental seaway and its isolation from the open ocean (Ron Blakey, http://deep timemaps.com/wp-content/uploads/2016/05/wismidjur.png; accessed 30 April 2018).

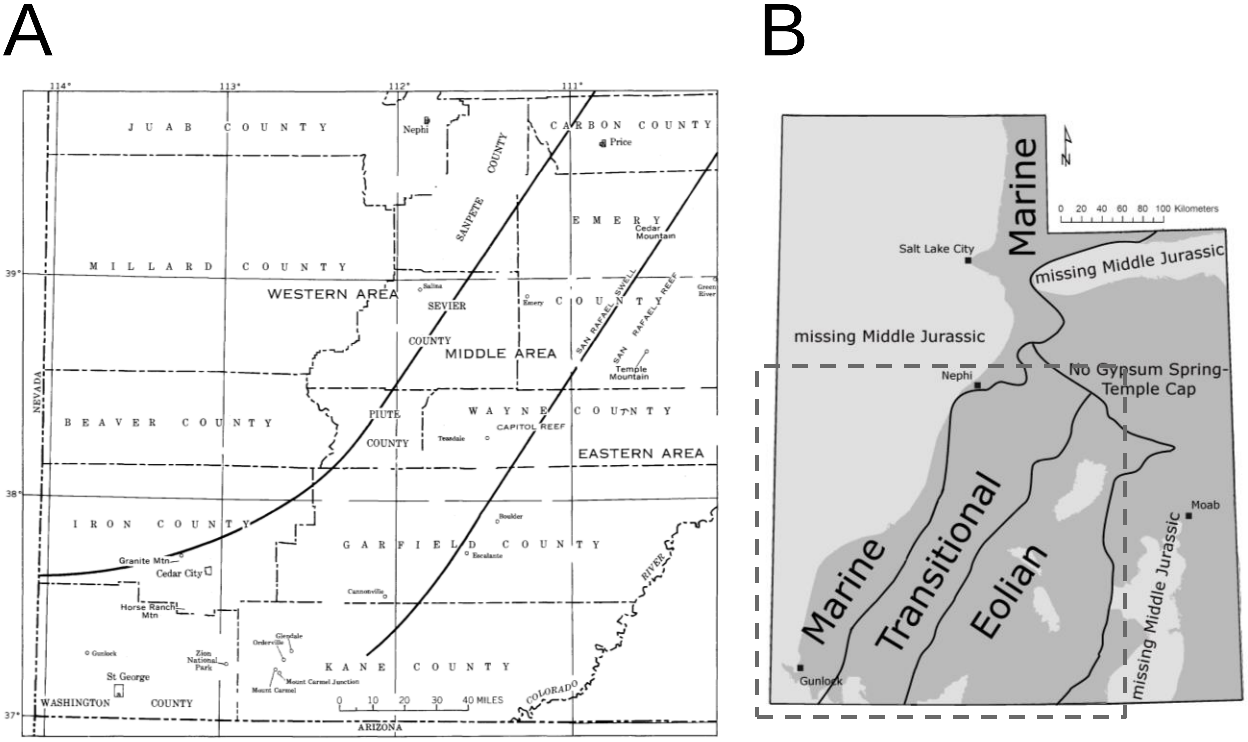

Figure 2. A: Paleodepth areas of Imlay (1964) in southwest Utah, with the "eastern area" representing the shallowest facies and the "eastern area" the deepest facies. The "middle area" has the greatest diversity and abundance of fossils. (Modified from Imlay 1964, Fig. 1). B: Generalized facies distribution in Utah, based on the Temple Cap and Gypsum Spring Formations. The seaway did not extend as far south and east during this time, but the deepening-northwest trend is the same. (Modified from Sprinkel et al. 2011, Fig. 10).

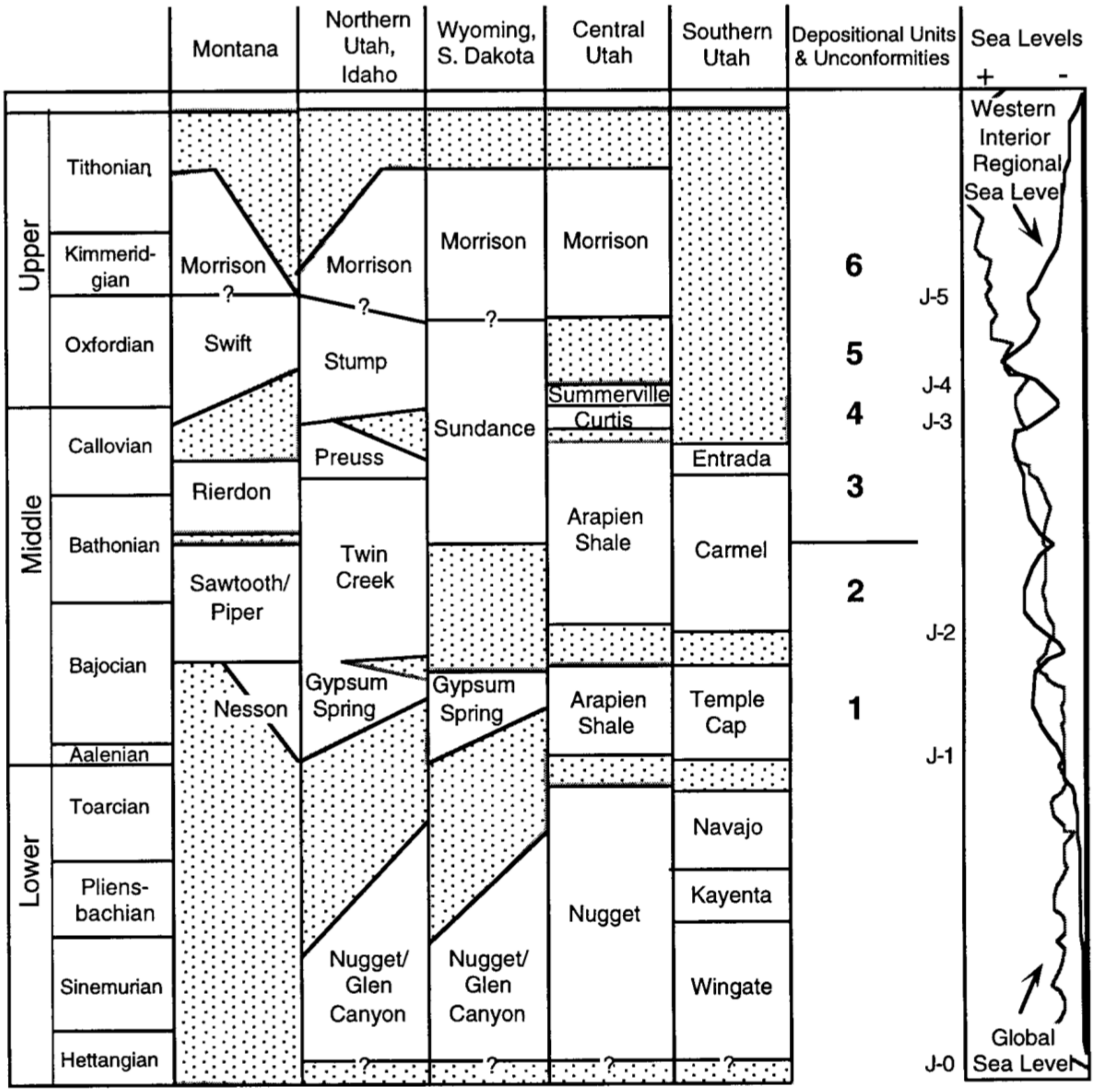

Figure 3. Jurassic formations of the US Western Interior in the sequence stratigraphic model of Tang (1996). Depositional sequences (Units 1 through 6) are defined by unconformities J1 through J5 and an additional unnamed unconformity between Units 2 and 3. Unit 1 represents the initial transgression of the Jurassic seaway. Stage assignments approximate. (Tang 1996, Fig. 2-3)

STRATIGRAPHY

The Carmel Formation is exposed in southern and eastern Utah and in areas of central Utah. It is laterally equivalent to the Arapien Formation to the west and the Twin Creek Limestone to the north (Fig. 4; Sprinkel et al. 2011). Most of the Carmel Formation overlies the Temple Cap Formation. This contact is locally unconformable and separated by the J2 unconformity. Where the Temple Cap Formation is missing, the Carmel instead unconformably overlies the Navajo Sandstone (Doelling et al. 2013). The Carmel is conformably overlain by the eolian Entrada

Sandstone except in southwest Utah, where it is unconformably overlain by Cretaceous conglomerates (Sprinkel et al. 2011).

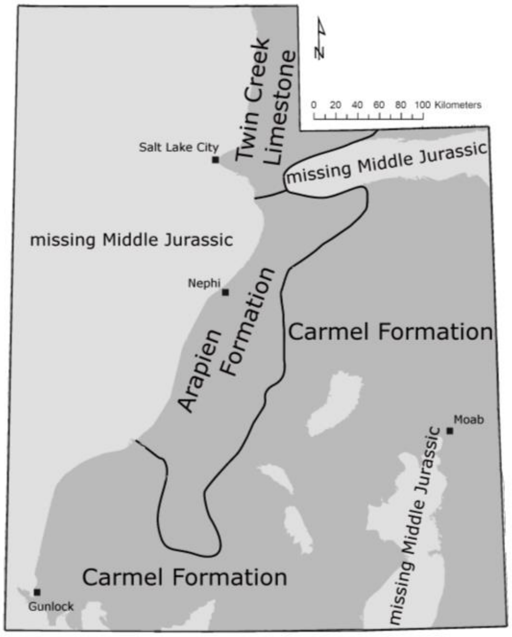

Figure 4. Geographic distribution of Middle Jurassic formations in Utah (based on the upper member of each formation). Modified from Sprinkel et al. (2011, Fig. 14).

The Carmel Formation is subdivided, from bottom to top, into the Co-op Creek, Crystal Creek, Paria River, and Windsor Members (Fig. 5; Sprinkel et al. 2011). The Co-op Creek Member is predominately limestone, ranging from carbonate mudstone to grainstone, and fossiliferous. The Co-op Creek Member thins to the east, eventually transitioning into the equivalent sandstone Judd Hollow Member (Doelling et al. 2013). The Crystal Creek Member is predominantly siltstone to medium-grained sandstone. The Paria River Member is also predominantly limestone, but often contains a thick bed of gypsum at the base. Like the Co-op Creek Member, the Paria River Member thins and transitions into sandstone to the southeast. The Windsor Member is divided into two subunits, a lower subunit containing thick gypsum beds and an upper subunit consisting of repeated cycles of thinner mudstone, siltstone, and gypsum beds (Sprinkel et al. 2011).

The Carmel Formation records two major transgressive-regressive cycles, with the Co-op Creek and Crystal Creek Members representing the first transgression and regression, respectively, and the Paria River and Winsor Members the second (Doelling et al. 2013). The Co-op Creek and Crystal Creek Members belong to Unit 2 in the sequence stratigraphic framework of Tang (1996), and the Paria River and Windsor Members belong to Unit 3 (Tang 1996).

According to Sprinkel et al. (2011), the Carmel Formation was deposited from approximately 169 Ma until approximately 162 Ma, based on radiometric dating of volcanic ash deposits and correlation of fossil dinoflagellate cysts and pollen (Fig. 5). These dates span the Bajocian, Bathonian, and Callovian ages of the Middle Jurassic. The Co-op Creek Member, where most published paleontological work has been conducted, was deposited from approximately 169 Ma until approximately 167 Ma, making it Bajocian to earliest Bathonian in age (Sprinkel et al. 2011).

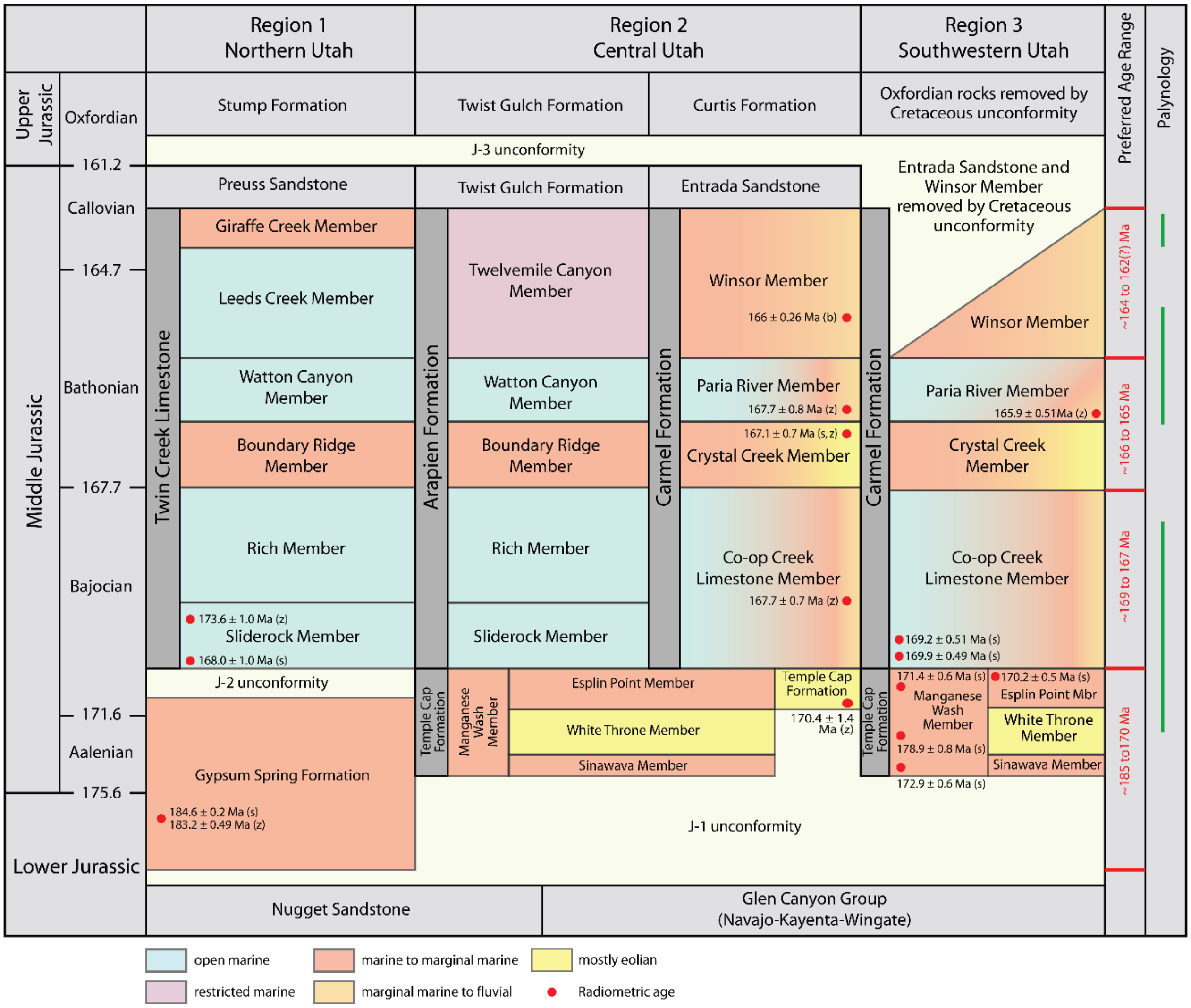

Figure 5. Depositional facies and absolute dates of the members of the Carmel and laterally equivalent formations in Utah (Sprinkel et al. 2011, Fig. 4).

STUDY AREA

Outcrops of the Carmel Formation in southwest Utah have been the focus of much previous paleontological and stratigraphic work and will be the focus of this study. Within southwest Utah, two regions have been consistently distinguished by previous authors (Fig. 6). One region is the area around the town of Gunlock, Utah, north of St. George (Nielson 1990). The other region is the area around Mount Carmel Junction and the town of Mount Carmel, Utah, the type locality of the Carmel Formation (Taylor 1981). In both regions, the Carmel was deposited along the gently sloping, shallow coastline of the seaway (Nielson 1990, Taylor 1981).

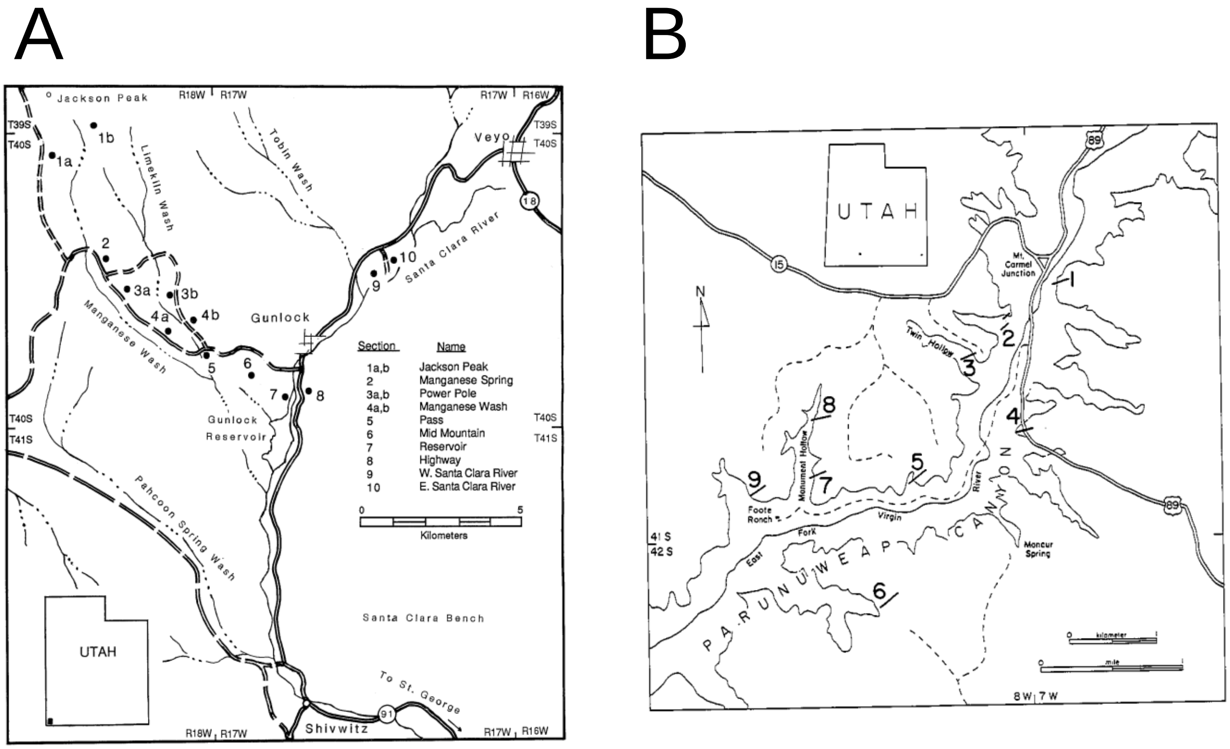

Figure 6. A: Map of the Gunlock region and its location in Utah (Nielson 1990, Fig. 1). B: Map of the Mount Carmel Junction region and its location in Utah (Taylor 1981, Fig. 1). The numbered localities on each map were used to construct the respective composite stratigraphies discussed below.

Gunlock

In the Gunlock area, Nielson (1990) divided the Carmel Formation into six informal members, A through F from bottom to top (Fig. 7). Members A through D are subdivisions of the Co-op Creek Member, Member E corresponds to the Crystal Creek Member, and Member F probably corresponds to the Paria Creek Member. Member F is overlain unconformably by Cretaceous conglomerates.

Member A consists of moderate yellow, dolomitic, carbonate mudstone grading upward into yellowish-grey, cross-bedded, oolitic packstone (Nielson 1990). The upper surface of member A is silicified, probably by silica from the volcanic ash bed at the base of member B. Member B consists of a pale green volcanic ash bed at the base, followed by moderate reddish brown siltstone to mudstone, followed by another volcanic ash bed. The ash beds contain black biotite crystals, generally lying parallel to bedding. No fossils have been found in member B.

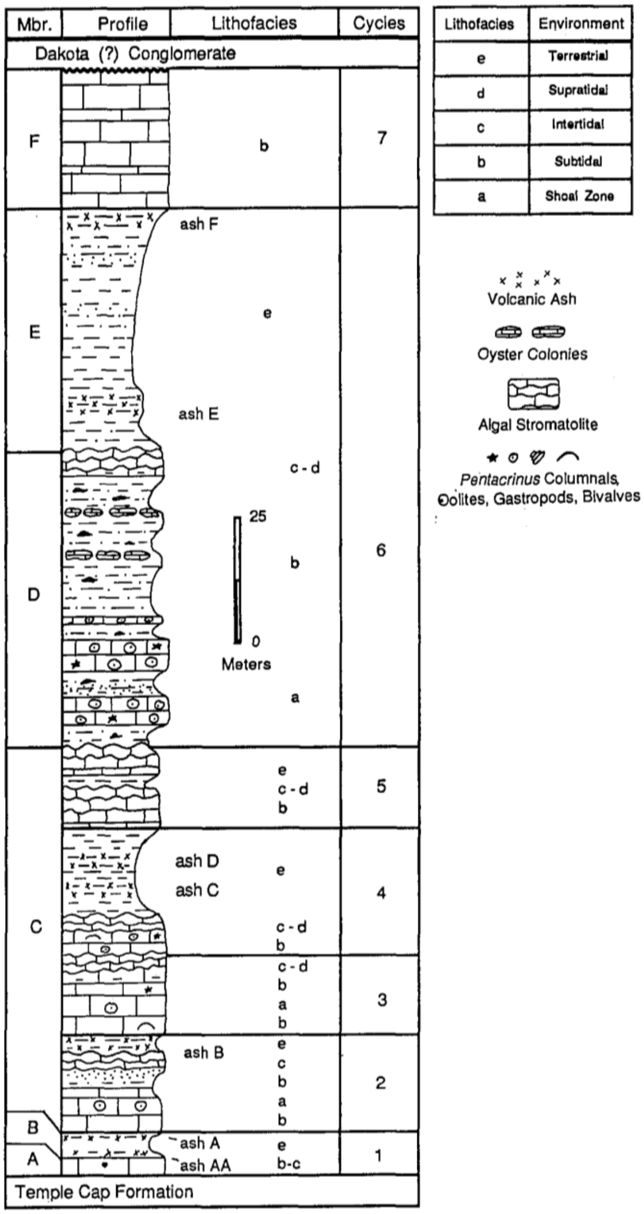

Figure 7. Composite stratigraphic column for the Carmel Formation in the Gunlock region, showing weathering profile, lithofacies, and interpreted depositional environment. Six shallowing upwards cycles are present in this region. (Modified from Nielson 1990, Figs. 33, 34, 35).

Member C consists of four repeating shallowing-upward cycles (Nielson 1990). An idealized cycle proceeds from dark yellowish-orange, oolitic packstones and yellowish-grey grainstones into carbonate mudstones and wackestones, then into yellowish-grey algal stromatolites, and finally pale yellowish-orange to light olive-grey clayey quartz siltstone. The carbonate mudstones and wackestones account for 60% of member C and are cut by channels filled by light yellowish-grey packstone with intraclasts consisting of carbonate mudstone. Member C contains three volcanic ash beds, which are similar to the beds in member B.

Member D consists of a single shallowing-upward sequence analogous to those in Member C (Nielson 1990). In the lower portion of member D, pale yellowish-orange, ooid-rich, muddy quartz siltstone is interbedded with similarly colored quartz sand-rich, oolitic grainstone. Thin beds of fossiliferous, oolitic grainstone also occur within the siltstone. Trace fossils are common. The upper portion of member D consists of light olive gray mudstone, grading into yellowish-gray, argillaceous, carbonate mudstone at the top of the member. The mudstones and carbonate mudstones contain horizons of pale orange, intraclastic, fossiliferous packstone, some of which formed synsedimentarily lithified hardgrounds.

Member E consists predominantly of dusky red quartz siltstone and mudstone with calcite cement (Nielson 1990). Member E contains two volcanic ash beds, which are similar to those in members B and C. No fossils have been found in member E. Member F consists of carbonate mudstone similar to that in member C. The upper half of member F is fractured and altered, producing a mottled reddish pink color. Faulting and erosion have removed members E and F from much of the region.

Mount Carmel Junction

All four members of the Carmel Formation are present at Mount Carmel Junction (Imlay 1980). Taylor (1981) subdivides the Co-op Creek Member at Mount Carmel Junction into lithofacies A through F from bottom to top, referred to here as I through VI (Fig. 8) to avoid confusion with the unrelated members A through F of Nielson (1990) in the Gunlock region. Apart from possible stromatolites in lithofacies II, only lithofacies III and VI are fossiliferous (Taylor 1981).

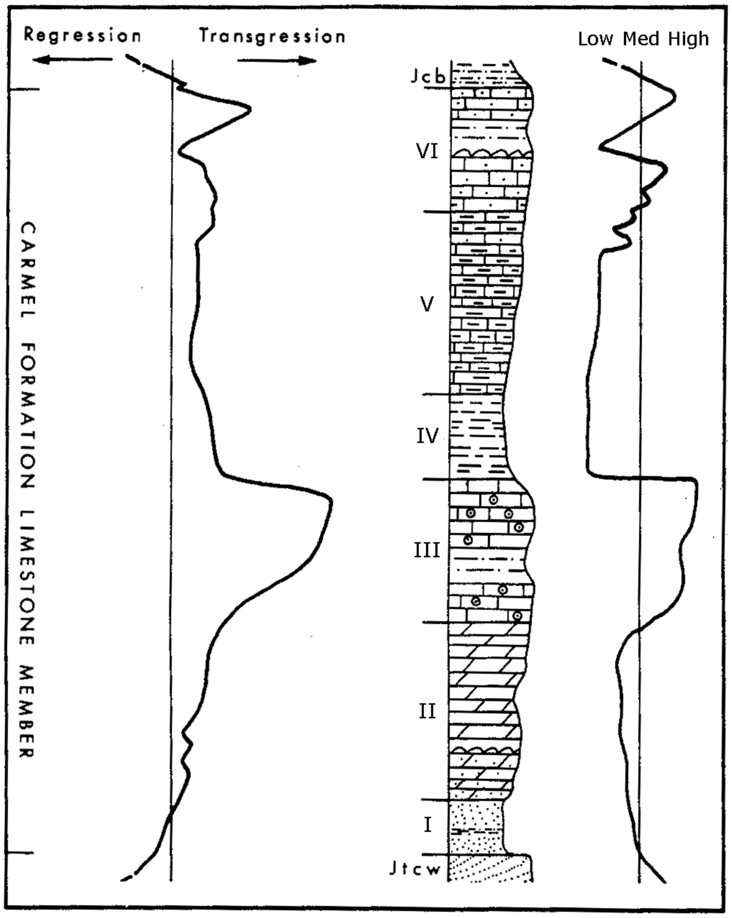

Figure 8. Composite stratigraphic column for the Co-op Creek Member of the Carmel Formation in the Mount Carmel region, showing weathering profile, transgressions and regressions (left), and depositional energy facies (right) (Modified from Taylor 1981, Fig. 30).

Lithofacies I consists predominantly of greenish grey and pale red sandstones (Taylor 1981). Euhedral, unaltered biotite crystals occur in one bed at some sites, possibly representing an ashfall deposit. Lithofacies II consists of grayish pink siltstone grading upwards into silty, dolomitic carbonate mudstone. Taylor (1981) reports stromatolites in lithofacies II, but Tang and Bottjer (1997) express doubt about this identification. Nodules and lenses of anhydrite are found near the top of the lithofacies. Lithofacies III consists of lower yellowish-gray packstone and grainstone with ooilitic and bioclastic grains and an upper light olive-grey wackestone containing recrystallized mollusc bioclasts. The wackestone is interpreted as highly bioturbated. Lithofacies IV consists of grayish green to purplish red shale. Lithofacies V consists of olive-grey, argillaceous carbonate mudstone.

The top of lithofacies V interfingers with and transitions into lithofacies VI, which consists of yellowish-grey, peloidal grainstone with a matrix of recrystallized carbonate mudstone, separated into two portions by a layer of siltstone. Bivalve coquinas occur in the upper portion. According to Taylor (1981), lithofacies VI also contains stromatolites. Taylor (1981) reports gastropod fossils from lithofacies VI at one site, the only gastropods found in his study. The top of lithofacies VI is ripple-marked, showing paleocurrents flowing broadly from north to south. Lithofacies VI is overlain by red beds of the Crystal Creek Member of the Carmel.

Paleoenvironment

The Gunlock and Mount Carmel regions of the Carmel Formation represent the southernmost coastline of the inland seaway (Fig. 9; Nielson 1990, Taylor 1981). The seaway was shallow, and the slope of the seafloor was very low (Nielson 1990). The region was tropical, and the paleoclimate was hot and arid.

Conditions in the supratidal and intertidal zones were evaporite-dominated and inhospitable (Nielson 1990, Taylor 1981). Evaporitic gypsum, anhydrite, chalcedony, halite (preserved as casts), and calcite were deposited in the supratidal sabkha. There is no evidence of anything living in the supratidal zone (Nielson 1990).

Tidal flats were hypersaline, but salinity was low enough to permit the growth of algae (Nielson 1990, Taylor 1981). Stromatolites were deposited in this facies, but some of the structures described as stromatolites may be the result of non-algal tidal flat deposition (Tang 1996). There are no other fossils, and algae were probably the only organisms living intertidally (Nielson 1990, Taylor 1981). Tides moved in and out through channels cut into the tidal flats, which have been filled by deposits of intraclastic packstone (Nielson 1990). The intraclasts in the packstone are probably derived from the supratidal sabkha.

Seaward of the tidal flats, restricted and low-energy lagoons formed in the lee of ooid shoals offshore (Nielson 1990, Taylor 1981). Poor water circulation in the lagoons may have produced hypersaline, hypoxic, high-temperature, or low-nutrient conditions (Nielson 1990). In addition to low-energy carbonate mudstones, storm beds of oolitic wackestone and packstone were deposited in lagoonal facies in the Gunlock area (Nielson 1990). Synsedimentarily lithified carbonate hardgrounds formed in these lagoons, including an extensive one in the Gunlock area discussed in detail below (Wilson and Palmer 1994).

Ooid shoals represent a moderate- to high-energy environment, and deposit cross-bedded oolitic packstones and grainstones. The ooid shoal deposits in the Gunlock area are unusually thin, indicating that the seaway was still very shallow in the shoal zone, possibly less than five meters deep (Nielson 1990). While ooid shoal deposits in the Carmel are fossiliferous, there is no evidence of animals living in situ in or on them (Nielson 1990). This is consistent with observations of modern ooid shoal systems. The presence of echinoderm bioclasts in the shoals indicates normal marine conditions (Taylor 1981).

Seaward and landward of the ooid shoals, tides and storms washed ooids into lower-energy, muddy sediment (Nielson 1990, Taylor 1981). The rocks of this facies contain the most trace fossils as well as abundant body fossils. This is also consistent with observations of modern ooid shoal systems (Nielson 1990).

During regressions of the seaway, deposition changed from predominantly carbonate to predominantly siliciclastic (Nielson 1990, Taylor 1981). Fine siltstones and mudstones were deposited in protected lagoons, followed by prograding mudstone, siltstone, and sandstone red beds. The red color of these beds is produced by oxidized iron, indicating deposition in oxidizing, subaerial conditions (Nielson 1990).

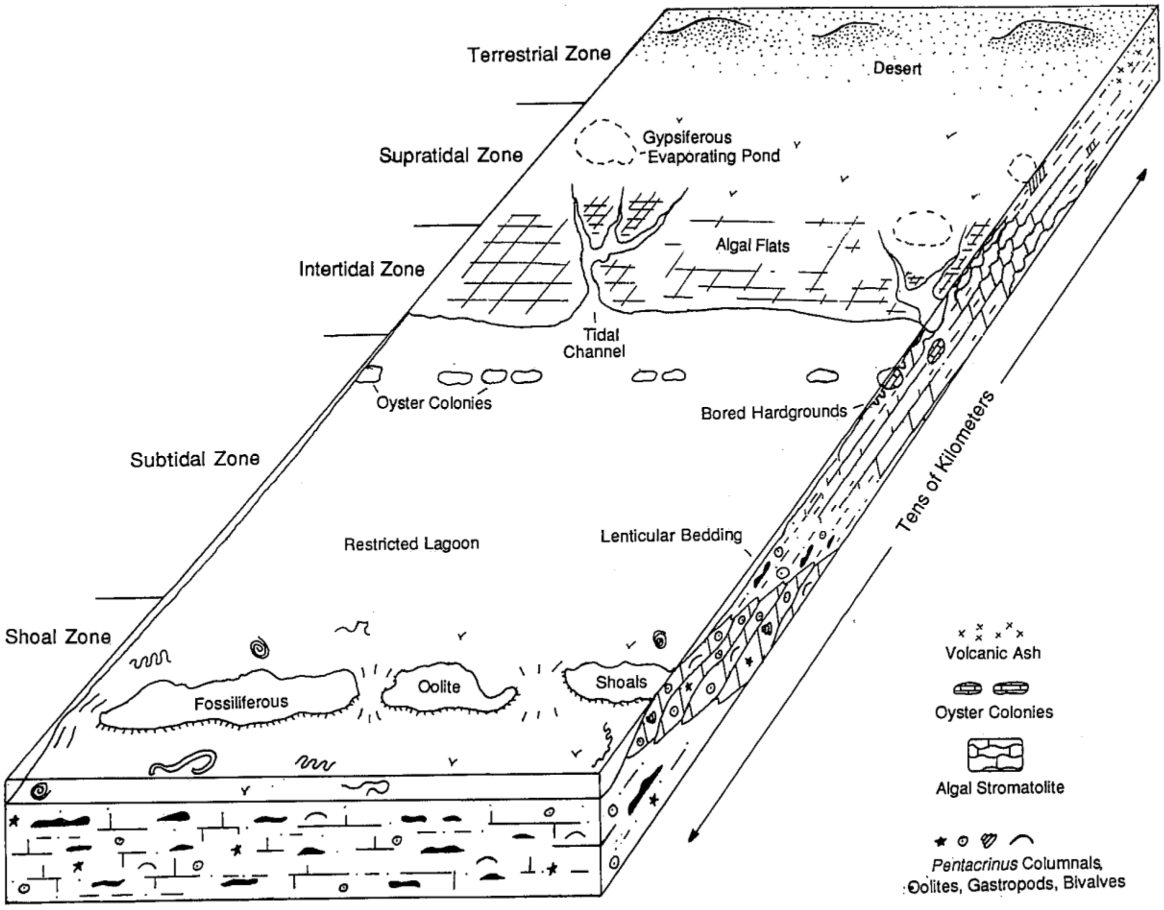

Figure 9. Depositional environments along the arid, gently sloping, shallow shoreline of the Jurassic inland seaway in what is now southwest Utah. (Nielson 1990, Fig. 33).

PALEONTOLOGY

Bivalves

Bivalves dominate fossil assemblages in deposits of the Jurassic seaway throughout the western United States; collections in the Carmel Formation (Imlay 1964, Tang 1996) and in the Sundance Formation (Danise and Holland 2017, Tang 1996) consist of more than 80 percent bivalves, and over 90 percent of individual fossil assemblages are bivalve-dominated (Tang 1996). In situ deposition and the preservation of molds of aragonitic shells at several sites suggests that this dominance is not just an artifact of taphonomic bias (Tang 1996).

Despite this, the bivalve fossil fauna of the Jurassic seaway is not high diversity. The number of species and genera is low (Tang 1996), and the fauna is dominated by only a handful of species that are both abundant and widespread (Imlay 1964). Individual fossil assemblages are also often dominated by only one or two of these bivalve species, which usually comprise over 80 percent of the assemblage (Tang 1996). Ecological diversity is also low, with assemblages numerically dominated by sessile benthic epifaunal filter feeders and low degrees of epifaunal and infaunal tiering. Differences between assemblages in the seaway are low (Tang 1996), and the bivalve species found in the Carmel are found throughout the seaway (Imlay 1964). Within the Carmel, Imlay (1964) describes a geographic pattern of distribution where bivalve fossil abundance and richness is greatest in a NE trending “middle area” of the Carmel representing intermediate water depths, and lower in shallower and deeper water facies to the east and west, respectively (Fig. 2).

The small oyster *Liostrea* was the most common genus in the seaway throughout its history (Tang 1996). *Liostrea* encrusted carbonate hardgrounds and the shells of other bivalves, cementing to the substrate with its left valve (Fig. 10; Wilson et al. 1998). The right valves are usually found separated and loose. Successive generations of *Liostrea* juveniles encrusted older *Liostrea* shells, building up thick rinds and free-rolling accumulations called ostreoliths.

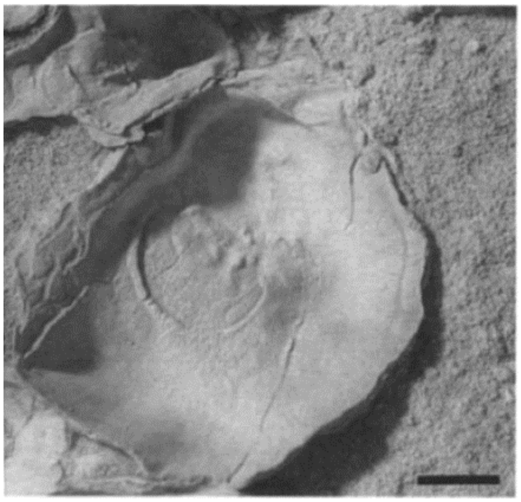

Figure 10. Left valve of *Liostrea strigilecula* encrusting a carbonate hardground from Member D of the Carmel Formation near Gunlock, Utah. Scale bar is 0.5 cm. (Modified from Wilson et al. 1998, Fig. 4A).

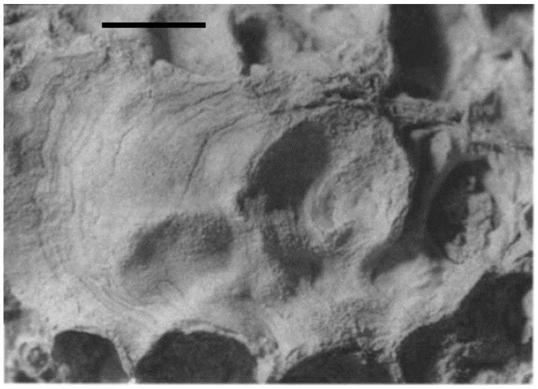

Figure 11. *Plicatula* sp. on the surface of a free-rolling *Liostrea* accumulation (an ostreolith). Scale bar is 0.5 cm. (Modified from Wilson et al. 1998, Fig. 4B).

Lima occidentalis, and *Camptonectes stygius* were the other dominant bivalve species in the Carmel Formation (Tang 1996). In four samples from Mount Carmel Junction, these species, together with *Liostrea*, comprise 86 to 96 percent of fossil elements.

In addition to the dominant bivalve species, an unidentified, very xenomorphic *Plicatula* species (Fig. 11) is found encrusting hardgrounds and *Liostrea* shells (Wilson and Palmer 1994). The mussel *Modiolus subimbricatus* also occurs in hardgrounds and *Liostrea* accumulations, occupying empty borings (*Gastrochaenolites*) or nestled between *Liostrea* valves. The bivalves *Isognomon* and *Astarte* are found preserved as bioimmurations as the nuclei of some ostreoliths (Wilson et al. 1998).

The predominance of bivalves over other taxa, the relatively homogenous distribution of bivalve species, and the dominance of only a few species within bivalve assemblages indicates a generalist fauna with little niche specialization and simple ecosystems (Tang 1996). This may be due to environmental stresses like salinity or low productivity (de Gibert and Ekdale 2002), frequent but small-scale environmental disturbance, or the barrier to colonization of the inland sea posed by its high latitude entrance and large north-south extent (Tang and Bottjer 1997).

Ostreoliths

Unusual spheroidal accumulations of *Liostrea strigilecula* shells (Fig. 12) are found in two horizons of Member D of the Carmel Formation near Gunlock, Utah (Wilson et al. 1998). They are formed by generations of *Liostrea* colonizing and building on the shells of previous individuals. This accumulation of *Liostrea* is also found on carbonate hardgrounds in the Carmel Formation (Wilson and Palmer 1994), but in the ostreoliths, *Liostrea* shells grow radially and relatively evenly from the nucleus (Fig. 13), indicating that the accumulation was free to rotate and expose new upwards surfaces (Wilson et al. 1998). The morphology of *Liostrea* shells in ostreoliths is more cup shaped than that of isolated *Liostrea* shells on hardgrounds (Fig. 12). When growing *Liostrea* shells encountered an obstacle on the substrate, they could change their growth direction to curve upwards, producing this cup shape. This capability is not universal in bivalves, and may have allowed *Liostrea* to form ostreoliths, by allowing individuals to pack tightly on the growing ostreolith and grow rapidly out from the nucleus.

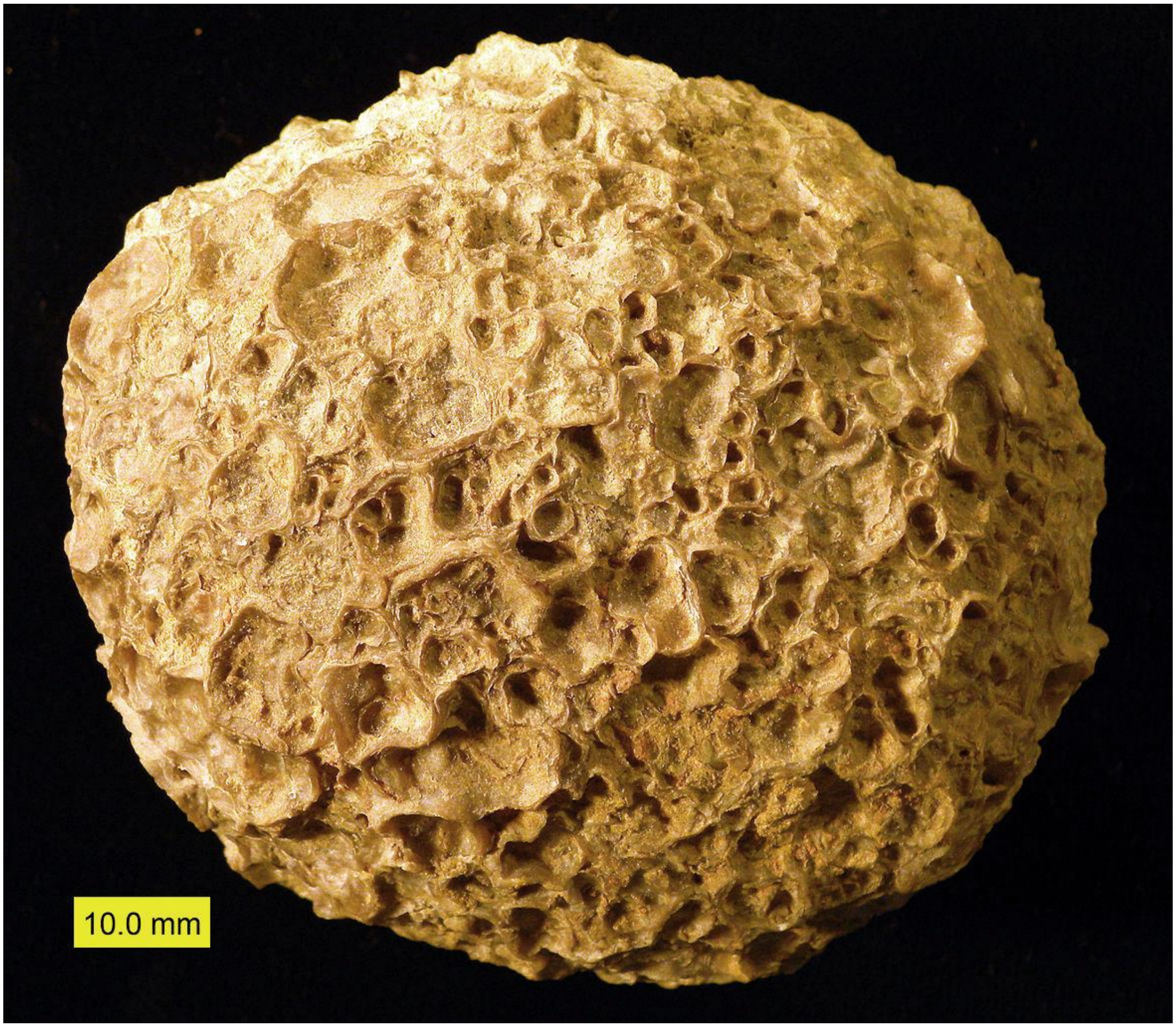

Figure 12. Exterior of an ostreolith from the Carmel Formation, showing the cemented left valves of *Liostrea strigilecula* that make up the ostreolith. Valves are cup-shaped compared to *Liostrea* valves that are not tightly packed (Fig. 10) (Mark Wilson, https://commons.wikimedia.org/wiki/File:OysterBall.JPG, accessed 2 May 2018).

The relatively even radial arrangement of *Liostrea* layers in ostreoliths implies an environment with sufficient energy to rotate the ostreoliths so all surfaces were exposed evenly, but only on an intermittent basis so that each generation of *Liostrea* had a chance to grow (Wilson et al. 1998). The accumulation of *Liostrea* on these ostreoliths also implies a soft-sediment setting with limited hard surfaces for juvenile *Liostrea* to recruit to. This is corroborated by the presence of oolitic, bioclastic grainstone trapped between *Liostrea* shells and overgrown by successive *Liostrea* generations, indicating that it was the sediment on which the ostreoliths formed.

Two types of ostreolith are distinguished, based on the initial nucleus of the accumulation (Wilson et al. 1998). The nucleus could either be the free-lying shell of another mollusc, producing subspherical ostreoliths up to about 15 cm in diameter, or a dislodged fragment of already-encrusted hardground, producing discoidal ostreoliths up to 25 cm thick and 50 cm in diameter.

In addition to *Liostrea*, the ostreoliths contain *Plicatula*, nestling *Modiolus*, the bryozoans *Microeciella duofluvina* and *Simplicidium*, an encrusting brachiopod *Discinisca*, and the bivalve boring trace *Gastrochaenolites* (Wilson et al. 1998).

Ostreoliths were originally described as unique to the Carmel Formation and the equivalent Twin Creek Limestone (Wilson et al. 1998) but have since been described from two sites in the Upper Jurassic of Poland (Zaton and Machalski 2013). These ostreoliths are not formed by *Liostrea,* but by another encrusting oyster, *Nanogyra nana*. Like the *Liostrea* ostreoliths in the Carmel, these ostreoliths nucleated on mollusc shells, and are formed by radial growth of generations of cemented left valves, with right valves absent. Unlike the Carmel ostreoliths, however, the oyster shells are encrusted by microbial mats, which Zaton and Machalski (2013) interpret as having aided cementation and growth of the ostreolith. As in the Carmel, *Plicatula*, encrusting bryozoans, brachiopods, and boring traces occur on the ostreoliths along with the primary ostreolith-builder. The Polish ostreoliths are slightly more diverse than the Carmel ostreoliths, also including encrusting serpulid worms and foraminifera, which is consistent with general trends of low diversity in the Carmel Formation

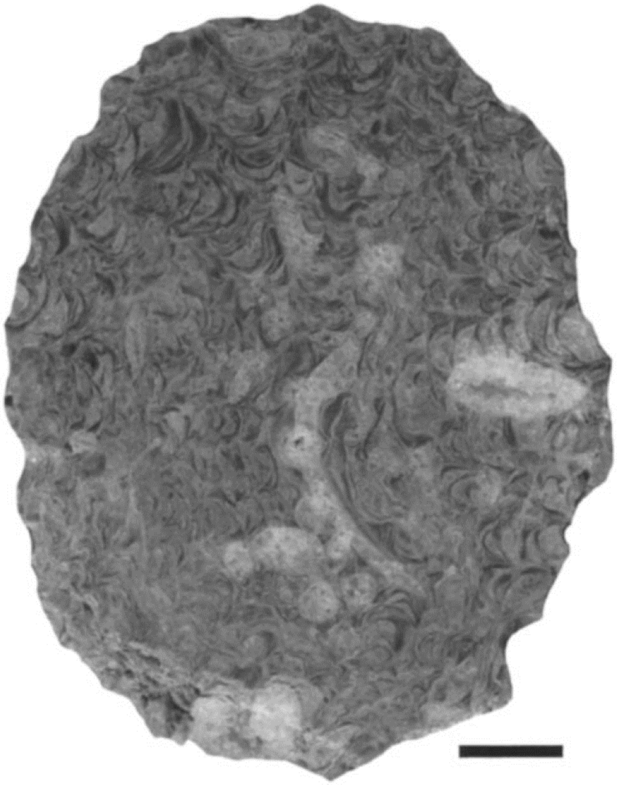

Figure 13. Cross-section of an ostreolith from Member D of the Carmel Formation near Gunlock, Utah showing the radial growth of successive generations of *Liostrea* shells. The original nucleus, a mollusc shell, is preserved in the center of the accumulation as an external mold filled with light-colored calcite. Scale is 1 cm (Wilson et al. 1998, Fig. 1).

Gastropods

Gastropod fossils are relatively widespread in the Carmel Formation (Imlay 1964). Preservation is generally poor (Sohl 1965). The original aragonitic shells have been replaced by silica or calcite or dissolved and preserved as external or internal molds. Many shells have been fragmented or worn by transport. Winnowed, size-sorted accumulations of numerous small gastropods occur in some areas, often mixed with other skeletal fragments (Fig. 14). The best preserved gastropod genus is the large, thick-shelled *Lyostoma.*

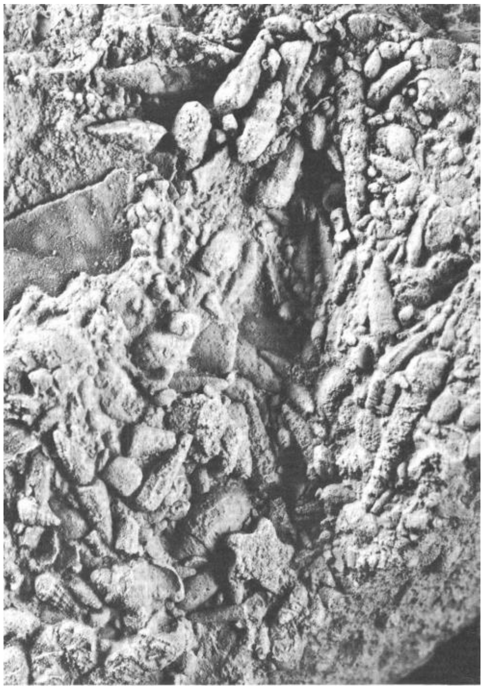

Figure 14. Size-sorted and abraded gastropod shells mixed with crinoid ossicles in a winnowed assemblage from the Twin Creek Limestone near Thistle, Utah. Scale uncertain. From Sohl (1965, plate 5, Fig. 3).

The gastropod fauna of the Carmel appears to follow similar patterns in diversity to the bivalve fauna. Overall species richness is low, and the highest diversity and abundance of both groups occurs in the intermediate-depth “middle area” of Imlay (1964) (Fig. 2; Imlay 1964, Sohl 1965). No winnowed small-shelled assemblages are found in Imlay’s “eastern area”. Gastropod fossil diversity is higher in the lower portion of the Co-op Creek Member than in the upper portion, a pattern not apparent in bivalve fossils (Sohl 1965). In the “eastern area”, gastropods are almost absent from the upper portion of the member. Sohl (1965) does not make an effort to separate taphonomic from paleoecological effects on gastropod fossil diversity and distribution in the Carmel.

No gastropod species predominate throughout the Carmel Formation. *Lyosoma enoda* and *L. powelli* are widespread but uncommon (Sohl 1965). *Cossmanea imlayi* and *Cylindrobullina*? sp. are less widespread, but are locally abundant at some sites.

In the Gunlock area, gastropods are the next most abundant fossil group after bivalves (Nielson 1990). Gastropod fossils are associated with ooid beds and are common in members A and D of Nielson (1990). *Cylindrobullina*? sp. and *Globularia*? sp. are locally abundant at sites in the Gunlock area (Sohl 1965). Nielson (1990) also reports indeterminate neritid gastropods in association with abundant *Cylindrobullina*? on the upper surface of member A at one site, and *Rhabdocolopus viriosus* in ooid beds in the middle of member D. In the Mount Carmel Junction area, Taylor (1981) found gastropod fossils only from his lithofacies VI at a single site in his study. Tang (1996) reports indeterminate gastropod fragments from elsewhere in the Mount Carmel Junction area, but no gastropod macrofossils.

Crinoids

Although most crinoid fossils in the Carmel Formation have historically been identified as *Pentacrinus astericus*, these fossils likely represent several species (Tang 1996). The total number of species is unclear, but at least some of the fossils in the Carmel Formation have been identified as *Isocrinus nicoleti*, and *I. knighti*, *I. wyomingensis*, and *Chariocrinus* sp. have been identified in deposits from other areas of the inland seaway (Hunter and Zonneveld 2008). Fewer crinoid species have been identified from the Middle Jurassic seaway of North America than from Middle Jurassic deposits in Europe, but this may be an artifact of less thorough investigation.

At Mount Carmel Junction, *Isocrinus nicoleti* ossicles form an encrinite, a limestone consisting of more than 50 percent crinoid ossicles (Tang et al. 2000). The encrinite occurs in tidal deposits in the Co-op Creek Member of the Carmel Formation. The encrinite is 1.08 meters thick at its thickest, indicating that it accumulated over several generations from a stable crinoid community. The *I. nicoleti* elements show very little transport, including some sets of articulated columnals (Fig. 15), suggesting that the crinoids lived on the accumulating crinoid gravel and added to it when they died.

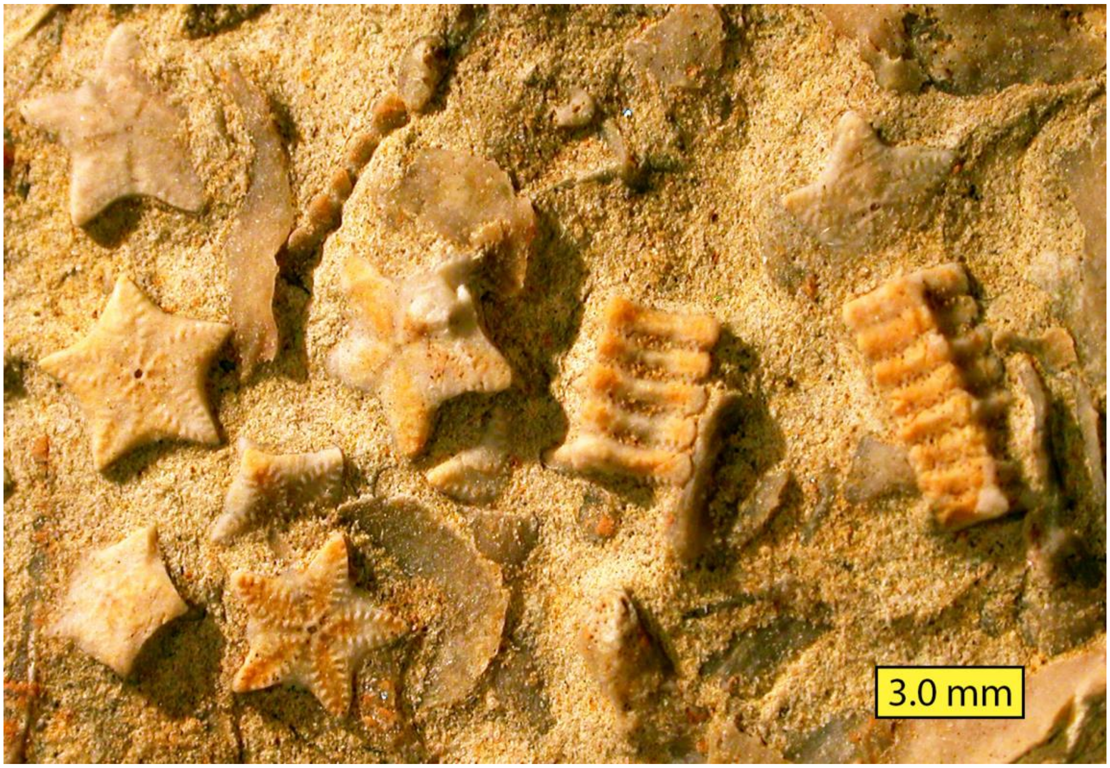

Figure 15. Partially articulated *Isocrinus nicoletti* columnals from the Mount Carmel Junction encrinite. (Mark Wilson, https://commons.wikimedia.org/ wiki/File:Isocrinus_nicoleti_Encrinite_Mt_Carmel.jpg; accessed 1 May 2018).

Encrinites are more typical of Paleozoic faunas, and this is one of the youngest encrinites found (Tang et al. 2000). The disappearance of encrinites from the fossil record is hypothesized to be a result of increased predation in the Mesozoic Marine Revolution. Tang et al. (2000) note the absence of ammonite, belemnite, and vertebrate fossils from the area, and interpret the Mount Carmel Junction encrinite as a relict community protected from predation by its geographic isolation at the southern tip of the seaway.

I. nicoleti is not endemic to the North American seaway, and its presence at the southern end of the seaway demonstrates an ability to cross a large latitudinal gradient from the northern entrance of the seaway (Tang et al. 2000). This may indicate that *I. nicoleti* was an ecological generalist, which is consistent with the bivalve-based interpretation of the Carmel Formation as low diversity and generalist-dominated (Tang 1996).

Brachiopods

Only two brachiopods have been found in the Carmel Formation, both from the Gunlock region (Baker and Wilson 1999). *Discinisca* is an encrusting inarticulate brachiopod found on ostreoliths at a single site in the Gunlock region (Wilson et al. 1998). It is not known from elsewhere in the seaway. *Stentorina sagittata* is a thecideidine brachiopod only known from the Carmel Formation (Baker and Wilson 1999). It was a cryptic encruster, especially in cavities formed under synsedimentarily lithified carbonate hardgrounds. Thecideidine brachiopods are a common component of this type of restricted cavity community in other sites from the Jurassic to the Recent (Wilson 1998).

Bryozoans

In contrast to low-diversity bivalve and gastropod faunas, cyclostome bryozoan species richness in the Carmel Formation is comparable to bryozoan species richness in the Middle Jurassic of Europe (Taylor and Wilson 1999). *Microeciella duofluvina* is widespread in the Carmel and in the laterally equivalent Twin Creek Limestone and is found encrusting bivalve shells, ostreoliths, and carbonate hardgrounds. *Patulopora cutleri* is found in the Mount Carmel Junction region and in the Twin Creek Limestone as abundant fragmentary material. *Patulopora* colonies originally formed erect unilamellar or bilamellar fronds. The diversity of cyclostome colony forms in the Carmel is also close to that in the Middle Jurassic of Europe (Taylor and Wilson 1999). Six of the seven colony forms described in Europe are found in the Carmel.

Ctenostome bryozoans are also found in the Carmel Formation. The soft bodied, non-boring ctenostome bryozoan *Simplicidium* was present in encrusting communities and is preserved as bioimmured molds on the underside of *Liostrea* shells where they overgrew it (Taylor and Wilson 1999).

Other Body Fossils

Other invertebrate groups found in the Carmel Formation include echinoids, serpulid worms, ammonites, and corals. Echinoid fragments are found in beds throughout the Carmel (Imlay 1964), and complete tests of regular echinoids have been found in the Mount Carmel and Gunlock regions (Taylor 1981, Nielson 1990). Serpulid worm tubes are found as encrusters on hard substrates, and colonies of serpulid tubes have been found in the Mount Carmel Junction area (Tang 1996). The ammonite *Zemistephanus* has been found in the San Rafael Swell region of the Carmel Formation in central Utah (Imlay 1964), but no ammonites are found in the Carmel south of the San Rafael Swell (Imlay 1980). This lack of ammonites is unusual for the Jurassic but is consistent with the scarcity of ammonite fossils in the Sundance Formation, farther north in the seaway (Danise and Holland 2017). Small colonial corals, probably *Ceonastrea hyatii*, have been found in the Gunlock region (Nielson 1990).

Ichnofossils

Ichnofossil assemblages from the San Rafael Swell region of the Carmel formation are characterized by low diversity, low behavioral complexity, low penetration into the sediment, low degrees of bioturbation, and unusually small size relative to specimens of the same ichnotaxa from other locations (de Gibert and Ekdale 1999). *Thalassinoides* and *Rhizocorallium*, deeper-tier crustacean burrows that are dominant in other shallow-water Jurassic carbonates, are almost entirely absent.

High salinity and low oxygen can cause reductions in diversity and body size and are potential causes for the unusual characteristics of the Carmel ichnofauna (de Gibert and Ekdale 1999). The ichnogenus *Chondrites*, abundant in the San Rafael Swell area, may also be an indicator of low oxygen in the sediment, but not necessarily in the bottom water above the seafloor. Hypoxic bottom water is considered unlikely due to the shallow depth and frequent influence of storms. Low primary productivity, and thus little organic material to eat in sediment, may also lead to low-diversity ichnofossil assemblages with small traces that do not penetrate far into the sediment (de Gibert and Ekdale 2002). The geographic barrier to colonization of the seaway, as described by Tang and Bottjer (1997), may also have restricted the diversity of tracemakers present.

de Gibert and Ekdale (1999) recognize three ichnofossil assemblages in the San Rafael Swell area. The most diverse is the *Chondrites-Teichichnus* assemblage, which occurs in a subtitdal facies with periodic storm deposition. It can be divided into a lower-diversity, more dominant pre-storm-event suite and a more diverse, less abundant post-event suite. The monospecific *Planolites* assemblage occurs in a higher-energy facies and is interpreted as opportunistic colonization of the seafloor between storm events. The *Skolithos-Arenicolites* assemblage occurs in carbonate mud firmgrounds alternating with oolitic storm deposits.

The trace fossils in the Gunlock area of the Carmel Formation are similar to those in the San Rafael Swell (de Gibert and Ekdale 1999). Kilbourne (1998) recognizes four assemblages from member D of the Carmel Formation in the region. The low-diversity, sparse Assemblage I occurs in fine-grained, low energy facies, and is interpreted as an initial phase of colonization. Assemblage II is more diverse and shows more bioturbation, interpreted as indicating reworking of the sediment over an extended period of time in a relatively low-energy environment with little sediment influx. Assemblage III is the most diverse in the region, although overall diversity is only moderate, and occurs in lagoonal facies. Assemblage IV is supratidal and consists solely of the insect track *Copeza propinquata*.

The Carmel Formation in the Gunlock area also includes synsedimentarily lithified carbonate hardgrounds, which are not found in the San Rafael Swell area (de Gibert and Ekdale 1999). The bivalve boring *Gastrochaenolites lapidicus* is common in these hardgrounds, sometimes containing the presumed tracemaker *Lithophaga* (Wilson and Palmer 1994). *Gastrochaenolites* also occurs in the ostreoliths found in the area (Wilson et al. 1998).

The enigmatic bilobed trace *Gyrochorte* is common throughout the seaway (Tang 1996). *Gyrochorte* characteristically occurs as convex epirelief together with corresponding concave hyporelief, representing the top and bottom of a planar trace through multiple layers of sediment (Fig. 16; de Gibert and Benner 2002). *Gyrochorte* is probably a deposit-feeding trace formed by the tracemaker, possibly a polychaete worm, moving through the sediment at an oblique angle by pushing sediment around and behind its body (Fig. 17). *Gyrochorte* often occurs in lower-diversity ichnofossil assemblages and in post-storm event deposits and is interpreted as a record of opportunistic colonization of recently deposited sediment.

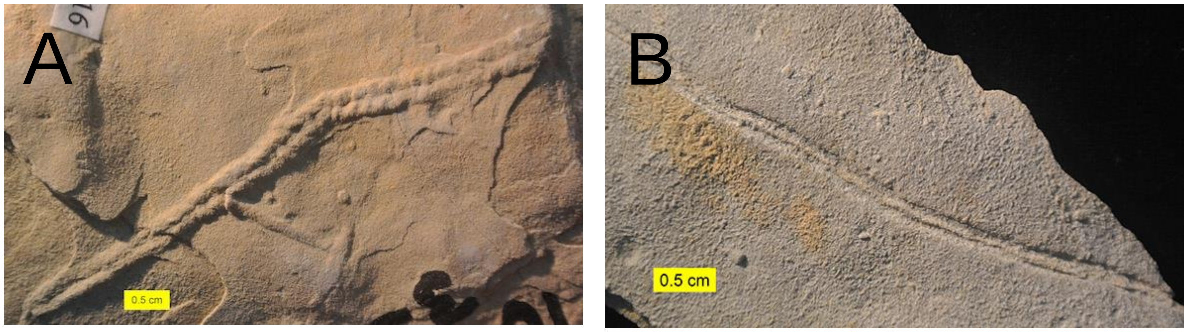

Figure 16. A: *Gyrochorte* in convex epirelief, from the Carmel Formation in the Gunlock area B: concave hyporelief, same slab. (A and B Mark Wilson, http://woostergeologists.scotblogs.wooster.edu/2017/11/10/woosters-fossil-of-the-week-a-middle-jurassic-trace-fossil-from-southwestern-utah/, accessed 2 May 2018)

The ophiuroid trace *Asteriactes lumbricalis* (Fig. 18) occurs in the lagoonal Association III of the Gunlock region, as well as in deeper water facies in the Arapien Formation near Nephi, Utah (Kilbourne 1998, de Gibert and Ekdale 2002) The presence of ophiuroids usually indicates normal or near-normal marine salinity, but a few species may be able to tolerate hypersaline conditions (de Gibert and Ekdale 2002).

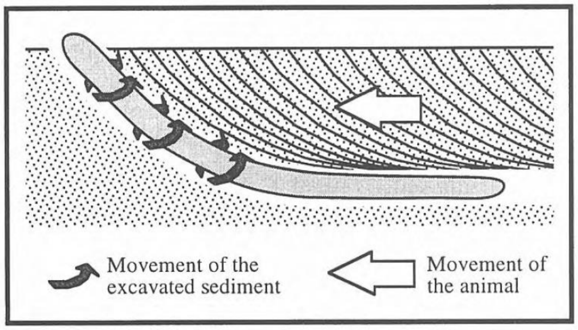

Figure 17. Reconstruction of the tracemaker and formation of *Gyrochorte* by de Gibert and Benner (2002). The sets of diagonal features shown in the plane of the trace are repeated inclined, bilobed, convex-up sheets, which are visible in exceptionally preserved specimens of *Gyrochorte* (de Gibert and Benner 2002, Fig. 8).

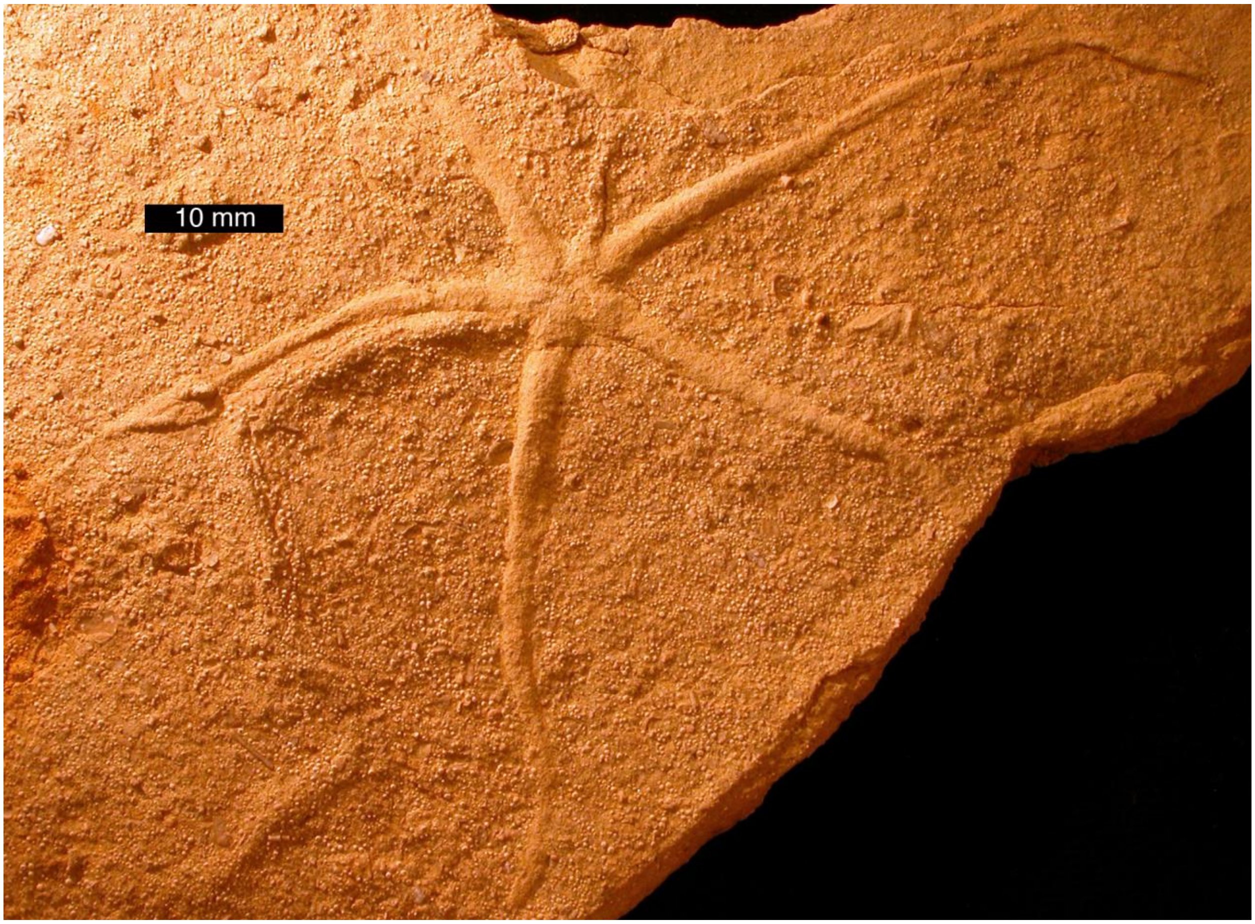

Figure 18. The ophiuroid resting trace *Asteriacites lumbricalis*, a possible indicator of normal marine salinity, in the Carmel Formation. (Mark Wilson, https://commons.wikimedia.org /wiki/File:AsteriacitesUtah.jpg; accessed 1 May 2018).

Carbonate Hardground Communities

Carbonate hardgrounds are ancient hard-substrate seafloors, formed by precipitation of carbonate cement in the pore spaces of marine sediment while it was still exposed on the seafloor (Wilson and Palmer 1994). These exposed hard substrates were then colonized by encrusting and boring faunas, which are potentially very distinct from contemporary soft-substrate faunas (Fig. 19). Hardground communities also offer unique opportunities for ecological study (Wilson 1998). Hardgrounds have been described in the Carmel Formation from near Teasdale, Utah (Tang 1996), and from the Gunlock area (Nielson 1990, Wilson and Palmer 1994).

Figure 19. Bored and encrusted surface of a carbonate hardground from the Gunlock area (Mark Wilson, https://commons.wikimedia.org/wiki/File:CarmelHdgd.jpg; accessed 2 May 2018).

The precise stratigraphic position of the Teasdale hardgrounds is unclear, but they belong to either the Co-op Creek or Crystal Creek Members of the Carmel (Tang 1996). The surface of the hardgrounds is hummocky and includes Y-shaped burrows. Tang (1996) interprets these as pre-cementation features that were deformed and preserved by the cementation of the hardground. The burrows are interpreted as the crustacean burrowing trace *Thalassanoides*, and the hummocky surface as general evidence of bioturbation. The post-cementation fauna consists of the borings *Gastrochaenolites* and *Trypanites* and a sole encruster, an unidentified colonial serpulid worm.

The hardgrounds of the Gunlock area occur in several horizons in “member D” of Nielson (1990), which corresponds to the upper part of the Co-op Creek Member (Nielson 1990, Wilson 1997). The largest and best-studied of these hardgrounds extends laterally for several kilometers (Wilson 1997). This hardground formed across a broad lagoon and spanned from higher-energy ooid shoal facies on its seaward side to low-energy facies on its landward side (Wilson and Palmer 1994). The lithology of the cemented hardground changes across this gradient, from interbedded sandy, oolitic grainstone and silty carbonate mudstone on the seaward side to packstones on the landward side.

The hardground fauna also varies across this facies gradient (Wilson and Palmer 1994). The seaward sandy, oolitic grainstone and silty carbonate mudstone hardground is encrusted by thick accumulations of successive generations of the oyster *Liostrea* (Fig. 20). *Gastrochaenolites* borings are found both in the hardground itself and in these accumulations of *Liostrea* shells. *Plicatula*, another encrusting bivalve, is also associated with *Liostrea* accumulations. In the landward packstone hardground, *Gastrochaenolites* borings are much denser, and encrusters are almost absent, except for scattered and very small *Liostrea* sheltering within borings. Truncation of *Gastrochaenolites* borings indicates very high erosion in this facies.

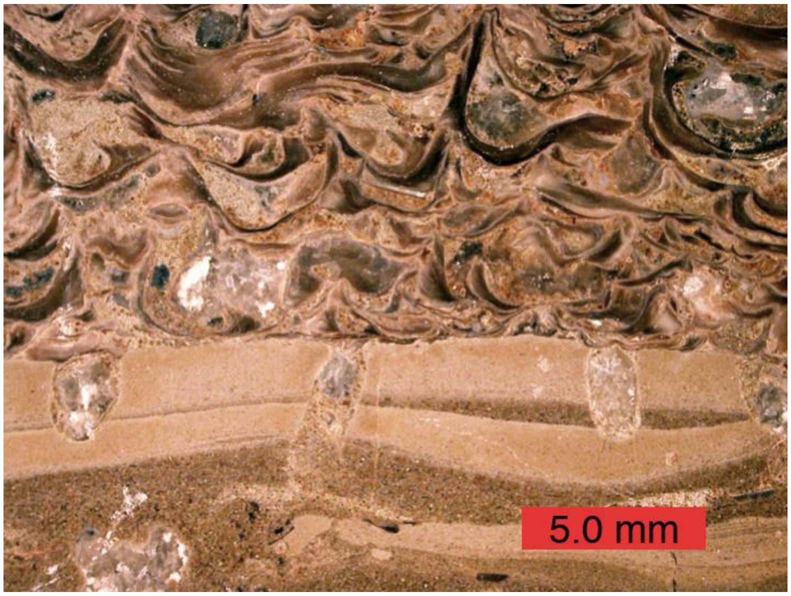

Figure 20. Cross section of a hardground from the Carmel Formation, showing the accumulation of encrusting *Liostrea* (top) and *Gastrochaenolites* borings (center, filled with sparry calcite). (Mark Wilson, https://commons. wikimedia. org/wiki/File: Carmel HardgroundSection.jpg; accessed 1 May 2018).

Cryptic communities are also present on this hardground (Wilson 1998). The hardground broke and was undercut in places, possibly by storms or currents, forming sheltered cavities (Wilson and Palmer 1994, Wilson 1998). These cavities extended back tens of centimeters under the hardground and were no more than 50 centimeters tall, although their initial height is unknown (Wilson 1998). The cavities were initially colonized by the same *Liostrea* and *Plicatula* assemblage found on the upper surface of the hardgrounds. As the cavities filled with sediment, *Liostrea* and *Plicatula* yielded to a low-biomass cryptic fauna of serpulids, bryozoans, calcareous sponges, and thecideidene brachiopods. This fauna is comparable to other restricted-circulation cryptic faunas from the Middle Jurassic to the present (Wilson 1998).

CONCLUSIONS AND PROPOSED RESEARCH

Previous paleoecological work in the Carmel Formation has found low species richness, low evenness, and low ecological diversity when compared to other Middle Jurassic localities (e.g. Imlay 1964, Tang and Bottjer 1997, de Gibert and Ekdale 1999). However, bryozoan species richness in the Carmel is comparable to species richness in Middle Jurassic sites in Europe, and carbonate hardgrounds in the Carmel show most of the groups expected from other Middle Jurassic hardgrounds (Taylor and Wilson 1999, Wilson 1998, Baker and Wilson 1999). Many prior studies do not explicitly discuss taphonomic biases in observed diversity. Tang (1996) does, and argues that the dominance of bivalves and the low number of bivalve species are not artifacts of taphonomic bias, since many of the sites she considers in her analysis are low-energy and not winnowed or transported, with some fossils still in life position. The Carmel Formation is also less well studied than comparable sites in Europe, which may lead to an underestimation of species richness since observed species richness is strongly dependent on sampling intensity.

Other previous work in the Carmel has described specific fossil assemblages or occurrences such as ostreoliths, carbonate hardgrounds, and encrinites. Some of these studies also suggest that the Carmel Formation is unusual paleoecologically. Ostreoliths have only been described from the Carmel, the laterally equivalent Twin Creek Limestone, and the Upper Jurassic of Poland (Wilson et al. 1998, Zaton and Machalski 2013), and encrinites are more typical of rocks older than the Carmel (Tang et al. 2000).

The purpose of this study is to continue research on the unusual paleoecological features of the Carmel Formation. The specific focus of future research is dependent on the samples collected in the field. Following the model of previous paleoecological work, I may continue to test the hypothesis that the Carmel fauna was characteristically or uniformly low-diversity, or I may describe the paleoecology in a distinctive type of fossil assemblage, such as ostreolith or hardground assemblages. Fieldwork will be conducted in the Gunlock area in May 2018.

In the field, I will measure stratigraphic columns to place collected fossils in their stratigraphic context. I will note sedimentary structures to determine depositional environments and collect lithologic samples of host rock if needed. Fossil collection methodology will depend on the final research subject, but may include bulk censusing of fossiliferous horizons, if feasible. Fossil samples will be labeled, and the location of each sample will be recorded. I will record depositional or other characteristics of each fossil location that will allow me to assess the taphonomy, space-averaging, and time-averaging of samples.

In the lab, fossils will be cleaned, labeled, and organized. Fossil specimens will be identified and classified systematically. I will prepare acetate peels and thin sections of specimens to aid in identification or to observe micro-scale features. I will continue to assess the taphonomy, space-averaging, and time-averaging of samples by observing the preservation of the specimens I collected.

If I collected bulk census samples, I will count individuals in each sample using an appropriate counting method, such as Number of Identified Specimens or Minimum Number of Individuals. The appropriate counting method will be determined using the interpreted time- and space-averaging of the bulk samples and the possible number of fossil elements per living organism. I will record the number of counted individuals under the selected method for each species in each sample.

Quantitative analysis of samples may include relative abundance distributions, rarefaction of samples to allow comparison of species richness between samples of different sizes, and computation of diversity indices such as Shannon's H or Simson's 1-D to quantify species richness and evenness of abundance.

To put the paleoecology of the Carmel Formation in a broader paleoecological and evolutionary context, I will compare my findings to previous findings in the literature. Comparisons between my findings in the Carmel and findings in other Middle Jurassic localities will allow me to assess the relative diversity of the Carmel fauna, which I can compare to the findings of previous work in the Carmel. I may also try to find paleoenvironmental analogies for the Carmel in deposits of different age, to see how the Carmel fits into longer-term ecological patterns in those environments, or to see if the same patterns of low diversity hold in similarly restricted seaways of other times.

BUDGET

Travel to and from the study area is $276, and my portion of housing expenses will be $485. Food will be around $35 per day. Equipment costs will be around $40, and general expenses in the field around $200. Fossil samples will be transported to the College of Wooster by Nick Weisenberg, so there will be no mailing costs. Materials for the preparation of acetate peels and thin sections will cost around $200.

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Dr. Shelley Judge has been an excellent advisor this semester, especially in encouraging me to stop reading and start writing.

I have many things to thank Dr. Wilson for, including arranging the details of fieldwork for this project, and providing half the images used in this paper. I am very much looking forward to working with him next year and in the field this summer.

I would also like to thank Charley Hankla and Michael Thomas for mutual commiseration throughout the Junior IS process.

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