PALEOECOLOGY OF FORAMINIFERA FROM THE LATE MIOCENE – EARLY PLIOCENE PULLEN AND SAINT GEORGE FORMATIONS, NORTHWESTERN CALIFORNIA

By

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A Thesis Presented to
the Faculty of Humboldt State University
In Partial Fulfillment of the Requirements for the Degree
Masters of Science in Environmental Systems: Geology

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December 2017

ABSTRACT

PALEOECOLOGY OF FORAMINIFERA FROM THE LATE MIOCENE – EARLY PLIOCENE PULLEN AND SAINT GEORGE FORMATIONS, NORTHWESTERN CALIFORNIA

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The Pullen and Saint George formations are coeval late Miocene-early Pliocene sedimentary formations in northwestern California. The type localities of both formations were studied from a micropaleontologic perspective that focused primarily on Foraminifera, but with additional observations of other fossil groups to reconstruct their past depositional environments. The results obtained in this study provided a photomicrographic inventory of the microfossils from both formations, aided in investigating changes in paleobathymetry of the formations during the late Miocene and early Pliocene based on Foraminifera, and allowed for interpretation of paleoecological signals from the foraminiferan associations. Foraminifera have not been previously described in the Saint George Formation and the Foraminifera of the section of the Pullen included this study had not been described in detail.

A monospecific association of *Elphidium* sp. was found in the Saint George Formation. This fact, coupled with the composition of the molluscan fauna, indicates that the strata of the Saint George Formation were deposited in a sheltered, likely brackish, shallow embayment. Sterrasters from the demosponge *Geodia* were also found, and also had not been previously described from the Saint George.

Foraminiferan associations in the Pullen Formation point to mid-to-lower bathyal depositional environments, supporting the interpretation of rapid subsidence near the Miocene-Pliocene boundary, followed by a slowly deepening environment following the initial subsidence. Foraminiferan evidence also suggests that periods of prolonged anoxia may have occurred during the deposition of the Pullen.

ACKNOWLEDGEMENTS

I would like to thank Dr. William Miller for being a supportive advisor. His vast knowledge of paleoecology and sedimentary geology was an invaluable resource for the completion of this thesis. His attention to detail in the writing and revisions of my thesis was crucial to creating a polished final draft. It was an honor to have him as an advisor.

My family and friends deserve many thanks as well. My mother Kathy and sister Tiffany both offered constant support throughout the process of researching and writing. My good friend Stephanie Robles, helped by keeping me motivated and on schedule. She assisted with collection of samples, made sure I met my deadlines and also assisted with the thesis formatting process. My colleagues, Jessica Vermeer and Michelle Robinson provided support at every step of the way, and were there for consultation whenever I had questions or needed suggestions. Thank you all.

Special thanks go to Jeffry Borgeld, Eileen Hemphill-Haley, Steve Tillinghast, and Lori Dengler of Humboldt State University. I thank Michelle Dostal of the Humboldt State Chemistry Department for the procurement of the liquid nitrogen needed for this study. Lastly, I acknowledge with thanks Laurie Marx of the Humboldt State Geology Department for logistical assistance, reassurance, and everything else that she does to ensure the success of the students.

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INTRODUCTION AND PURPOSE

This study focused on the type localities of two late Miocene-early Pliocene formations in Northern California. The Pullen and Saint George Formations were both deposited in nearshore to shelf-margin environments and initiation of sedimentation began during the late Miocene epoch (Aalto, 2006). In order to understand the similarities and differences of these two coeval formations, and to determine the paleoecologic conditions in their depositional environments, both were examined from a micropaleontologic perspective with a focus on the Foraminifera. Foraminifera have not been described, or even noted as being found, in any published studies of the Saint George Formation. Haller (1980) reported on the Foraminifera at the type locality of the Pullen Formation, but his data appear to be incomplete, owing to a low sampling density. The goal of this research was to provide a photomicrographic inventory of the microfossil associations (primarily Foraminifera) within the Saint George and Pullen, to investigate changes in paleobathymetry of the formations during the late Miocene and early Pliocene based on Foraminifera, and to interpret paleoecological signals of the Foraminifera found in both formations. Macrofossil occurrence is also included in this study; however the primary focus is on the microfossils.

Saint George Formation

Originally described by Maxson (1933), the type locality of the Saint George Formation is located at the northern end of Pebble Beach in Crescent City, California, south of the Crescent City Airport (Fig. 1) (Back, 1957). The sea cliffs at Pebble Beach provide good access to the upper and middle portions of the Saint George Formation, whereas the basal portion can only be examined in a wave-cut platform that is exposed at extreme low tides during times when beach sand is not present.

The Saint George Formation is approximately 44 m thick at Pebble Beach, strikes to the northwest (28°) and dips shallowly (15°) to the northeast. From well drilling logs, Back (1957) estimated that the formation can be as thick as 121 m in other areas underlying Crescent City. The Saint George Formation is overlain and underlain by unconformities, lying superjacent to the late Mesozoic Franciscan Complex and subjacent to the late Pleistocene Battery Formation (Back, 1957). A 5-m-thick basal conglomerate overlies a paleosol derived from saprolitic Franciscan Complex sandstone, marking the base of the formation (Robinson, 2001). During the El Nino event of 1997, large storm waves eroded the sand at Pebble Beach, exposing a previously undescribed fossilized Miocene forest in the wave cut platform of the lowermost portion of the Saint George. Carbonized stumps in growth positions were seen exposed in the basal portion of the section (Robinson, 2001). The burial of this paleoforest was attributed to rapid, tectonically induced subsidence or large-scale slumping with a possible tsunami deposit

Figure 1 - A Google Earth aerial photo showing the location of the St. George Formation study area and type locality at the northern end of Pebble Beach in Crescent City, California (marked with a red box, 41°46’18’’N/124°14’27’’W). Inset: an exposure in the beach cliff face of one of the shelly deposits dominated by *Macoma* fossils. The head of the rock hammer is 18 cm long for scale.

blanketing the paleoforest subsequent to subsidence (Robinson, 2001). Fragments of carbonized wood can be found throughout the entire section of the Saint George Formation at Pebble Beach, probably derived ultimately from this paleoforest and redeposited many times (W. Miller, 2016, personal communication).

The Saint George at Pebble Beach is primarily composed of a bluish-gray (when unweathered) sandy mudstone. Bivalve fossils are found throughout the section. Heavily weathered areas are reddish-brown, and moderately weathered areas appear light tan. Induration is variable within the formation, with some zones being relatively unconsolidated and others highly indurated or concretionary. The exposure at Pebble Beach is jointed and fractured in most areas. Instances of hummocky cross-stratification can be observed within the upper portion of the exposure, indicating oscillatory currents or waves during deposition (Yang et al., 2006).

The shelly deposits of the Saint George Formation are not rich in species and are composed primarily of bivalves, mostly *Macoma*, *Clinocardium*, and *Solen*. Small gastropod shells can also be found, but occur with much less frequency than the *Macoma* shells. A pinniped phalangeal bone was found in a densely packed shell deposit, but this appears to be a rarity. One specimen of an epibiont bryozoan (*Membranipora* sp.) has also been collected from the Saint George (K. Givins, 2012, personal communication). The overwhelming dominance of one bivalve mollusk genus (*Macoma*) in the Saint George could indicate a harsh depositional environment that was subject to salinity crashes, or possibly a brackish water embayment (W. Miller, 2015, personal communication).

Pullen Formation

The type locality of the Pullen Formation is a northwest striking (42°) and northeast dipping (59°) succession extending along the eastern bank of the Eel River north of Scotia, California, about 800 m upriver from the Eagle Prairie Bridge (Fig. 2) (Ogle, 1953). The Pullen Formation marks the basal portion of the Miocene-Pleistocene Wildcat Group, made up in ascending order of the Pullen, Eel River, Rio Dell, Scotia Bluffs, and Carlotta formations (Ogle, 1953). The Pullen is approximately 337 m thick at Scotia and is primarily composed of massive dark gray mudstones and siltstones with less frequently occurring sandstones and glauconitic intervals near the base (Ogle, 1953). The Pullen is unconformably superjacent to the Mesozoic Yager Complex and conformably subjacent to the Pliocene Eel River Formation. At the type locality, the base of the Pullen (contact with Yager) is currently covered by fluvial deposits, as is the uppermost portion. Approximately 90 m of section was exposed along the Eel River at the time of this study. Starting at the contact with the uppermost basal sandstone unit (Fig. 2), the mudstones of the formation that were sampled for this study extend downdip and upsection along the southern margin of the river.

Macrofossil occurrence is very limited within the exposed section along the Eel River. Small mollusks are rare and are typically poorly preserved (Haller, 1980). Articulated tests of the bivalves *Anadara trilineata*, *Yoldia* sp., and *Clinocardium* sp. have previously been found within the basal portion of the Pullen (Miller and Aalto, 2008).

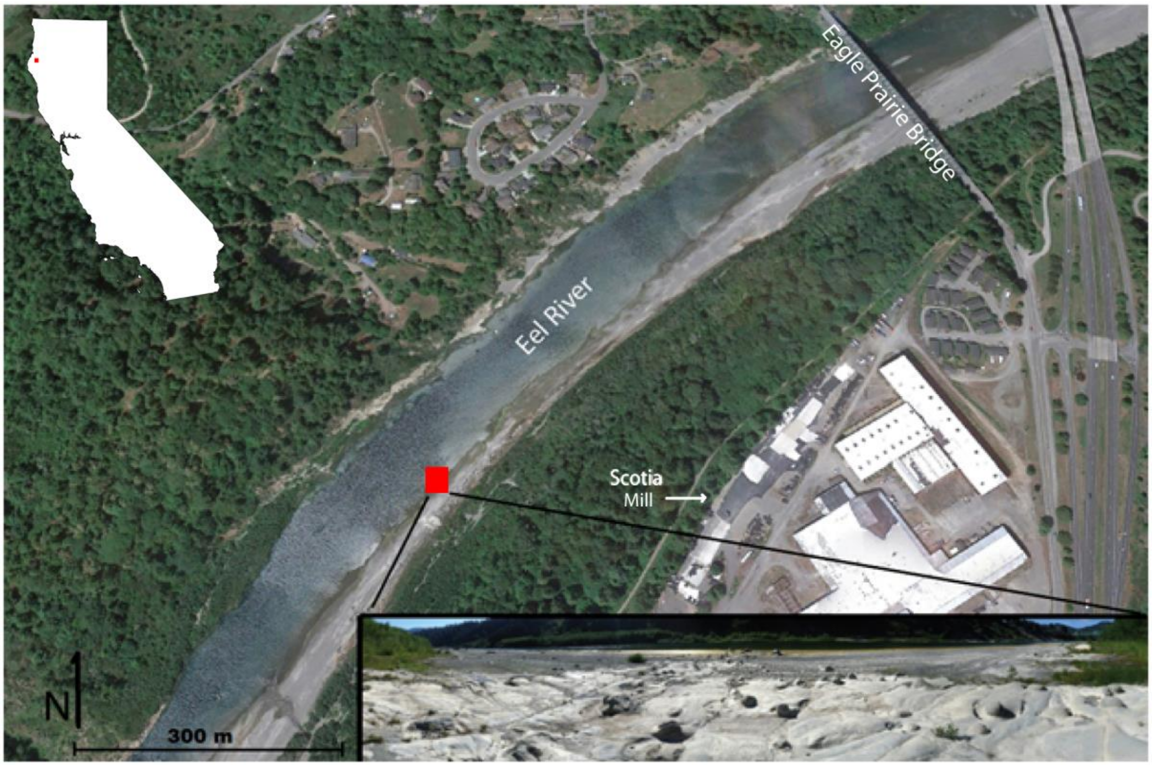


Figure 2 - A Google Earth aerial photo showing the study area (type locality) of the Pullen Formation alongside the right bank of the Eel River in Scotia, California (marked with a red box, 40°29’12’’N/124°6’22’’W). Note the Scotia Mill to the east and the Eagle Prairie Bridge to the northeast. The inset panoramic image looks northwest and shows the uppermost portion of the basal sandstone unit with multiple, highly indurated, 10-40 cm spheroidal concretions that occur in irregular intervals along strike.

Haller (1980) reported abundant radiolarians and diatoms in the Eel River section of the Pullen Formation. From this study, Foraminifera are found sporadically throughout the exposed section. Haller's (1980) study focused on the Foraminifera found in the Pullen Formation as well as the rest of the Wildcat Group. This study includes the first report of additional species of Foraminifera from the Eel River section of the Pullen Formation that were not included in Haller’s earlier work.

Trace fossils also occur in the Pullen. Within the concretions of sandstone beds in the lower Pullen, clusters of the trace fossil *Rosselia socialis* have been found (Miller and Aalto, 2008). The recognition of the *Rosselia* ichnofabric was key to better understanding the paleobathymetric conditions at the time of deposition.

METHODS

Sampling

Samples of the Saint George and Pullen formations were collected from their type localities with a rock hammer and chisel. The samples were bagged, numbered and the stratigraphic level from which they were taken was recorded. Strikes and dips of both formations were measured with a Brunton Compass. Stratigraphic measurements were made with a 2 m staff or measuring tape.

From the Saint George Formation, shelly deposits throughout the exposure were targeted for sampling (Fig. 3), as the possibility of Foraminifera preservation within these intervals was expected to be high. A protective zone for microfossils can occur within the steinkerns that are formed by fossilized bivalves and are of particular interest for sampling (W. Miller, 2015, personal communication). The stratigraphic levels between prominent shell beds within the Saint George were also sampled. In all, 27 samples were obtained from the Saint George for this study.

At Scotia, approximately 90 m of section was exposed and available for sampling at the time of this study. A portion of the exposed Pullen Formation mudstones was sampled at 3 m intervals. Twenty samples were taken in total. A measuring tape was laid out, extending up-section (downdip) from the sandstone/mudstone contact (Fig. 4) and samples were collected along that transect line. Because of the proximity to the Eel River, a thin layer (5-20 cm) of modern fluvial overburden had to be scraped away in order to access the mudstone. Care was taken to only collect unweathered mudstone, free of contamination from the fluvial deposits.

No macrofossils were found in samples of the mudstone from the Pullen Formation sampled in this interval; however, samples from the Saint George Formation containing macrofossils were photographed and the macrofossils were identified. Extraction of intact molluscan valves without damage from the Saint George was nearly impossible, so identifications were based on exterior shell morphology of shells imbedded in the matrix, or the interior characteristics of broken shells that fell out of the sandy mudstone matrix. This left a degree of uncertainty in identification of some of the mollusks.

Figure 3 - Shelly deposit within the middle portion of the Saint George Formation dominated by the bivalve *Macoma*. The head of the rock hammer is 18 cm long. Lag deposits, such as the one pictured above, can be found throughout the Saint George Formation**.**

Figure 4 - Outcrop of the Pullen Formation along the Eel River. Note the spheroidal concretions present in the sandstone bed. Mudstone samples were collected along a 60 m long transect (yellow line) perpendicular to strike and up-section from the outcrop in the foreground, in a northeast direction toward the Eagle Prairie Bridge. The 40 cm scale applies to the spheroidal concretions in the foreground.

Disaggregation and Examination

The samples needed to be disaggregated so that they could be processed for microfossils. A relatively new and novel method of disaggregation utilizing liquid nitrogen (Remin et al., 2012) was used in this study. The liquid nitrogen method of disaggregation involves a series of rapid freeze-thaw cycles similar to the Glauber's salt method (an antiquated freeze-thaw disaggregation method); however, it is much less demanding of time (Remin et al., 2012).

Samples were broken down with a rock hammer into ~ 1 cm^3 pieces and then soaked in distilled water overnight. After soaking, the distilled water was decanted and discarded. The samples were then submersed in liquid nitrogen in an open container, rapidly freezing the samples. Once all of the liquid nitrogen had completely vaporized, boiling, distilled water was poured over the top of the samples, thermally shocking the sample and weakening its cohesiveness. The samples were then gently massaged between the fingers under water, and the water and loose sediment was stirred and decanted over a 63 μm sieve. A 63 μm sieve is the standard size used to isolate small, calcareous Foraminifera, as it can catch the smaller and juvenile specimens (Haynes, 1981). This process was repeated multiple times until sufficient disintegration occurred. The number of freeze/thaw cycles varied dependent upon sample induration. The Pullen samples disaggregated relatively easily (5-7 cycles), but significantly more (12-15) cycles were needed for the more indurated Saint George samples. Distilled water was then used to wash the sample on the sieve until the runoff was clear. This ensured that a majority of the silt and clay size particles had been removed, greatly aiding in the isolation and retrieval of any microfossils.

Foraminifera are much easier to see under magnification and reflected light when wet, so immediately after disaggregation the portion of wet sediment trapped in the sieve was searched under a light microscope for any microfossils. The samples were rewet periodically during inspection, as samples tended to dry out quickly under the light microscope. Foraminifera test abundance in each sample was categorized low, medium, or high based on the amount of time it took to collect 50 specimens. Any specimens found were removed with a small, 3-bristled paintbrush and transferred to a labeled, gridded, standard micropaleontologic sticky-slide and stored for further study. A minimum of 50 specimens were collected per Pullen sample containing Foraminifera. In all, 601 Foraminifera specimens were collected from Pullen samples. Foraminifera in samples of the Saint George were very rare and monospecific. Only 14 specimens were collected in total from all samples from the Saint George Formation.

Scanning Electron Microscopy

High-resolution photomicrographs of the most well-preserved specimens of all species were produced using the Everhart-Thornley Detector (ETD) feature of the FEI Quanta 250 scanning electron microscope (SEM) at Humboldt State University. The micrographs give a visual representation of the microfossil inventories of both formations. In order to obtain these images, several steps were taken. Many of the foraminiferan tests had a thin layer of clay particles that needed to be removed prior to photographing. The use of a sodium hexametaphosphate solution aids in the cleaning process and was used in this study. A solution of sodium hexametaphosphate was mixed in a 1 g to 200 ml ratio with distilled water. Under magnification, specimens were immersed in a drop of the solution and gently agitated with a small, 3-bristled paintbrush. This process seemed to be mildly effective on some specimens, but left others relatively unchanged and covered with a thin detrital layer. Once the tests were cleaned as well as possible, they were transferred to a small sticky-stub designed to fit in the viewing stage of the SEM. The sticky stubs were then coated with gold for 75 sec before being mounted on the stage within the vacuum chamber of the SEM. After mounting on the stage, the vacuum chamber door was closed, and micrographs were taken of the specimens.

Identification

Identifications of specimens were based on the morphology of the Foraminifera tests. Chamber structure and aperture type are two of the most important morphologic characteristics that aid in identification (Loeblich and Tappan, 1988). While Foraminifera can exhibit many different chamber morphologies, the specimens found in this study exhibited the more common types: single chambered, uniserial, biserial, triserial, planispiral involute, streptospiral, and trochospiral (Fig. 5). Once the chamber morphology was identified for a specimen, the aperture type was also determined. The composition of the fossilized test itself is diagnostic in identification and also needed to be determined. There are two common test-wall composition types of Foraminifera: agglutinated and calcareous. Agglutinated (arenaceous) tests are made up of particles collected from the environment by the organism, whereas the calcareous tests are created by secretion of $CaCO_3$ by the foraminiferan itself. Only calcareous specimens were found in this study; as any agglutinated taxa were absent in the samples. The calcareous composition type is also further subdivided into three categories: microgranular (extinct by the end of the Permian Period), hyaline, and porcelaneous (Loeblich and Tappan, 1988). After chamber structure, aperture morphology and test composition were determined for a specimen, multiple resources were consulted for identifications. These included Cushman, 1915; Bandy, 1953; Haller, 1980; Loeblich and Tappan, 1988; Gupta, 2002; and Holburn, 2013.

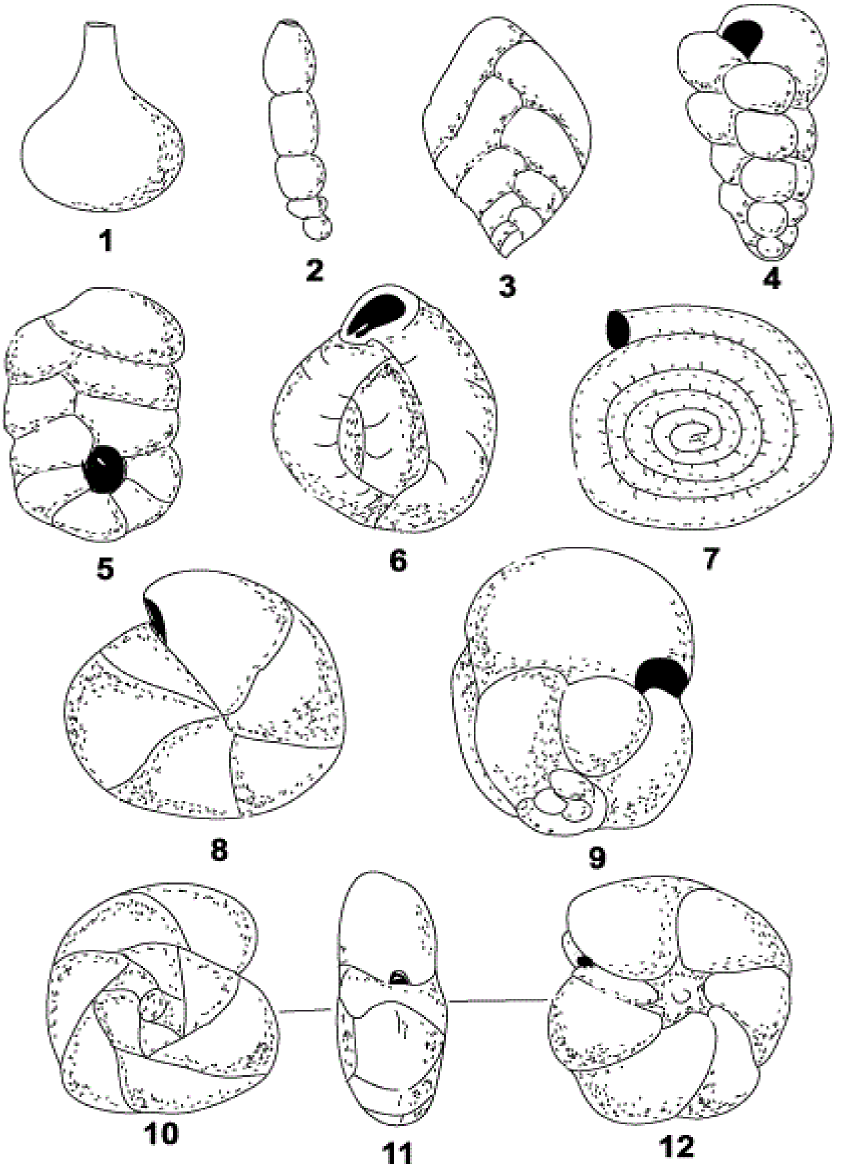


Figure 5 - Sketches of the principal types of foraminiferan chamber arrangement: 1, single-chambered; 2, uniserial; 3, biserial; 4, triserial; 5, planispiral to biserial; 6, milioline; 7, planispiral evolute; 8, planispiral involute; 9, streptospiral; 10-12; trochospiral. (reproduced from Gupta, 2002, fig. 2.10).

GEOLOGIC SETTING

Both the Saint George Formation and Pullen Formation lie within the Cascadia Subduction Zone (CSZ) in Northern California (Fig. 6). The CSZ is a region where the Gorda and Juan de Fuca plates are subducting beneath the North American Plate. The subduction of these plates is responsible for large earthquakes in the area, with associated subsidence, tsunamis, and liquefaction along the coast (Atwater et al., 1995). The CSZ is recognized to have the potential to create a magnitude 9+ earthquake on the moment magnitude scale (Rong et al., 2014). Evidence of a past large earthquake around 300 years ago, and the resulting subsidence, is recorded in buried forests that are thought to have been killed by tidal submergence following rapid coseismic subsidence (Atwater et al., 1995). These buried forests occur in numerous localities along the northwest coast of the United States, including Humboldt Bay, California; the Nehalem River, Oregon; and the Copalis River and Willapa Bay in Washington (Atwater et al., 1995). Possible evidence of a similar event can be seen in the basal portion of the late Miocene Saint George Formation, which contains a paleosol superjacent to the Franciscan Complex with tree stumps in growth positions, also pointing to rapid burial and subsidence (Robinson, 2001).

Many northwest-trending reverse faults occur on the eastern side of the CSZ as a result of stress caused by the easterly subducting Gorda and Juan de Fuca plates coupled with the northerly migration of the Mendocino Triple Junction (Atwater et al., 1995). The Saint George Formation has been uplifted and tilted to the north, likely caused by activity on the northwest-trending, northeast-dipping Saint George Thrust Fault (Fig. 7) (Robinson, 2001). The Saint George Fault lies just offshore from Point Saint George, at the northern end of Pebble Beach (Polenz and Kelsey, 1999). Based on a soil development model, Polenz and Kelsey (1999) determined that the uplift rate at Point Saint George averaged between 0.01 to 0.05 m/ky.

Forearc basins, which act as sediment traps, are formed in subduction zones between the axes of trench-slope breaks and the magmatic arcs as a result of compressional tectonic forces (Fig. 8). The Eel River Basin is one such forearc basin of the CSZ that formed in the late Miocene and overlies parts of the Central and Coastal belts of the Franciscan Complex (Nilsen and Clarke, 1989; Gulick and Meltzer 2002). The Saint George Formation is thought to be part of the Eel River Basin shelf sediment blanket (Nilsen and Clarke, 1989). The Eel River Basin was much larger 5 Ma and more elongate than it is presently. The northward migration of the Mendocino Triple Junction has shortened the basin to its present form (Fig. 9) (Mountain et al., 2009). The Wimer Formation (Diller, 1902) lies 10-15 km east of Crescent City, is composed of mostly fine grained fossiliferous sediments, and is probably coeval with the Saint George Formation (Aalto, 2006). This formation is also thought to be part of the shelf sediment blanket of the Eel River Basin (Aalto, 2006).

Deposition within the southerly portion of the Eel River Basin is recorded in the Wildcat Group, with the Pullen Formation being the lowest and oldest subdivision (Nilsen and Clarke, 1989). The Eel River Basin begins inland and just north of the Mendocino Triple Junction and extends north offshore of southern Oregon (Fig. 9). More

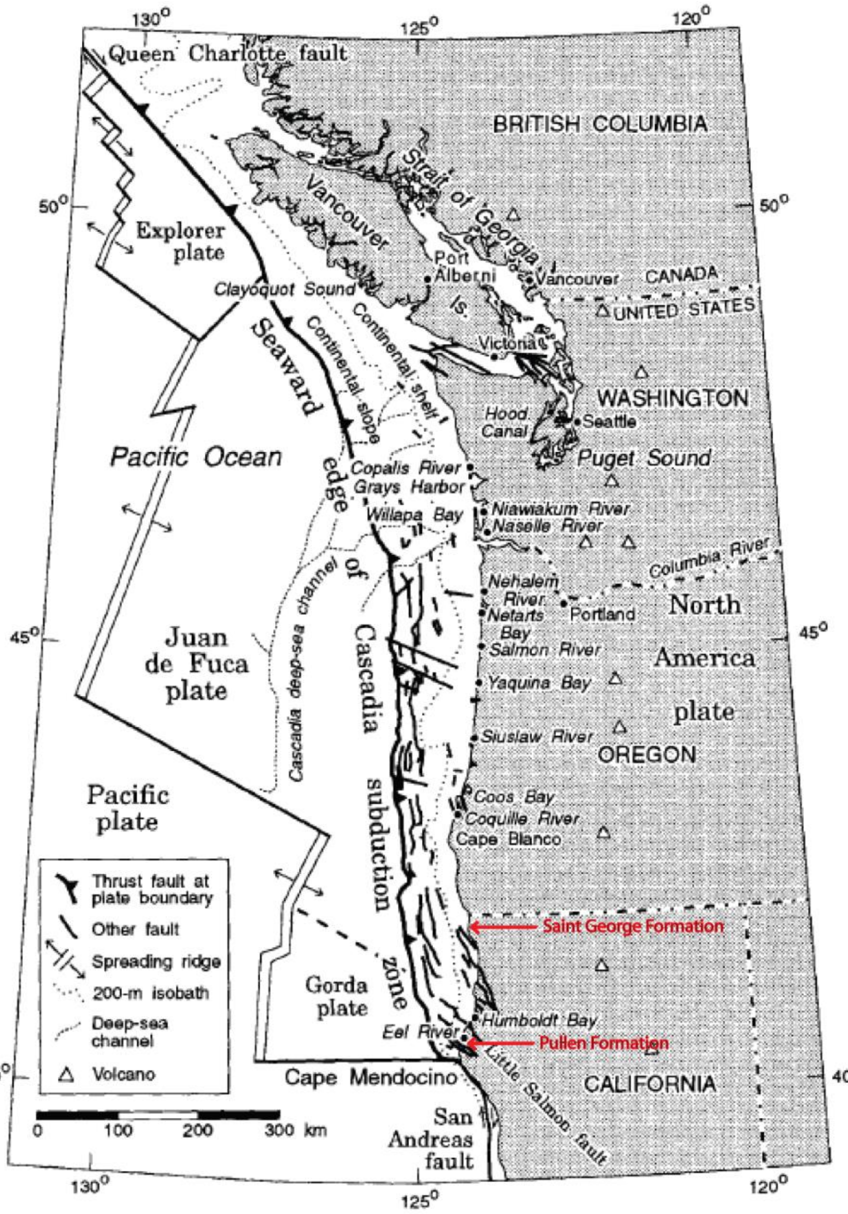


Figure 6 - Map of the Cascadia Subduction Zone showing the Juan de Fuca and Gorda plates that are subducting beneath the North American plate. Note the locations, marked in red, of the type localities of the Saint George and Pullen formations just north of the Mendocino Triple Junction at Cape Mendocino (modified from Atwater et al., 1995, fig. 1).

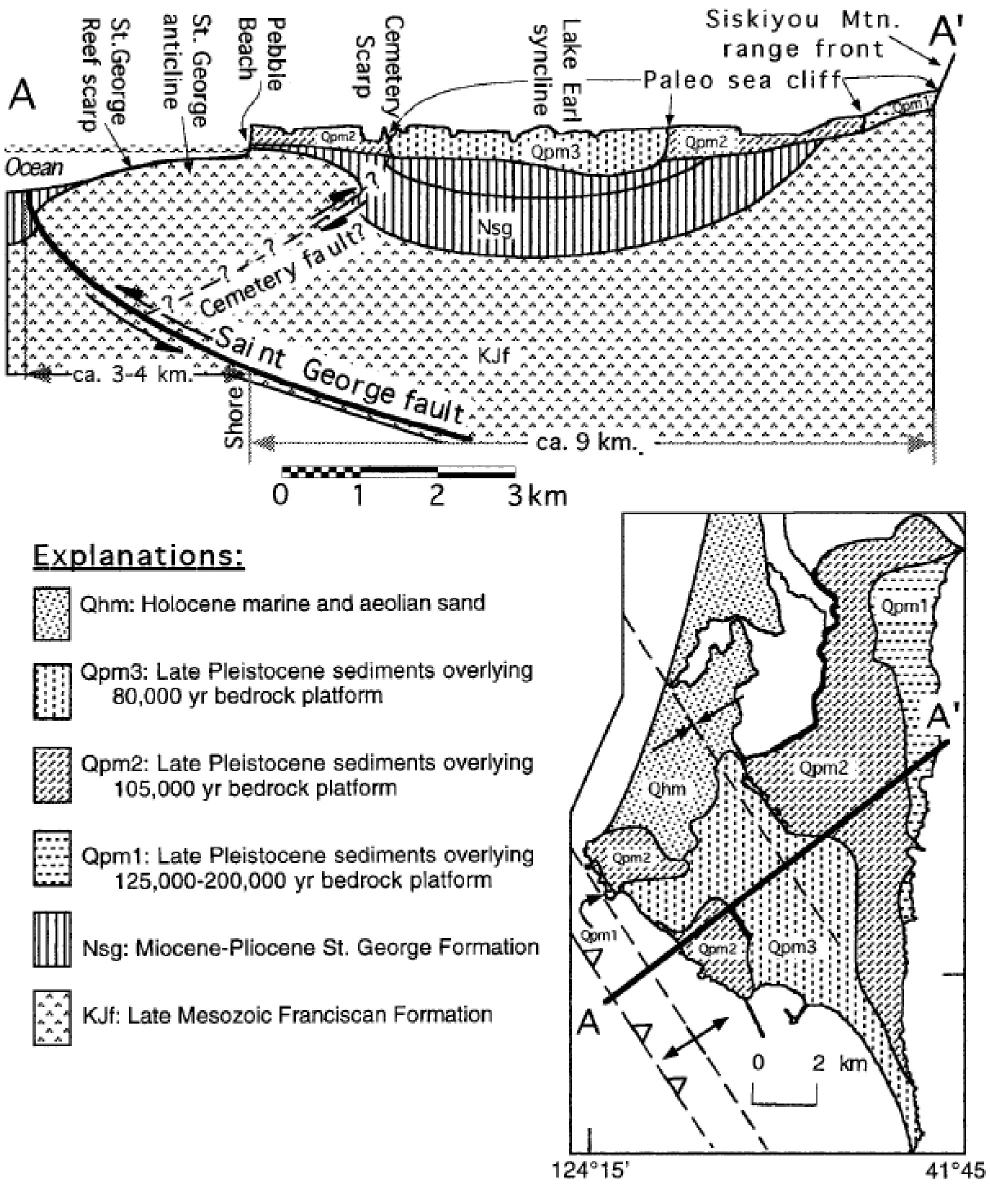


Figure 7 - Cross-section and map showing the location of the St. George fault just offshore of Pebble Beach and the geology of the area (reproduced from Polenz and Kelsey, 1999, fig. 8).

than 3,600 m of sediment accumulated in the now onshore portion of the Eel River Basin, which occupies most of the Eel River Valley. Two phases of deposition are recorded in this sequence. The first phase occurred during the early-middle Miocene (Bear River beds), which is unconformably succeeded by the second phase, occurring during the late Miocene-early Pliocene (Wildcat Group) (Nilsen and Clarke, 1989). The geologic column of both the onshore and offshore portions of the basin includes ~4,200 m of Neogene strata, much of which is interpreted to be Pliocene and Pleistocene in age (Haller, 1980). Based upon an $^{40}Ar/^{39}Ar$ laser probe analysis of detrital mica grains, Aalto (2006) considers the provenance of the Wildcat Group to be derived not only from local sources, but also in part from the Idaho Batholith.

Like the Saint George Formation, the basal portion of the Wildcat Group (Pullen Formation) accumulated at shallow depths, possibly as part of the Eel River Basin shelf sediment blanket (Aalto, 1996). The Wildcat Group records an initially shallow eastern shoreline transgression and a subsequent rapid deepening of the continental shelf to bathyal-abyssal depths, a later infilling of the shelf during the Plio-Pleistocene, and ultimately a westward regression of the shoreline during the Pleistocene (Miller and Aalto, 2008). This westward shoreline regression is attributed to rapid regional uplift that occurred during the middle Pleistocene caused by tectonic interactions between the Gorda Plate, the North American Plate, and the Mendocino Triple Junction (Aalto, 2006). These same tectonic forces also caused significant northeast-southwest contraction in the region and created many folds (Kelsey and Carver, 1988). One such fold is the Eel River Syncline in which the Wildcat Group sediments are preserved. The Eel River Syncline is the dominant structural feature of the Eel River Valley (Ogle, 1953). The region is also heavily faulted, dominated by northwest-trending reverse faults, including the Little Salmon Fault, which lies just north of the Eel River Valley (Fig. 10).

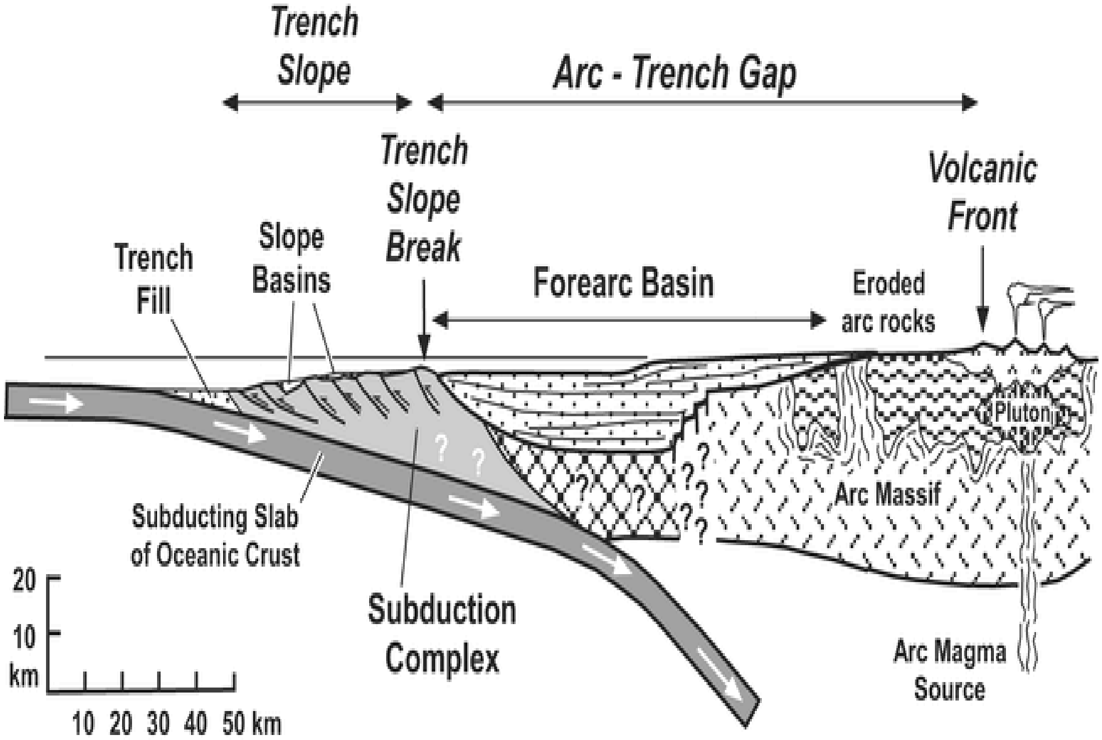


Figure 8 - Diagram of an active subduction zone, showing the location of the forearc basin relative to the trench slope break and the volcanic front. The Eel River Basin is a forearc basin (reproduced from Dorobek, 2008, fig. 4).

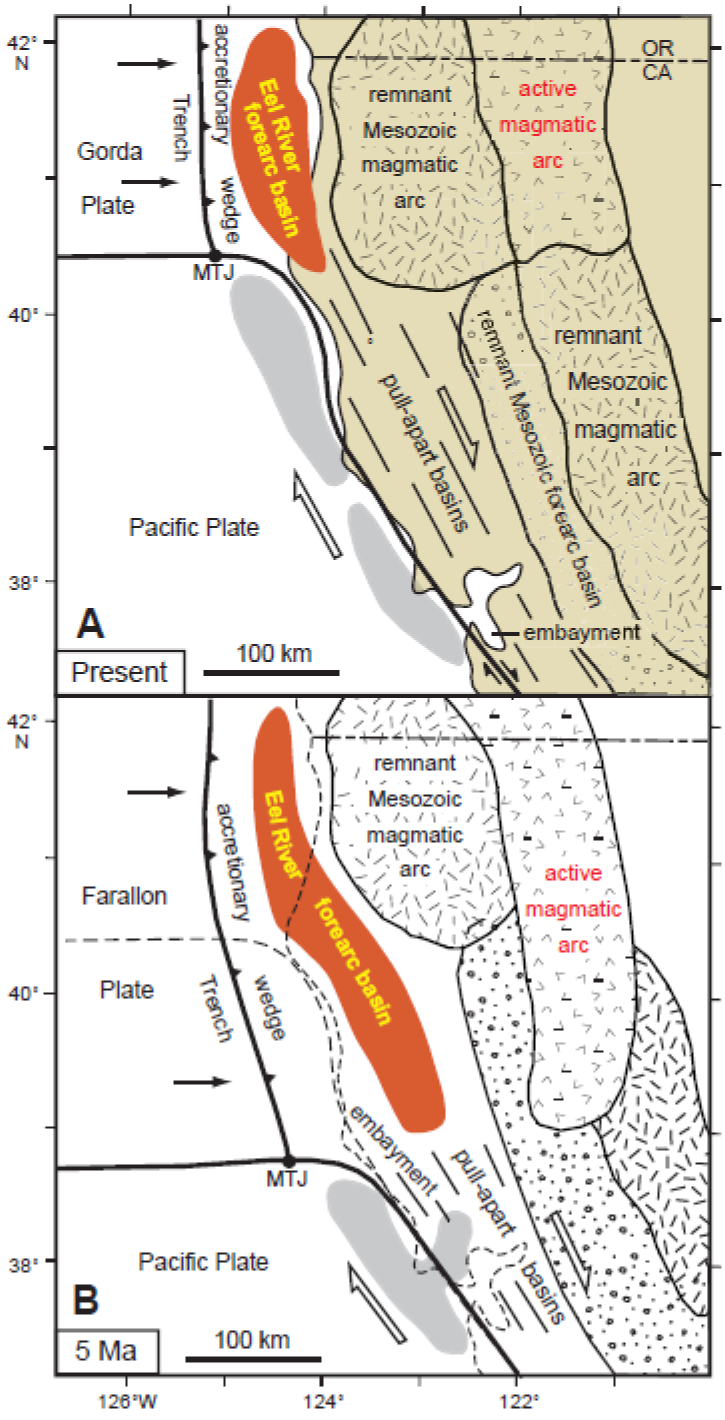


Figure 9 - Maps depicting the evolution and shortening of the Eel River Basin from 5 ma to present (reproduced from Mountain et al., 2009, fig. 7).

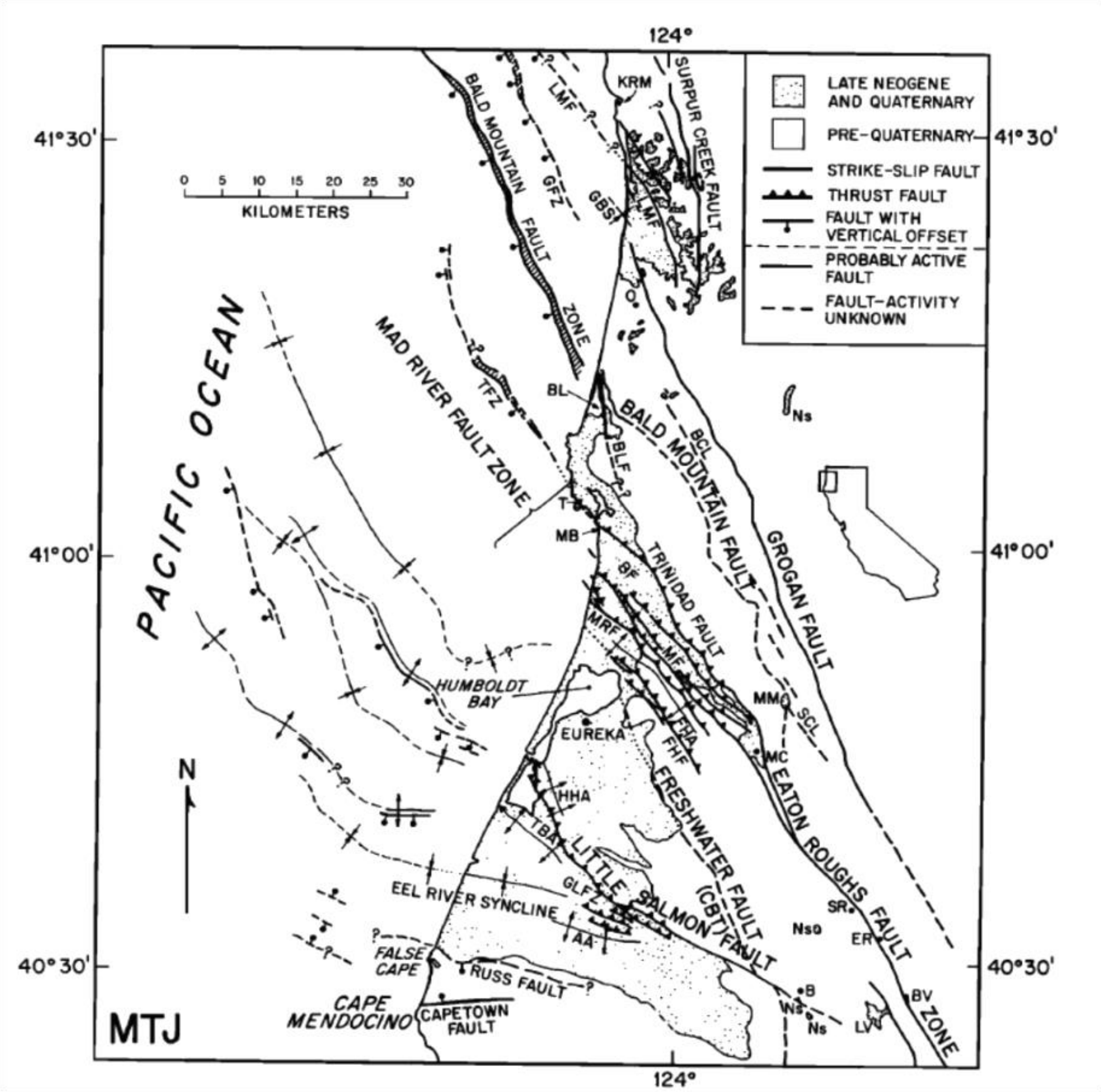


Figure 10 - Tectonic map north of Cape Mendocino (reproduced from Kelsey and Carver, 1988, fig. 2).

STRATIGRAPHY AND PALEONTOLOGY

Saint George Formation

Stratigraphy

At Pebble Beach, this study recognizes 12 distinct bedding units within the Saint George Formation, which are lettered A-L in Figure 11. Bedding planes within the succession are not apparent in the majority of the Saint George Formation, however the bedding units were delineated based on occurrence of prominent shell beds and sedimentary structures.

Bedding unit A is the ~5 m basal portion of the Saint George and was not available for inspection in this study, as it was covered by beach sand. Its description is taken from the previous work of Robinson (2001) and Aalto et al. (2006). During the El Nino of 1997, large waves washed away the beach sand overlying this unit allowing it to be studied. Robinson (2001) describes the lowermost portion of this unit as a paleosol, derived from the subjacent Franciscan Complex sandstone. An angular unconformity separates the Franciscan Complex from the paleosol, which contains partially carbonized tree stumps preserved in growth positions. Unconformably overlying the paleosol is a possible tsunami deposit, composed of very poorly sorted basal conglomerate with clasts ranging from 5-cm gravels to silt, and made up of angular to subangular quartz, greenstone, sandstone, locally derived cobbles and large carbonized wood fragments (Robinson, 2001). This matrix-supported basal conglomerate fines upwards to a greenish-gray pebble conglomerate in which sorting and rounding increase.

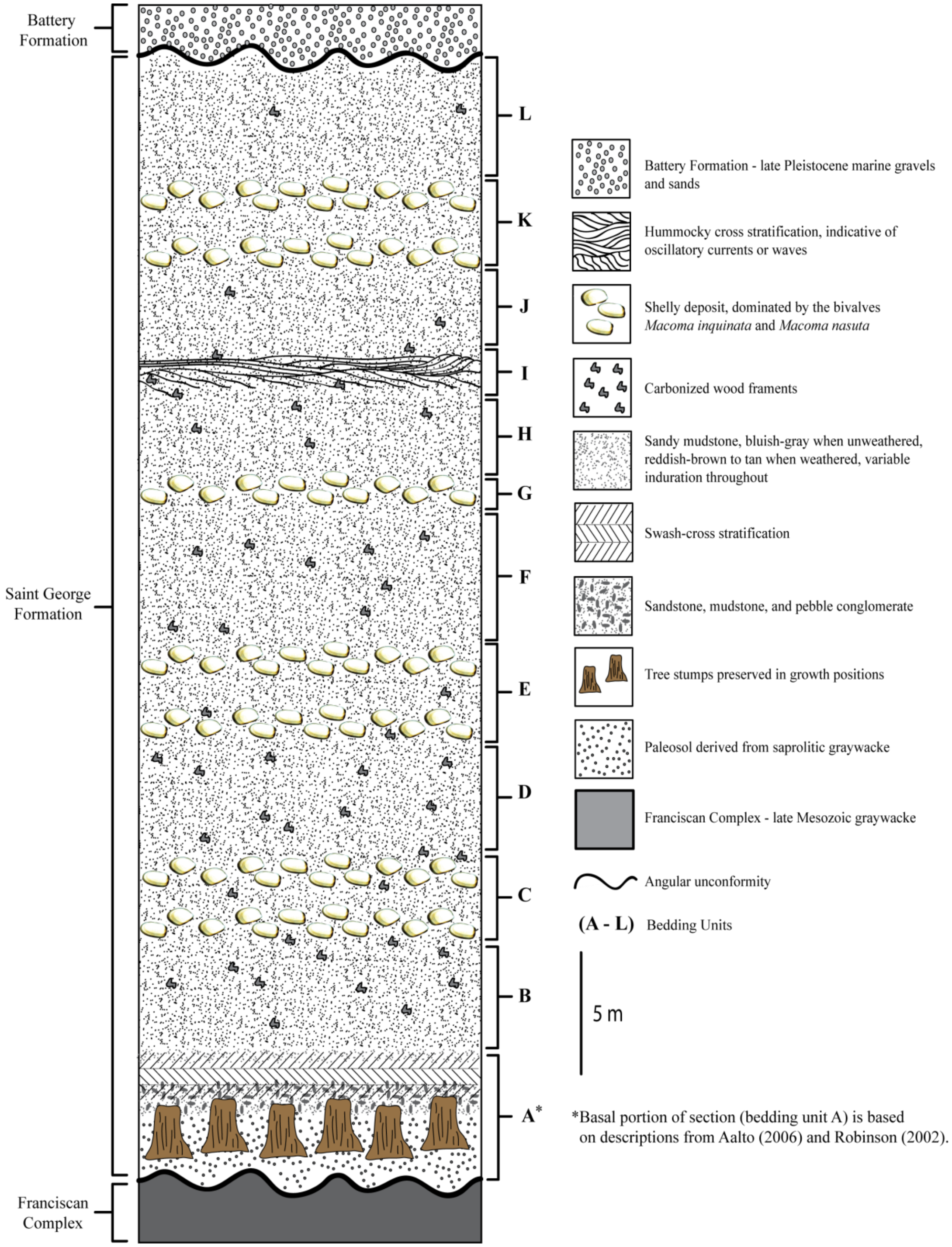


Figure 11 - Stratigraphic column of the Saint George Formation as interpreted by this study. Basal portion characteristics (bedding unit A) are based on descriptions by Robinson (2002) and Aalto (2006).

Superjacent to the pebble conglomerate, the unit continues to fine upward to a muddy sandstone and then to a sandy mudstone, in which swash cross-stratification can be observed (Robinson, 2001). Conspicuous bioturbation occurs in the uppermost portion of the unit, and examples of the trace fossils *Ophiomorpha* and *Thalassinoides* can be found in this uppermost portion (W. Miller, 2017, personal communication).

Bedding unit B overlies bedding unit A and is made up of a massive bluish-gray sandy mudstone with subangular clasts of quartz and feldspar, along with clay minerals. This sandy mudstone can be seen throughout all of the succeeding bedding units in the Saint George, with minor variations in textures. Large carbonized wood fragments occur throughout this unit, with an observed length of 10 cm or more in some cases. Macrofossil occurrence is very sparse and composed primarily of the molluscan bivalves *Macoma* sp. cf. *M. inquinata* and *Macoma nasuta* in life positions. The unit is ~4 m thick and lacks any visible sedimentary structures. No microfossils were found in this unit.

Bedding unit C lies superjacent to bedding unit B and is made of the same bluish-gray sandy mudstone. Macrofossils are abundant in this ~2 m thick unit, also composed mainly of *Macoma* sp. cf. *M. inquinata* and *Macoma nasuta* arranged in two distinct layers, forming what Aalto et al. (2006) referred to as a “shell couplet”. Many of the fossilized bivalves are disarticulated and jumbled into densely packed bedding layers, which were likely formed from storm-related winnowing, resulting in a lag deposit. Foraminifera are absent from this unit; however, a specimen of the epiphytic diatom *Arachnoidiscus japonicus* was found within a *Macoma* steinkern (Fig. 12). Carbonized

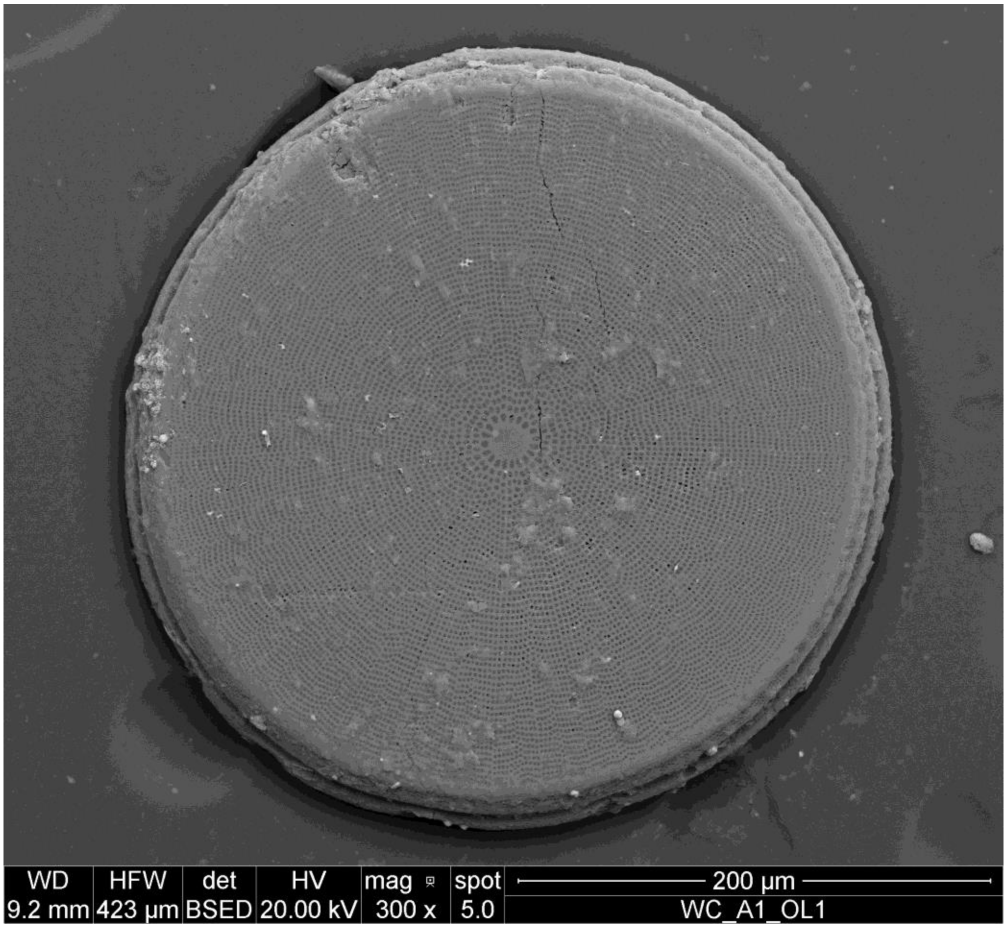


Figure 12 - SEM micrograph of the ephiphytic diatom *Arachnoidiscus japonicus* found within the Saint George Formation, bedding unit C. This is the only species of diatom found in this study.

wood fragments can also be found within the shelly deposit, but are smaller (<7 cm length) and slightly less abundant than those of unit B.

Bedding unit D is ~4.5 m thick and overlies the shelly deposits of unit C. The same massive, bluish-gray sandy mudstone is present in this unit, and much like unit B, sparse macrofossils can be found within it in life positions. Carbonized wood fragments remain frequent in this bedding unit, but are a slightly smaller and less frequent than in unit C. Foraminifera are absent from this unit, although two ovate sterraster microscleres from the demosponge genus *Geodia* were found in samples (Fig. 13).

Bedding unit E is succeeded by unit D and is ~3.5 m thick. It is composed of another pair of shelly lag deposits dominated by *Macoma* shells supported in a matrix of bluish-gray sandy mudstone. It is texturally and structurally similar unit C, in that it contains two layers of densely packed bivalve shells and is only slightly thicker. Carbonized wood fragments were also found, but were much less abundant and smaller (<4 cm length) than those in unit C. Unit E is the lowermost bedding unit within the Saint George in which Foraminifera were found. Three poorly preserved specimens of the genus *Elphidium* were obtained from a shelly sample collected from this unit (Fig. 14).

Bedding unit F is the thickest unit at ~6 m and is slightly finer grained than the subjacent units. The color of the sandy mudstone remains a bluish-gray and is massive like units D and B, lacking any obvious physical sedimentary structures. Induration within this unit is variable laterally, and in some places is extremely well indurated (concretionary) and difficult to sample. This unit also contains very sparse bivalve fossils in life positions and has less and smaller carbonized wood fragments than the subjacent bedding units. No microfossils were found within this unit.

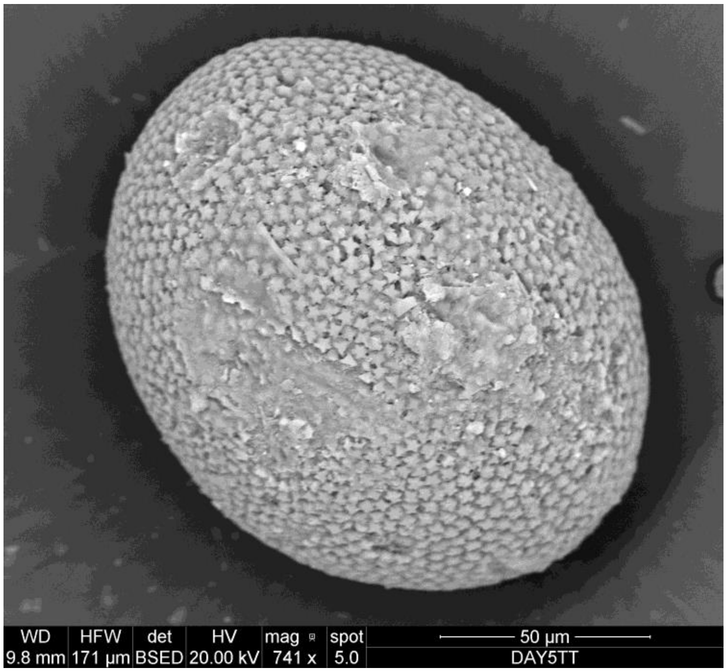


Figure 13 - SEM photomicrograph of a sterraster microscleres from the *Geodia* genus of demosponges. It was found in bedding unit D of the Saint George Formation.

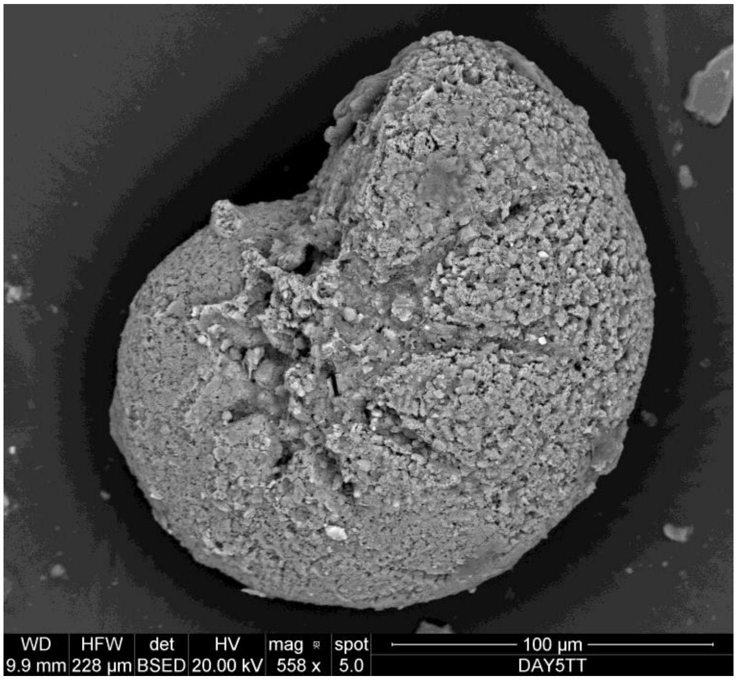


Figure 14 - SEM photomicrograph of a poorly preserved *Elphidium* sp. specimen from unit E of the Saint George Formation.

Bedding unit G is different from the other units, containing shelly lag deposits that do not exhibit the two-layer coupling. It is ~0.5 m thick and the blue-gray mudstone matrix is slightly sandier than that of the other bedding units. This unit is dominated by a single shelly layer, again dominated by *Macoma*. This is the second unit in which Foraminifera were found. Four specimens of poorly preserved *Elphidium* sp. were found within one *Macoma* steinkern. Carbonized wood can also be seen in this unit, but fragments are no larger than 3 cm in length and are less abundant than subjacent units.

Bedding unit H overlies unit G and the bluish-gray mudstone exhibits a similar texture to that of unit F. It is also similar to unit F in terms of the scattered bivalve fossils and carbonized wood occurrence. The carbonized wood fragments found in this unit tend to be 1 cm or smaller. No Foraminifera were found within this unit, but three specimens of *Geodia* sterrasters were found in a sample. This unit is ~4 m thick.

Bedding unit I is delineated based on its different texture and sedimentary structure, and is ~1 m thick. Hummocky cross-stratification can be seen in this unit, which indicates oscillatory currents or waves during deposition (Fig. 15) (Yang et al., 2006). Lithology is sandier than any other bedding unit in the Saint George, with the exception of bedding unit A, and is a muddy sandstone rather than a sandy mudstone as in the other units. Carbonized wood in this unit is more frequent and fragments are larger than lower units and occur within the hummocky cross-stratification. The carbonized wood fragments are ~7 cm or less in length. No other fossils were found in this bedding unit.

Bedding unit J is ~4 m thick and lacks any shelly lag deposits. Very sporadic macrofossil shells can be seen within it in life position. Carbonized wood fragments, while present in this unit, continue the trend of getting smaller and less abundant moving upsection. No microfossils were found in this unit, and no physical sedimentary structures were observed.

Bedding unit K is ~2.5 m thick, contains six thin lag deposits dominated by *Macoma* shells (Fig. 16), and is supported by the typical bluish-gray mudstone matrix. The shelly deposits are somewhat evenly spaced vertically, being between 20 to 45 cm apart, and are thinner than the shelly deposits of subjacent bedding units. A pinniped phalangeal bone (Fig. 17) was found within this unit, as were specimens of *Arachnoidiscus japonicus*, *Geodia* sterrasters, and poorly preserved tests of *Elphidium* sp.

Bedding unit L is the uppermost unit in the Saint George Formation at this locality and is ~5.5 m thick. Even smaller (< 5 mm length) and less abundant carbonized wood fragments are found within this unit. The same bluish-gray sandy mudstone in this unit does contain some bivalve fauna with shells preserved in life positions. Foraminifera were not found in this unit, but more sterrasters from *Geodia* sponges were found within samples. The contact with the late Pleistocene Battery Formation is above this unit; the contact is an angular unconformity.

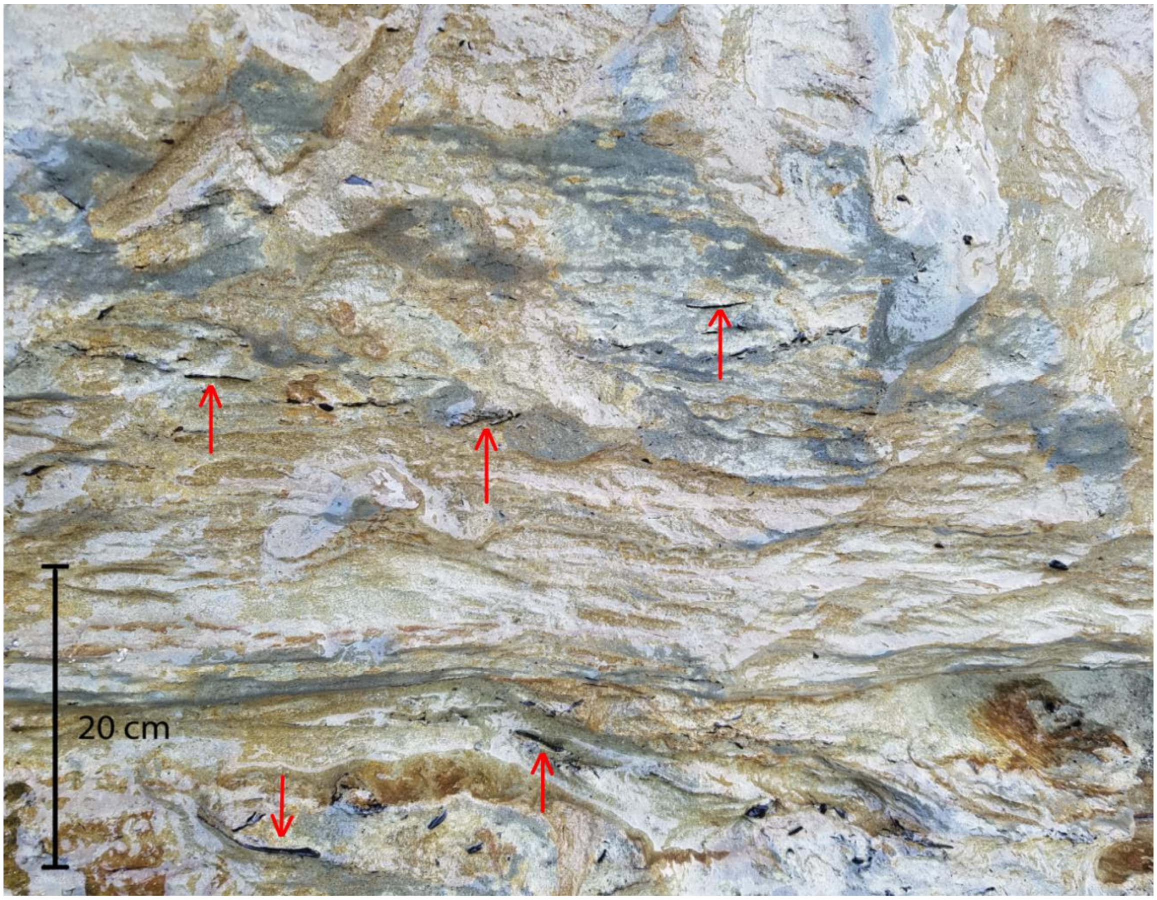


Figure 15 - Hummocky cross-stratification of the Saint George Formation, unit I. This bedform is indicative of oscillatory currents or waves. Note the black carbonized wood fragments seen within the muddy sandstone (red arrows).

Figure 16 - Photograph of bedding unit K. Note the six nearly evenly spaced shelly lag deposits indicated with red arrows. An Estwing rock hammer is in the lower right for scale. The head of the hammer is ~18 cm long.

Figure 17 - Photo of an in situ pinniped phalangeal bone found in bedding unit K with shells and molds of *Macoma*. The bone is to the upper left hand side of the centimeter scale card and indicated with a red arrow.

Paleontology

In this study, a very few fossilized species, both macro and micro, were found within the sampled strata of the Saint George Formation (Table 1; Appendix A, Plate 6). The pinniped phalangeal bone in the lag deposit of bedding unit K was the only vertebrate fossil found. The trace fossils *Thalassinoides* and *Ophiomorpha* that occur at the top of bedding unit A were not seen in any of the overlying bedding units.

As mentioned before, the shelly lag deposits are dominated by two species of *Macoma* (*Macoma* sp. cf. *M. inquinata* and *Macoma nasuta*) which look very similar but can be distinguished from each other based upon the extent of the pallial sinus relative to the adductor muscle scar on the interior of the left valve (Hiebert, 2016). These *Macoma* shells account for >90% of the shells within the beds. The remaining ~10% of the mollusk shells include *Clinocardium* sp. (Fig. 18), *Solen* sp. (Fig. 19), and rare *Nassarius* sp. A specimen of the epibiont bryozoan *Membranipora* sp. was also collected from the Saint George (K. Givins, 2012, personal communication); however, the stratigraphic level in which the specimen was found is unknown.

Back (1957) reported that in one location of the Saint George Formation he found an association containing *Clinocardium* sp., ?*Cryptomya* sp., *Macoma nasuta*, a juvenile specimen of *Protothaca* sp. cf. *P. staleyi*, ?*Saxidomus* sp., *Solen* sp. cf. *S. sicarius*, and a cast of the gastropod ?*Ocenebra* sp.. The exact location (both stratigraphic and geographic) of the sample containing this fauna is not reported in his study. Back's (1957) association is similar to the association found in this study.

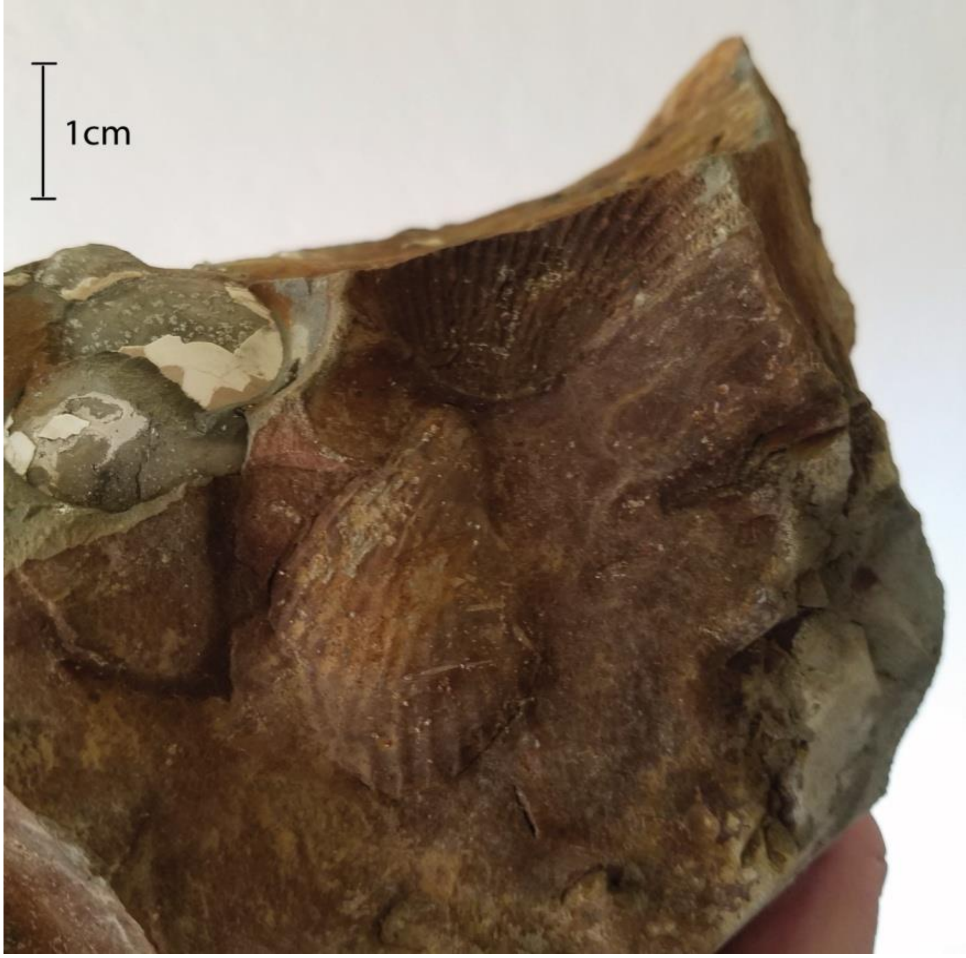


Figure 18 - Photograph of a mold of *Clinocardium* sp. alongside some smaller *Macoma*. The sample was taken from bedding unit E of the Saint George Formation.

Figure 19 - *Solen* sp. shells of various sizes occurring with abundant *Macoma* in bedding unit G.

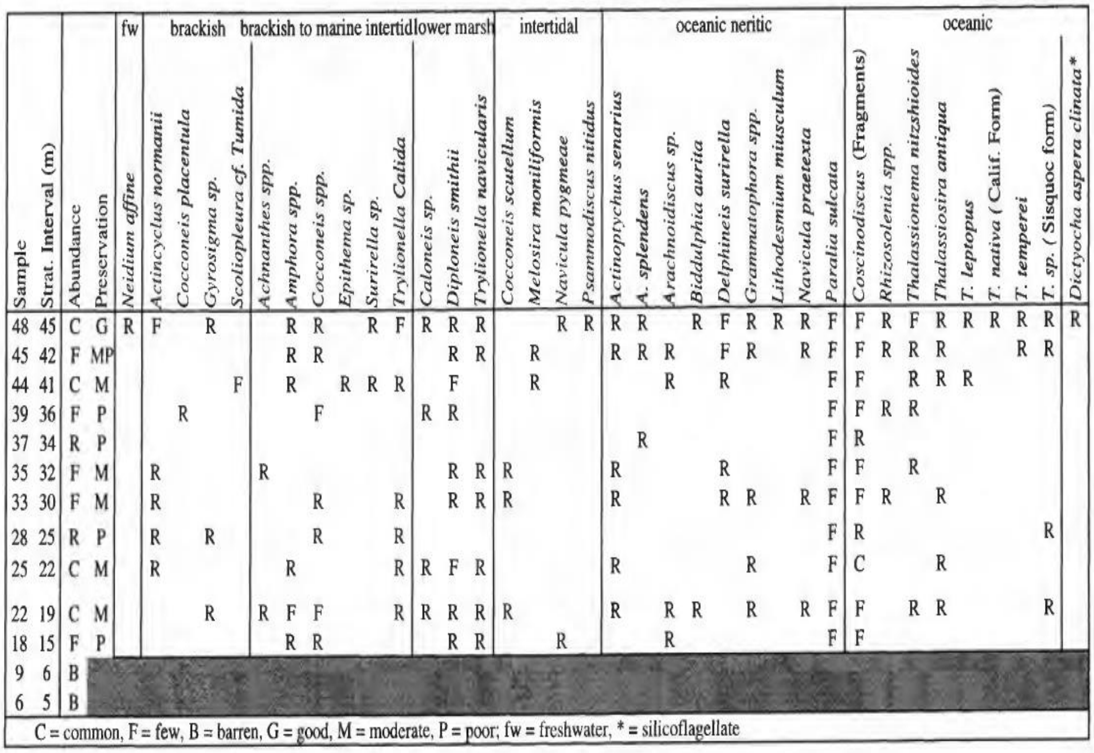
Table 1 - Table showing distribution of fossil taxa in the Saint George Formation. An 'X' indicates that at least one specimen was found in the corresponding interval. Stratigraphic level above base is measured from the contact of the basal paleosol covering the Franciscan Complex.

	MOLLUSCAN FAUNA	*Macoma nasuta*	*Macoma* sp. cf. *M.inquinata*	*Clinocardium* sp.	*Solen* sp.	*Nassarius* sp.
Bedding Unit	**Stratigraphic level (m) above base**					
L	38 to 44	X	X			
K	35 to 38	X	X	X	X	X
J	32 to 35	X	X			
I	30 to 32					
H	26 to 30	X	X			
G	25 to 26	X	X	X	X	
F	19 to 25	X	X			
E	15.5 to 19	X	X	X	X	
D	11 to 15.5	X	X			
C	9 to 11	X	X	X	X	
B	5 to 9	X	X			
	MICROFOSSILS	*Elphidium* sp.	*Arachnoidiscus japonicus*	*Geodia* sp. (sterrasters)		
Bedding Unit	**Stratigraphic level (m) above base**					
L	38 to 44			X		
K	35 to 38	X	X	X		
J	32 to 35					
I	30 to 32					
H	26 to 30			X		
G	25 to 26	X				
F	19 to 25					
E	15.5 to 19	X				
D	11 to 15.5			X		
C	9 to 11		X			
B	5 to 9					

The shell beds of the Saint George exhibit preservation of a molluscan fossil association dominated by *Macoma*. The stratigraphic position of the beds does not indicate much, if any, change in the diversity of fauna throughout the entire section and *Macoma* remains consistently dominant. Only one specimen of the gastropod *Nassarius* was found in bedding unit K. It must be noted that this study did not focus on the macrofossils, but rather the microfossils. Volumetric measurements of samples to determine shell to matrix ratios were not conducted and samples were not searched in extreme detail for macrofossils.

Microfossils larger than 63 μm are rare in the Saint George. The large epiphytic diatom *Arachnoidiscus japonicus* has been reported previously in the Saint George (Barron, 1999) and was found in this study also; however, the foraminiferan *Elphidium* sp. and sterrasters from the demosponge *Geodia* have not been described in any previous work on this formation. Occurrences of *Elphidium* sp. were confined to the steinkerns and matrix samples found within the prominent shell beds, but the *Geodia* sterrasters were found both within shell beds and in the stratigraphic intervals between the shelly beds. Preservation of *Elphidium* sp. was poor in all of the 14 specimens found, making identification to the species level impossible. *Geodia* sterrasters are siliceous and preservation was good in the recovered specimens. It is possible that the sterrasters originated from *Geodia mesotriaena*, a shallow water extant species that ranges from southern Alaska to the Gulf of Mexico (Dickinson, 1945). Dickinson (1945) notes that sterrasters from this species are 50 - 100 μm or larger in diameter, and specimens found in this study fall within that size range.

Arachnoidiscus japonicus was the only diatom found in the Saint George Formation during this study. Because of its large size, it remained in the 63 μm sieve used during sample processing. However, a detailed study of the diatoms found within the Saint George was conducted by the U.S Geological Survey, in which 35 different species of diatom and one silicoflagellate were identified (Fig. 20) (Robinson, 2001).



				fw	brackish				brackish to marine intertid						lower marsh			intertidal				oceanic neritic									oceanic								
Sample	Strat. Interval (m)	Abundance	Preservation	*Neidium affine*	*Actincyclus normanii*	*Cocconeis placentula*	*Gyrosigma sp.*	*Scoliopleura cf. Tumida*	*Achnanthes spp.*	*Amphora spp.*	*Cocconeis spp.*	*Epithema sp.*	*Surirella sp.*	*Trylionella Calida*	*Caloneis sp.*	*Diploneis smithii*	*Trylionella navicularis*	*Cocconeis scutellum*	*Melosira moniliformis*	*Navicula pygmeae*	*Psammodiscus nitidus*	*Actinoptychus senarius*	*A. splendens*	*Arachnoidiscus sp.*	*Biddulphia aurita*	*Delphineis surirella*	*Grammatophora spp.*	*Lithodesmium miusculum*	*Navicula praetexta*	*Paralia sulcata*	*Coscinodiscus* (Fragments)	*Rhizosolenia spp.*	*Thalassionema nitzshioides*	*Thalassiosira antiqua*	*T. leptopus*	*T. nativa* (Calif. Form)	*T. temperei*	*T. sp.* (Sisquoc form)	*Dictyocha aspera clinata**
48	45	C	G	R	F		R			R	R		R	F	R	R	R			R	R	R	R		R	F	R	R	R	F	F	R	F	R	R	R	R	R	R
45	42	F	MP							R	R					R	R		R			R	R	R		F	R		R	F	F	R	R	R			R	R	
44	41	C	M					F		R		R	R	R		F			R					R		R				F	F		R	R	R				
39	36	F	P			R					F				R	R														F	F	R	R						
37	34	R	P																				R							F	R								
35	32	F	M		R				R							R	R	R				R				R				F	F		R						
33	30	F	M		R						R			R		R	R	R				R				R	R		R	F	F	R		R					
28	25	R	P		R		R				R			R																F	R							R	
25	22	C	M		R					R				R	R	F	R					R					R			F	C			R					
22	19	C	M				R		R	F	F			R	R	R	R	R				R		R	R		R		R	F	F		R	R				R	
18	15	F	P							R	R					R	R			R				R						F	F								
9	6	B																																					
6	5	B																																					

C = common, F = few, B = barren, G = good, M = moderate, P = poor; fw = freshwater, * = silicoflagellate

Figure 20 - Inventory, distribution, preservation quality, and habitat of diatoms from the Saint George Formation (reproduced from Robinson, 2001, table 3).

Pullen Formation

Stratigraphy

Ogle (1953) described the late Miocene Pullen Formation at Scotia as being predominantly mudstone and 337 m thick, of which only ~90 m of the unit were exposed at the time the field work for this study was conducted. As at the type locality of the Saint George Formation, the basal portion of the type locality of the Pullen Formation at Scotia was covered by sediment and not available for observation or sampling during the time of this study. The upper portion of the Pullen at Scotia was also covered and could not be studied. The descriptions herein of the covered upper and basal intervals of the Pullen are taken from previous works, mainly Ogle (1953) and Miller and Aalto (2008).

Basal Pullen Stratigraphy. Owing to a landslide, and subsequent diversion of the Eel River in the winter of 2006, the base of the Pullen at Scotia was exposed and could be observed and studied (Miller and Aalto, 2008). An angular unconformity with the Paleogene Yager Complex occurs at the base of the Pullen at this location. The lowermost portion of the base of the Pullen is composed of 3.1 m of poorly sorted pebble-cobble breccia in a muddy sandstone matrix that is normally graded (Miller and Aalto, 2008). The brecciated clasts are angular to subangular pieces of Yager Complex turbidites. The breccia is overlain by 1.7 m of bioturbated and ripple cross-laminated sandstone. Overlying the sandstone is a 0.7-m-thick normally graded conglomerate, also consisting of Yager derived clasts that exhibit better rounding than at the contact with the Yager (Miller and Aalto, 2008). Superjacent to the 0.7 m conglomerate is a thick (25 m), massive bioturbated sandstone that fines upward to a sandy mudstone. Several conglomerate lenses occur in this bed, composed of subrounded, Yager-derived clasts (Miller and Aalto, 2008). Ogle (1953) also notes the thick sandstone bed at the top of the basal interval of the Pullen as having conglomerate lenses composed of Yager-derived clasts. Ogle (1953) states that this sandstone bed thins to the west and is not encountered again west of the (presently inaccessible) Price Creek outcrop of the Pullen.

Stratigraphy (Studied Section). The uppermost 7.5 m of the basal sandstone interval was exposed at Scotia during the time of this study. The sandstone is massive, light gray, fine-grained, and has numerous spheroidal concretions up to 40 cm in diameter that extend horizontally in distinct layers along strike (Fig. 4). Very sparse shell fragments can be seen in the sandstone and no Foraminifera were found in samples taken from it. Overlying the sandstone bed is a bed of massive mudstone. Twenty samples (P36 - P55) of the mudstone were taken at 3 m intervals along outcrop (= 2.6 m stratigraphic intervals) starting at the contact with the sandstone. A total of 60 m was sampled, which (accounting for dip) represents 51.4 m of stratigraphic succession. This 51.4 m sampling interval was partitioned into 17 biostratigraphic zones based on foraminiferan taxonomic composition, species richness, and relative abundance within the samples. These zones are lettered A-Q, with A being the lowermost zone and Q being the uppermost (Fig. 21). The lithology of all zones exhibits only very minor variations. The mudstone is dark gray and composed of quartz, feldspars, lithic fragments, and clay minerals. Foraminifera are present in some zones and apparently absent in others. Where found, foraminiferan abundance per sample volume is described as high, medium or low based on the amount of processing time it took to recover 50 specimens per sample. Diatoms are present within this mudstone interval (Ogle, 1953) but were not included in this study, as none were found during sample processing. The lack of diatoms is probably due to the use of a 63 μm sieve, which allowed the smaller diatoms to wash through, and out of the sieve.

The boundaries of the zones (Fig. 21) are generalized and are more than likely not representative of the true biostratigraphic boundaries. The section would need to be studied at much more acute resolution than 3 m intervals in order to truly and accurately delineate microfossil zones in the sampled section studied. Such resolution is beyond the scope of this project.

Zones B, E, G, I, M, and P did not contain any Foraminifera. The zones that did contain foraminiferans are described below and photomicrographs are shown in Appendix A, Plates 1-5.

Zone A is delineated based on sample P36. Foraminiferan abundance in this zone is high. Fourteen different species of Foraminifera were found in this zone: *Bulimina subacuminata, Cassidulina translucens, Epistominella pacifica, Epistominella* sp., *Globobulimina affinis, Globigerina bulloides, Hansenisca* sp. cf. *H. soldanii,* ?*Oolina* sp., *Orbulina universa, Plectofrondicularia californica, Siphonodosaria insecta, Uvigerina hootsi, Uvigerina peregrina*, and *Uvigerina subperegrina*. This is the only zone of the studied section in which ?*Oolina* sp. and the pelagic species *Orbulina universa* were found.

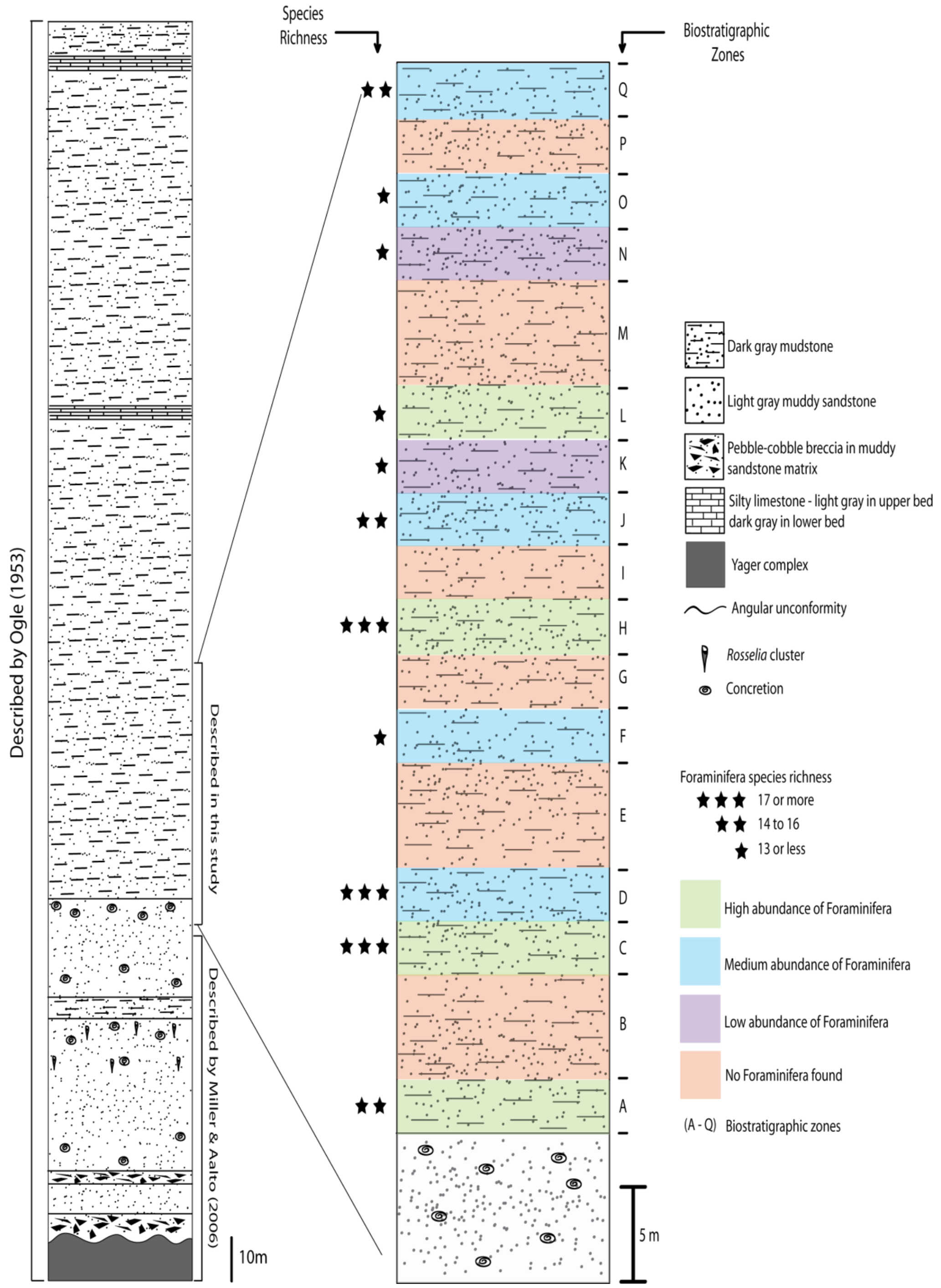


Figure 21 - Stratigraphic column (left) of the Pullen Formation. The enlarged, color coded biostratigraphic column shows subdivisions based on foraminiferan taxa, species richness, and abundance estimates.

Zone C is delineated based on sample P39. Foraminiferan abundance in this zone is high. Seventeen different species of Foraminifera were found in this zone: *Cassidulina translucens, Cibicides mckannai , Epistominella pacifica*, *Epistominella* sp., *Fissurina* sp. cf. *F. lucida*, *Glandulonodosaria* sp. cf. *G. ambigua*, *Globobulimina affinis*, *Lagena striata*, ?*Nodosaria* sp., *Nodosaria tympaniplectriformis, Plectofrondicularia californica, Siphonodosaria insecta, Uvigerina* sp. cf. *U. hannai*, *Uvigerina hootsi*, *Uvigerina peregrina*, *Uvigerina subperegrina*, and *Uvigerinella* sp. cf. *U. californica*. Only single specimens of *Uvigerina* sp. cf. *U. hannai*, *Fissurina* sp. cf. *F. lucida*, and *Glandulonodosaria* sp. cf. *G. ambigua* were found in this zone, and were not seen anywhere else in the studied section.

Zone D is delineated based on sample P40. Foraminferan abundance in this zone is medium. Eighteen species of Foraminifera were found in this zone: ?*Bulimina* sp., *Bulimina subacuminata*, *Epistominella pacifica, ?Fursenkoina* sp., *Glandulina* sp. cf. *G. laevigata*, *Globobulimina affinis, Globigerina bulloides,* ?*Lagena* sp., ?*Lenticulina sp., Nodosaria tympaniplectriformis, Plectofrondicularia advena*, *Pyrgo* sp. cf. *P. oblonga, Pyrgo* sp. cf. *P. rotalaria*, *Siphonodosaria insecta*, *Uvigerina peregrina*, *Uvigerina subperegrina*, *Uvigerinella* sp. cf. *U. californica*, and *Valvulineria* sp. cf. *V. araucana*. The only specimens of *?Fursenkoina* sp., *Glandulina* sp. cf. *G. laevigata*, *Pyrgo* sp. cf. *P. oblonga*, and *Pyrgo* sp. cf. *P. rotalaria* in this study were collected in this zone. The two *Pyrgo* species are the only species found in this study with porcelaneous test walls.

Zone F is delineated based on sample P43. Foraminferan abundance in this zone is medium. Nine species of Foraminifera were found here: *Cibicides mckannai*, *Globobulimina affinis*, *Lagena striata*, *Pullenia* sp. cf. *P. subcarinata*, *Siphonodosaria insecta*, *Uvigerina hootsi*, *Uvigerina peregrina*, *Uvigerina subperegrina*, and *Uvigerinella* sp. cf. *U. californica*. The only example of *Pullenia* sp. cf. *P. subcarinata* in this study was found in this zone.

Zone H is delineated based on sample P45. Foraminiferan abundance in this zone is high. Nineteen species were found in this zone: *Bulimina* sp., *Bulimina subacuminata*, *Cassidulina minuta*, *Cassidulina translucens*, *Cibicides mckannai*, *Eponides* sp. cf. *E. repandus*, *Epistominella pacifica*, *Epistominella* sp., *Globigerina bulloides*, *Hansenisca* sp. cf. *H. soldanii*, *?Lagena* sp., *Lagena striata*, *Nodosaria tympaniplectriformis*, *Plectofrondicularia advena*, *Pullenia* sp. cf. *P. bulloides*, *Siphonodosaria insecta*, *Uvigerina hootsi*, *Uvigerina peregrina*, and *Uvigerina subperegrina*. The only specimens of *Eponides* sp. cf. *E. repandus* and *Pullenia* sp. cf. *P. bulloides* in this study were collected from this zone.

Zone J is delineated based on sample P47. Abundance in this zone is medium. Fifteen species were found in this zone: *Bulimina* sp., *Bulimina subacuminata*, *Cassidulina minuta*, *Cassidulina translucens*, *Cibicides mckannai*, *Epistominella pacifica*, *Epistominella* sp., *Hansenisca* sp. cf. *H. soldanii*, ?*Lagena* sp., *Lagena striata*, *Plectofrondicularia advena*, *Siphonodosaria insecta*, *Uvigerina hootsi*, *Uvigerina peregrina*, and *Uvigerina subperegrina*.

Zone K is delineated based on sample P48. Foraminiferan abundance in this zone is low. Twelve species of Foraminifera were collected: *Bulimina subacuminata*, *Cassidulina minuta*, *Cassidulina translucens*, *Epistominella pacifica*, *Globobulimina affinis*, *Globigerina bulloides*, *Lenticulina* sp. cf. *L. calcar*, *Guttulina* sp. cf. *G. ovata*, *Siphonodosaria insecta*, *Uvigerina hootsi*, *Uvigerina peregrina*, and *Uvigerina subperegrina*. This zone records the only occurrence of *Lenticulina* sp. cf. *L. calcar* and *Guttulina* sp. cf. *G. ovata* in this study.

Zone L is delineated based on sample P49. Foraminiferan abundance in this zone is high. Eleven species were found in this zone: *Bulimina* sp., *Bulimina subacuminata*, *Cassidulina translucens*, *Cibicides mckannai*, *Epistominella pacifica*, *Epistominella* sp., *Globobulimina affinis*, *Globigerina bulloides*, ?*Lagena* sp., *Uvigerina hootsi*, and *Uvigerina peregrina*.

Zone N is delineated based on sample P52. Foraminiferan abundance in this zone is low. Eleven species were found: *Bulimina* sp., *Bulimina subacuminata*, *Epistominella pacifica*, *Epistominella* sp., *Globigerina bulloides*, ?*Lagena* sp., ?*Lenticulina* sp., *Plectofrondicularia californica*, *Uvigerina hootsi*, *Uvigerina peregrina*, and *Uvigerina subperegrina*.

Zone O is delineated based on sample P53. Foraminiferan abundance in this zone is medium. Nine species were found: *Bulimina subacuminata*, *Cassidulina translucens*, *Cibicides mckannai*, *Epistominella pacifica*, *Globobulimina affinis*, ?*Lagena* sp., *Lagena striata*, *Uvigerina peregrina*, and *Uvigerina subperegrina*.

Zone Q is delineated based on sample P55. Foraminiferan abundance in this zone is medium. Fourteen species were found: *Bulimina subacuminata, Cassidulina minuta, Cibicides mckannai, Epistominella pacifica, Globobulimina affinis, Hansenisca* sp. cf. *H. soldanii*, ?*Lagena* sp., ?*Lenticulina* sp., *Plectofrondicularia advena*, *Plectofrondicularia californica*, *Siphonodosaria insecta*, *Uvigerina hootsi*, *Uvigerina peregrina*, and *Uvigerina subperegrina*.

<u>Stratigraphy above studied section</u>. Detailed descriptions of the lithology of the upper portion of the Pullen at Scotia are included in work by Ogle (1953), but are very limited in detail, in terms of the stratigraphic positions of Foraminifera found within the succession. Ogle (1953) describes the portion of the Pullen above the basal sandstone as the “upper mudstone member”. He notes that minor lithologic variation, such as scattered calcareous nodules and thin glauconitic intervals that occur within the mudstone at various stratigraphic levels. Three limestone beds are also included within Ogles upper mudstone member. The lowermost sandy, yellow weathering limestone bed is described as being 0.6 m thick and lies 12 m above the contact with the basal sandstone (Ogle, 1953). This limestone bed should be within the strata sampled in this study, but was not observed after extensive searching, and thus is not included in the stratigraphic column (Fig. 21). The second limestone bed is described as a dark gray impure limestone that weathers to yellow-orange and is also 0.6 m thick. This limestone bed lies 120 m above the contact with the basal sandstone (Ogle, 1953). The uppermost limestone bed is described as a light gray silty and brecciated limestone that is 0.6 m thick and lies 10 m below the top of the Pullen Formation (Ogle, 1953). These limestone layers could

represent times in which the rate of the deposition of siliceous sediment was at a stop or very low, and the production of biogenic carbonate was high.

Paleontology

In the Pullen Formation, 38 species of Foraminifera were found within the sampled section (Table 2). Of those, 12 were included (26 not reported) in Haller's (1980) study, based on a total of three samples from the Pullen Formation at Scotia. Two of Haller’s (1980) samples (D-1379 and D-1380) were taken from the upper portion of the Pullen Formation, which was not accessible for this study. However, Haller’s sample D-1378 was taken 55 m above the base of the formation, in proximity to strata sampled for this study. Haller (1980) reported only two foraminiferan species from sample D-1378, *Cyclammina cancellata* and *Cyclammina* sp., neither of which were observed in any of the Scotia samples evaluated here.

This study concurs with Haller’s (1980) observations that Foraminifera are limited to certain stratigraphic intervals, but differs in his assertion that foraminiferan associations are impoverished with regard to number of species in intervals where they are found. Taxa documented for the first time here from the lower portion of the Pullen Formation at the Scotia locality include: *Bulimina subacuminata, Eponides* sp. cf. *E. repandus, Epistominella pacifica, Fissurina* sp. cf. *F. lucida, ?Fursenkoina* sp., *Glandulina* sp. cf. *G. laevigata, Glandulonodosaria* sp. cf. *G. ambigua, Globobulimina affinis, Guttulina ovata, Hansenisca* sp. cf. *H. soldanii, Lagena striata, Lenticulina* sp. cf. *L. calcar, Nodosaria tympaniplectriformis,* ?*Oolina* sp., *Orbulina universa,* *Plectofrondicularia californica*, *Pullenia* sp. cf. *P. subcarinata*, *Pullenia* sp. cf. *P. bulloides, Pyrgo* sp. cf. *P. oblonga, Pyrgo* sp. cf. *P. rotalaria, Siphonodosaria insecta, Uvigerina* sp. cf. *U. hannai, Uvigerina hootsi, Uvigerina subperegrina*, *Uvigerinella* sp. cf. *U. californica,* and *Valvulineria* sp. cf. *V. araucana*.

With the exception of some very small shell fragments (<1 cm) in the concretions of the upper portion of the basal sandstone unit, macrofossils were not observed in the exposed parts of the Pullen during this study. Haller (1980) also reports that macrofossils are very scarce and poorly preserved in the middle and upper portion of the type section at Scotia, but does not describe the species he found. In the middle portion of the basal section of the Pullen, clusters of *Anadara trilineata* (Fig. 22) were found by Miller and Aalto (2008). Other identifiable molluscan macrofossils in the basal section are rare and include *Clinocardium* sp. and *Yoldia* sp. (Miller and Aalto, 2008). Clusters of the trace fossil *Rosselia socialis* occur within the basal sandstone beds, as well as the ichnospecies *Schaubcylindrichnus formosus* and ?*Palaeophycus* isp. (Miller and Aalto, 2008). In his report, Ogle (1953) also notes that macrofossils are poorly preserved in the basal sandstone of the Pullen, but was able to identify the bivalves *Spondylus* n. sp. and *Anadara* sp. cf. *A. osmonti*. Roth (1979) also states that macrofossil in the Pullen are rare, poorly preserved and primarily composed of the bivalves *Delectopecten randolphi* and *Yoldia* sp. Within the basal portion he also notes the infrequent occurrence of the bivalves: *Anadara trilineata*, *Megacrenella* sp., *Chlamys* sp., *Swiftopecten* sp., *Clinocardium* sp., *Nemocardium* sp., *Solen* sp., *Panopea estrellana*, and *Thracia* *trapzoides* (Roth, 1979). Foraminiferan associations indicating a late Miocene age in the lower portion of the basal Pullen strata were also found (Ogle, 1953).

Table 2 - Pullen Formation Foraminifera relative abundance of species by sample. V = very common >10%, C = common <10 % but > 5%, U = uncommon <5%

Biostratigraphic Zone	**A**	**B**	**B**	**C**	**D**	**E**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**M**	**N**	**O**	**P**	**Q**
Sample Number **Species**	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
Bulimina sp.					U					U		C		U			U			
†*Bulimina subacuminata*	C				U					U		V	V	V			C	U		C
Cassidulina minuta										U		U	U							U
Cassidulina translucens	U			U						U		C	V	C				C		
Cibicides mckannai				C				U		U		U		C				U		U
Elphidium sp.												U								
Eponides sp. cf. *E. repandus*										U										
Epistominella pacifica	V			V	V					U		V	V	C			C	V		V
Epistominella sp.	U			U						U		U		U			C			
Fissurina sp. cf. *F. lucida*				U	V															
Glandulina sp. cf. *G. laevigata*					U															
†*Glandulonodosaria ambigua*				U																
Globobulimina affinis	U			U	U			V					C	V				U		U
Globigerina bulloides	C				U					U			U	U			U			
Guttulina sp. cf. *G. ovata*													U							
Hansenisca sp. cf. *H. soldanii*	V									C		U								V
?*Lagena* sp.					U					U		U		U			V	U		C
Lagena striata				U				U		U		U						U		
?*Lenticulina* sp.					U												U			C
Lenticulina sp. cf. *L. calcar*													U							
Nodosaria sp.				U	V															
†*Nodosaria tympaniplectriformis*				U	U					U										
?*Oolina* sp.	U																			
Orbulina universa	C																			
†*Plectofrondicularia advena*					U					U		C								U
†*Plectofrondicularia californica*	V			C													V			U
Pullenia sp. cf. *P. subcarinata*								U												
Pullenia sp. cf. P. *bulloides*										U										
Pyrgo sp. cf. *P. oblonga*					U															
Pyrgo sp. cf. *P. rotalaria*					U															
†*Siphonodosaria insecta*	C			V	V			C		V		C	U							C
†*Uvigerina* sp. cf. *U. hannai*				U	V															
Uvigerina hootsi	C			V				V		C		C	V	U			C			C
Uvigerina peregrina	U			U	U			U		U		U	U	U			V	U		U
†*Uvigerina subperegrina*	U			U	V			V		V		V	V				V	V		C
Uvigerinella sp. cf. *U.californica*				C	C			V												
Valvulineria sp. cf. *V. araucana*					U															
?*Fursenkoina* sp.					U															

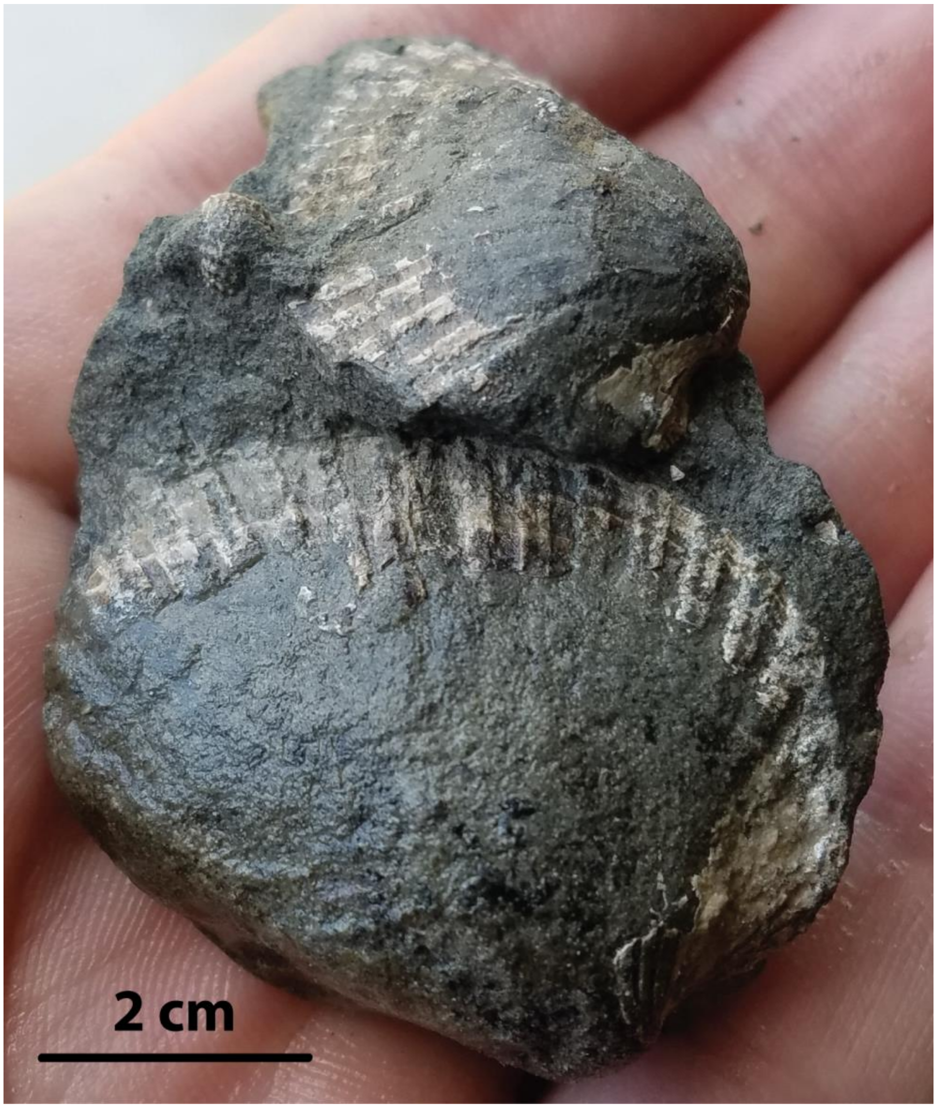


Figure 22 - Photograph of a cluster of poorly preserved *Anadara trilineata* in sandstone from the middle portion of the basal section of the Pullen Formation (sample collected by Miller and Aalto, 2008).

INTERPRETATION AND PALEOECOLOGY

Saint George Formation

Paleobathymetry

The depositional environment of the Saint George Formation was interpreted by Aalto (2006) and Robinson, (2001) as being either open shelf, below wave base or an embayment with open ocean access. The molluscan fauna of the Saint George, although low in species richness, is very similar to that found in the neighboring Wimer Formation (Watkins, 1974). Watkins (1974) notes the dominance of *Macoma nasuta* and *Cryptomya californica* in strata that he interpreted to be deposited in a protected coastal mudflat of intertidal or very shallow subtidal depth with brackish conditions. *Nassarius* sp., *Solen perrini*, cardiid indet., cheilostome bryozoans, and internal and external molds of a very infrequently occurring rotaloid foraminiferan can all be found in the Wimer (Watkins, 1974). His “cardiid indet.” could be the same as *Clinocardium* sp. found in the Saint George in this study, and *Solen perrini* could be conspecific with *Solen* sp. Although Watkins (1974) did not describe the size of the rare rotaloid foraminiferan molds that he found, it is possible that they are those of *Elphidium* sp, as it also exhibits a rotaloid morphology. Watkins (1974) noted that diatoms occurred in the Wimer, but did not identify them. *Geodia* sterrasters, or sponge spicules of any sort, were not mentioned in Watkins (1974) study.

The fossil deposits found in the Saint George Formation consist entirely of shallow-water taxa. *Macoma nasuta* has a depth range of intertidal to 50 m (Cowles, 2005). *Macoma inquinata* also has a maximum depth of 50 m (Harbo, 1997). Bivalve species occurring in Northern California and Oregon, *Solen sicarius* and *Clinocardium nuttallii*, are also present at that depth range in modern environments, and *Nassarius fossatus* is found in muddy embayments in the northeast Pacific at depths no greater than 18 m (Cowles, 2005). The microfossils of the Saint George also point towards a shallow environment. Many species of *Elphidium* occur in the intertidal zone and are known to inhabit mudflats and salt marshes (Korsun et al., 2013). The demosponge *Geodia mesotriaena* can be found growing on and under rocks within the intertidal and shallow subtidal zones in modern environments (Dickinson, 1945). *Arachnoidiscus japonicus* has a larger depth range, but also can be found attached to algae within the shallow sublittoral zone (Al-Handal and Wulff, 2008). In all, no species were found in the Saint George that indicated a deep water environment.

Brackish water habitats often exhibit low biodiversity, like that of the Saint George (Lecuyer, 2014). Of the small number of species found in the Saint George in this study, all but one are tolerant of brackish waters. *Macoma nasuta*, *Macoma inquinata*, and *Solen sicarius* frequently occur in brackish embayments (Cooper, 1870). Many species of *Elphidium* are well known for their tolerances of brackish waters and are present in estuarine environments around the world (Gupta, 2002). *Elphidium williamsoni* is one such species occurring in the Pacific northwest that prefers a brackish environment (Murray, 2002). Species of the demosponge genus *Geodia* can also occur in brackish conditions (Corriero et al., 2007). While *Arachnoidiscus japonicus* is considered a marine neritic species, many of the diatoms identified in the Saint George indicate a brackish habitat (Fig. 20). Both the macrofossils and microfossils of the Saint George are highly indicative of a brackish environment, or at very least an environment that was subject to periodic salinity fluctuations.

The association dominated by *Macoma nasuta* and *Cryptomya californica* in the Wimer Formation is also very similar to molluscan associations in modern muddy deposits in San Francisco Bay (Atwater et al., 1977). It is possible that the late Miocene subsidence event, marked at the base of the Saint George Formation by the submergence of the paleoforest, initiated the formation of a large, shallow, brackish embayment, much like that of San Francisco Bay, albeit with less access to the open ocean. This embayment could have extended over the entire Crescent City area and further inland to where the now-uplifted Wimer deposits are found. The fine-grained textures characteristic of the Saint George, coupled with the low species richness of molluscan and monospecific foraminiferan associations tolerant of brackish conditions, support this interpretation and will be discussed below.

Stanton and Dodd (1970) conducted a study of the modern benthic invertebrates of San Francisco Bay, a very large brackish estuary (Peterson, 2007). They noted a dominance of *Macoma* and an absence of *Cryptomya* occurring at the transition between the inner bay and the middle bay (Stanton and Dodd, 1970). Molluscan associations in the middle bay also included *Clinocardium*, *Solen* and *Nassarius* (Stanton and Dodd, 1970). Based on molluscan faunal evidence, this middle bay depositional environment could be analogous to that of the Saint George. The *Cryptomya* and *Macoma* dominated association found in the inner bay zone of San Francisco Bay (Stanton and Dodd, 1970) is much like the molluscan association described by Watkins (1974) in the Wimer Formation.

The foraminiferan associations of the Saint George Formation are monospecific, as only *Elphidium* sp. was found in this study. Hayward (2014) conducted a study of monospecific foraminiferan associations in New Zealand. The monospecific faunas included in his study only occur in sheltered, often brackish, intertidal or shallow subtidal environments at depths no greater than 25 m (Hayward, 2014). In Hayward's study (2014), *Elphidium excavatum clavatum*, *Elphidium williamsoni*, and *Elphidium gunteri* represented monospecific foraminiferan associations in sheltered intertidal to shallow-subtidal lagoonal, estuarine and inlet environments. None of the monospecific *Elphidium* associations are known to occur on exposed coasts or in open ocean depositional environments (Hayward, 2014). Monospecific foraminiferan associations in strata can occur due to environmental conditions or as a result of taphonomic processes (Hayward, 2014). The environmental conditions of the Saint George at the time of deposition were likely unfavorable for most species preferring normal marine salinity, as is represented by low diversity and high dominance of both the foraminiferans and the mollusks. In addition, many of the taxa prefer estuarine environments or have living counterparts that prefer such environments.

The monospecific Foraminifera association and the *Macoma*-dominated molluscan association of the Saint George are indicative of deposition within a brackish, sheltered bay at shallow depths and probably not an open-shelf environment. It is within reason that the sandy mudstone of the Saint George Formation represents a mid-bay depositional environment, considering the San Francisco Bay model, and that the coeval Wimer Formation represents an inner-bay to mudflat depositional environment of a shallow embayment that was formed in the Crescent City area during a tectonically-induced subsidence event that occurred during the late Miocene.

Preservation Patterns

The prominent shell beds found within the Saint George are likely storm-related deposits and are probably winnowed lags resulting from currents produced during storm events. Storm-produced bottom currents are known to create shell "pavements" like those found in the Saint George (Fig. 23). During normal sedimentation and favorable environmental conditions, the benthic organisms at the seafloor are spread out with varying abundance (Chen, 1996). During a large storm, bottom currents become strong enough to entrain and transport small sediments, leaving the larger bioclasts behind and creating a densely shell-packed deposit (Chen, 1996). After the storm currents subside, normal deposition returns and fills the interstices of the shell bed with sediment. This cycle continues over time, and results in cyclical preservation of shell pavements that are often the most obvious signs of sedimentary layering in otherwise massive shallow marine and estuarine successions. While the productivity of the local molluscan taxa plays a key role, Chen (1996) notes that the thickness of the lag deposit is also dependent on the strength and duration of the storm currents.

The lack of obvious bedding, other than the shell deposits, in the Saint George Formation is likely caused by bioturbation. Bioturbation is known to erase depositional lamination in marine environments and homogenize grain size (Zijlstra, 1995). When organisms burrow through sedimentary layering, they mask, disrupt, or completely obliterate bedforms by mixing up the sediments both laterally and vertically. If sufficient bioturbation occurs, primary bedding can be completely obscured. In the Saint George Formation, Robinson (2001) notes extensive bioturbation throughout the strata, which is in concurrence with the author's observations.

Bedding unit I (Fig. 11) of the Saint George Formation exhibits hummocky cross-stratification. Hummocky cross-stratification is indicative of oscillatory currents or waves (Yang et al., 2006). This type of stratification is commonly found in silt and fine sand, and is identified by randomly oriented antiformal hummocks and synformal swales (Dodd, 1982). Hummocky bed sets can range in thickness from a few centimeters to tens of meters (Dodd, 1982). The hummocky cross-stratification in bedding unit I of the Saint George could be storm related, and representative of an event that was much larger than those that created the shelly lag deposits. The waves/currents of this large storm had sufficient energy to completely relocate any molluscan shells (assuming they were there to begin with), as none are found in bedding unit I. The grain size of bedding unit I is also noticeably coarser than any other bedding unit as it is a muddy sandstone, rather than a sandy mudstone. This coarser grained sediment was likely transported during a large storm from a nearby source and redeposited in the Saint George. Hummocky cross-stratification is also a common sedimentary structure in tsunamiites (Shiki, 2008), which is also a possible deposition mechanism in bedding unit I. The unit could record the

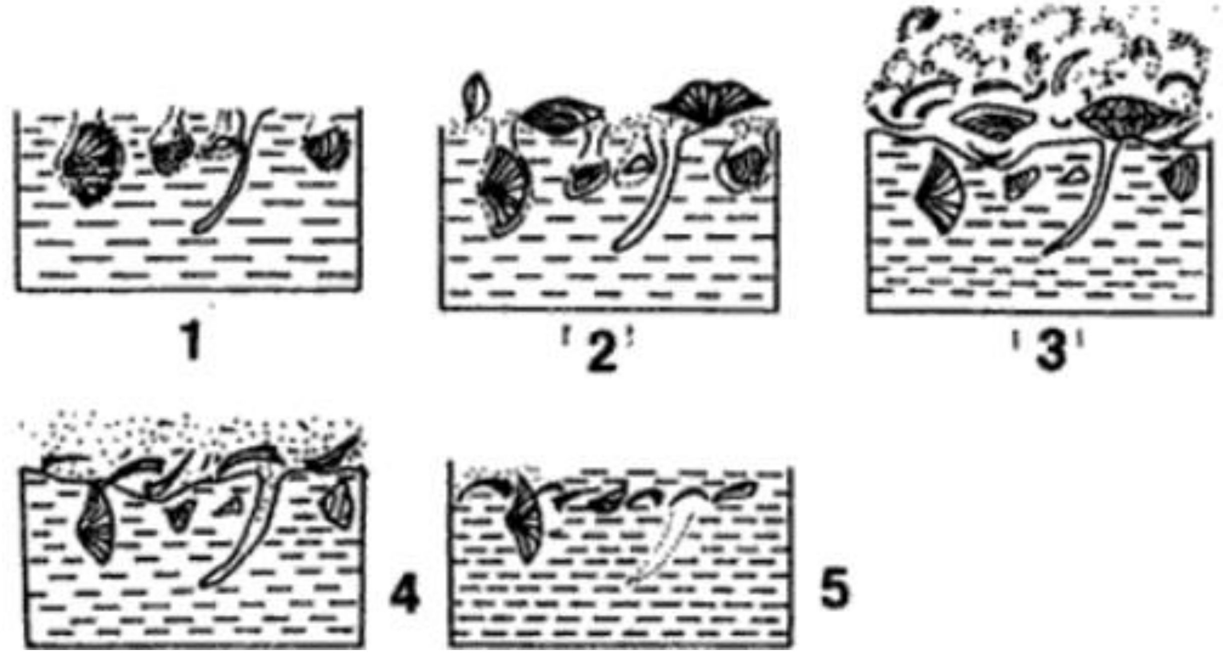


Figure 23 - Evolution of a storm current derived lag deposit and the resulting shell pavement. 1, normal deposition with fauna in life position; 2, normal deposition over time, resulting in vertical distribution of live and dead fauna; 3, storm current entrainment and winnowing of fine sediment fraction; 4, a return to normal (post-storm current) deposition; 5, preserved shell pavement after diagenetic compaction (reproduced from Chen, 1996, fig. 4).

resulting deposition of a series of tsunami waves following a very large earthquake in the CSZ, or tsunami waves generated by a distal event.

Pullen Formation

Paleobathymetry and Temperature

Miller and Aalto (2008) refuted a previous interpretation by McCrory (1989), that the basal portion of the Pullen Formation was deposited at bathyal depths. They based their argument upon the occurrence of the trace fossil *Rosselia socialis*, found in abundance within the basal sandstone beds. *Rosselia socialis* ichnofabric is indicative of a littoral to inner-shelf depositional setting with high net sedimentation rates and is not found in bathyal deposits (Miller and Aalto, 2008). The occurrence of *Anadara trilineata* within the basal sandstone also supports that interpretation, as most species of *Anadara* occur in shallow shelf environments (Miller and Aalto, 2008). Furthermore, Ogle (1953) states that the occurrence of *Spondylus* found within the basal sandstones of the Pullen at Scotia indicates a shallow environment. Thus, the macrofossil evidence indicates that the basal portion of the Pullen was deposited in a nearshore environment, after which rapid regional subsidence occurred, creating a significantly deeper depositional environment represented by the middle and upper portions of the Pullen.

Previous interpretations based on Foraminifera in the mudstones of the middle and upper portions of the type locality of the Pullen Formation at Scotia indicate a bathyal depth at the time of deposition (Ogle, 1953; Haller, 1980). Ogle (1953) also states that significant deepening in various westward locations of the Pullen can be seen in the overall biostratigraphic succession, and that benthic foraminiferans indicative of possible abyssal depths can be found in some of the upper sections of the Pullen in westward areas.

Published depth ranges (both upper and lower) of Foraminifera vary greatly from region to region. For instance, Phleger (1963) states that the lower depth range for *Cibicides mckannai* is 180 m in southern California and Mexico, yet Smith (1964) states that the same species is found in samples from depths greater than 3200 m in the Pacific offshore of Central America. Phleger (1963) was aware of such variations and notes that even in his own published work there exists large differences in lower depth ranges of *Elphidium gunteri* that were recorded between samples. He also states that "meaningful boundaries between foraminiferal depth associations are difficult to determine and often are based largely on the opinion of the person who defines them" (Phleger, 1963, p. 280). Therefore, rather than looking at depth ranges of benthic Foraminifera from around the world, the paleodepths inferred in this study of the Pullen Formation are taken from a study of modern foraminiferan associations of Northern California (Bandy, 1953, 1966, 1972).

In this study, the benthic foraminiferan associations found in the Pullen are characteristic of bathyal depths, which is in agreement with Haller (1980) and Ogle (1953). The bathyal zone is defined as having depths between 200 and 3000 m (Gebruck et al. 1997). The commonly occurring and depth diagnostic species *Uvigerina peregrina, Epistominella pacifica, Bulimina subacuminata,* and *Cassidulina translucens* have been described in modern marine sediments offshore from San Francisco (Bandy, 1953), and were used as the basis for depth interpretation in this study. In Bandy's (1953) study, the occurrence of *Uvigerina peregrina* indicated a bathyal setting in general, of which three bathyal subzones (upper, middle and lower) were delineated based on the co-occurrence of other foraminiferan species. The middle bathyal (450-900 m) zone is marked by a foraminiferan association including *Uvigerina peregrina* and *Epistominella pacifica*, whereas a co-occurrence of *Uvigerina peregrina* with *Bulimina subacuminata* and *Cassidulina translucens* indicates deposition in the lower bathyal (900-1800 m) zone (Bandy, 1953).

Uvigerina peregrina can be found throughout all of the biostratigraphic zones containing Foraminifera described in this study, indicating an overall bathyal depth. Furthermore, *Epistominella pacifica* can also be found in all but 1 zone (Zone F). The co-occurrence of these two species point towards a mid-bathyal depositional environment, like that described by Bandy (1953). However, species indicating a lower bathyal depth (*Bulimina subacuminata* and *Cassidulina translucens*) can also be found in the studied section, but are found in greater abundance upsection (Zones J, K, L, N, O and Q). The increase in occurrence of the lower bathyal diagnostic species likely records a deepening of the depositional environment in the studied section and a transition from middle bathyal to lower bathyal conditions over time. This record of a deepening trend moving upsection is in agreement with Ogle's (1953) interpretation, as he noted that the during deposition of the upper Pullen beds, depths may have been as great as 1200-1800 m.

Two species of planktic Foraminifera (*Globigerina bulloides* and *Orbulina universa*) were found in this study (Table 2). *Orbulina universa* was only found in zone

A, and with relatively high abundance. *Globigerina bulloides* was also found in relatively high abundance in zone A, but could also be found sporadically throughout the overlying succession (zones D, H, K, L, and N), albeit with lower abundance. Generally, the ratio of planktic Foraminifera to benthic Foraminifera (P/B ratio) increases from the nearshore area to the continental edge, after which it decreases sharply with depth (Zwann et al., 1990). This same general pattern is found within the Pullen strata, as the P/B ratio is highest at Zone A and significantly decreases upsection, indicating a deepening marine environment.

Ocean surface temperatures during the Mohnian Stage of the late Miocene record a cooling event based on planktic foraminiferan data, followed by a warmer cycle in the latest Miocene and into the Pliocene (Bandy, 1972). Temperatures in Bandy's (1953) study of benthic Foraminifera ranged from 8.8° C at the upper bathyal zone, down to 1.8° C at lower bathyal depths, and are likely similar to temperatures during deposition of the Pullen Formation. However, temperature does not seem to be an important controlling factor for bathyal benthic foraminiferan associations (Bandy and Chierici, 1966). Bandy and Chierici (1966) state that depth is the main controlling factor for bathyal species, as some modern bathyal Foraminifera with very wide depth ranges can be found in shallow, warm water in one area and deeper cooler waters in another area, indicating that temperature is not a large limiting factor in their distribution (Bandy and Chierici, 1966). In most benthic species of the neritic zone however, temperature is said to be the predominant controlling factor (Cushman, 1948).

Preservation Patterns

Agglutinated Foraminifera are apparently absent in the samples taken for this study. One possibility for their apparent absence is that the use of liquid nitrogen during the sample disaggregation process could have destroyed specimens. The rapid freezing and thawing may have damaged their arenaceous tests and relinquished the grains back to loose sediment. The disaggregation process used in this study was modeled after a foraminiferan extraction method from Remin et al. (2012); in their study they do not make mention of the disaggregation process in terms of the preservation of agglutinated foraminiferan tests.

The absence of agglutinated species in sedimentary rocks has also been attributed to diagenetic processes (Gibson, 1994), which is another possibility why agglutinated taxa are absent in the samples from the Pullen examined in this study. Bellanger (2011) reports a complete lack of agglutinated Foraminifera from the Newport Member of the Miocene Astoria Formation in Oregon. The majority of the specimens described in Bellanger's study were hyaline, and porcelaneous varieties were rare. This pattern is similar to the Pullen samples. Only two porcelaneous species were found in this study (*Pyrgo* sp. cf. *P. oblonga* and *Pyrgo* sp. cf. *P. rotalaria*), and the remainder of the species found were hyaline. The preservation potential of agglutinated varieties is much lower than that of Foraminifera with hyaline test walls, and the lack of agglutinated tests in samples could be attributed to this poor preservation potential and diagenetic processes that can destroy their tests prior to lithification of matrix sediments (Bellanger, 2011). It must be noted however, both Ogle (1953) and Haller (1980) reported agglutinated

Foraminifera in the Pullen. In fact, of Haller's (1980) three samples, the lowermost sample (D-1378) only had two reported species of Foraminifera, and both belonged to the same genus of agglutinated Foraminifera (*Cyclammina cancellata* and *Cyclammina* sp.).

No Foraminifera were found in biozones B, E, G, I, M, and P. There are a few possibilities that might account for this pattern. Medioli et al. (1985) state that apparent foraminiferan “barren zones” can be created by the winnowing of foraminiferan tests into the water column and subsequent transportation away from their environments during periods of high energy from waves or bottom currents. Rapid deposition of sediment can also be responsible for zones lacking Foraminifera (Tappan, 1951). Epibenthic Foraminifera live at the sediment water interface or in the upper centimeters of the sediment (Gupta, 2002). If sediment deposition was rapid enough, benthic Foraminifera would not have time to establish populations, as they would not be able to live and reproduce in such a dynamic environment.

A more likely possibility that could be responsible for the zones in the Pullen lacking foraminiferan tests is that times of prolonged anoxia at the sea floor excluded most taxa. One way that ocean anoxia occurs is due to upwelling and the associated increased decomposition of organic-walled phytoplankton, algae, and other organic remains at the sea floor. The eastern Pacific is subject to hypoxic/anoxic conditions in modern times under such conditions (Helly and Levin, 2004). Changes in, or the stagnation of, ocean currents resulting from variation in climate are said to be another causal mechanism in creating anoxic and hypoxic environments in the oceans (Chan et al., 2008) The hypoxic/anoxic conditions created from these processes can create oxygen minimum zones at the bathyal depths of the continental shelf break and slope which can persist over time (Helly and Levin 2004). Gupta (2002) states that anoxic conditions may inhibit the reproduction of Foraminifera and that after prolonged anoxia a total absence can occur. A study of benthic Foraminifera in the Santa Barbara Basin showed that some species could survive short periods in an anoxic environment, but that survival in prolonged anoxia did not occur (Bernhard and Reimers, 1991). Gupta (2002) also points out that higher concentration of toxic substances, particularly sulfides, are associated with anoxic environments and could be a contributing factor in limiting the potential for Foraminifera to establish substantial numbers.

Abundance and Diversity

Holburn et al. (2013, p. 2) states that "deep water benthic Foraminifera are generally cosmopolitan and their distribution within ocean basins is primarily controlled by environmental parameters." The influx of near surface organic carbon to the ocean floor provides a food source for benthic organisms, including Foraminifera. Foraminifera feed primarily on diatoms, algae, bacteria, and other organic matter (Murray, 2002). The availability of these food sources is likely to act as one of the primary limiting factors on absolute abundance of benthic foraminifera found at bathyal depths (Gupta, 2002). However, another factor can also influence the abundance of Foraminifera in a given area. In one study of benthic Foraminifera in the Arabian Sea off of Oman, changes in the levels of organic carbon influx did not seem to be primary limiting factor for abundance of benthic foraminiferan associations in the oxygen minimum zone at bathyal depths;

oxygen levels were thought to be the primary controlling factor (Naidu and Malmgren, 1995). However, both oxygen levels and food supply must be within tolerable levels for Foraminifera to occur in large populations.

Absolute abundance of Foraminifera in this study was not determined by counting specimens per sample volume, as much of the matrix sediment was lost during the wet sieving of samples following disaggregation. Instead, relative abundances were determined qualitatively as low, medium or high per sample based on the time taken to locate 50 specimens of foraminiferan tests in the loose sample sediments under magnification (Fig. 21). A low relative abundance (zones F, K, L, N, and O) could represent a time of sediment deposition when organic carbon influx and/or oxygen levels created an inhospitable habitat for Foraminifera. A medium relative abundance (zones A, J and Q) could represent somewhat favorable oxygen and organic carbon conditions for the foraminiferan associations, whereas the highest relative abundances (zones C, D, and H) possibly represent optimal conditions for Foraminifera to flourish.

While relative abundance varied considerably in the various biozones of the studied Pullen strata, the species richness remained relatively constant, only slightly decreasing over time (with increased depth). Evenness refers to the relative abundances of each species in a given area. In order to determine the ecologic diversity of the samples studied, 1-D values for Simpson's index of diversity were calculated. This diversity index incorporates both richness and evenness in its values. The equation used to determine D is [$D = \sum(\frac{ni(ni-1)}{N(N-1)})$]. In this equation n_i represents the number of individuals of a species, N represents the total number of specimens, and D represents dominance. Since D is a measure of dominance, as D increases, diversity decreases. This is why Simpson’s index is usually reported as its complement 1-D. Simpson's index 1-D gives values between 0 and 1 which correspond to the diversity of the sample, with high values representing a more diverse sample and low values representing a less diverse sample (more dominance).

In this study, a total of 26 genera and 38 species were identified in the Pullen Formation samples (Table 2): 24 benthic and 2 planktic genera; and 36 calcareous benthic and 2 planktic species. Most deep-sea (bathyal-abyssal) foraminiferan associations consist of a few common species and numerous rare ones (Gooday, 1999). This pattern is reflected in the foraminiferan associations found in the samples of the Pullen Formation. Common species such as *Epistominella pacifica, Uvigerina peregrina, Bulimina subacuminata*, and *Cassidulina translucens* are found in large numbers throughout the sampled interval, with the rare species occurring in some zones, but not in others (Fig. 24). The Simpson index 1-D values, shows a gradual decline moving upsection into deeper water in the studied part of the Pullen (Fig. 25). A pattern like this, of decreasing foraminiferan diversity with depth down the continental slope, is the general pattern seen at the continental margin of California (Douglas, 1981). However, once abyssal depths are reached, diversity tends to increase (Gooday, 1999).

Some of the more common genera found in this study were *Epistominella, Uvigerina, Cassidulina, Bulimina, and Globobulimina*. Gupta and Machain-Castillo (1993) report that these genera are amongst the few that tend to dominate foraminiferan associations at bathyal depths with oxygen-poor habitats. This same pattern is seen in the foraminiferan associations found in the Pullen.

Foraminifera have the ability to rapidly repopulate an area after a prolonged anoxic event. Gooday and Jorrison (2012) noted this kind of rapid recovery in local abundance in which the benthic foraminiferan populations were obliterated by anoxic events that lasted thousands of years in the eastern Mediterranean Sea. They report that post-event repopulation seems almost instantaneous in terms of geologic time (Gooday and Jorrison, 2012). The ability to repopulate an area rapidly is likely the result of the fact that Foraminifera produce propagules, which can be entrained and travel in currents in the water column (Gooday and Jorrison, 2012). Prolonged periods of complete anoxia are probably somewhat localized biogeographically, and since many modern benthic Foraminifera are known to be cosmopolitan, the repopulation of an otherwise barren area via foraminiferan propagules seems to be the likely mechanism. From data obtained in laboratory experiments, Alve and Goldstein (2003) also reported that propagule transport appears to be the primary way in which Foraminifera distribution and patch recovery occur. No Foraminifera were found in biozones F, K, L, N, and O in this study, which may have resulted from prolonged anoxic events. However, the biozones following those possible anoxic events have relatively the same ecologic diversity as the biozones prior to

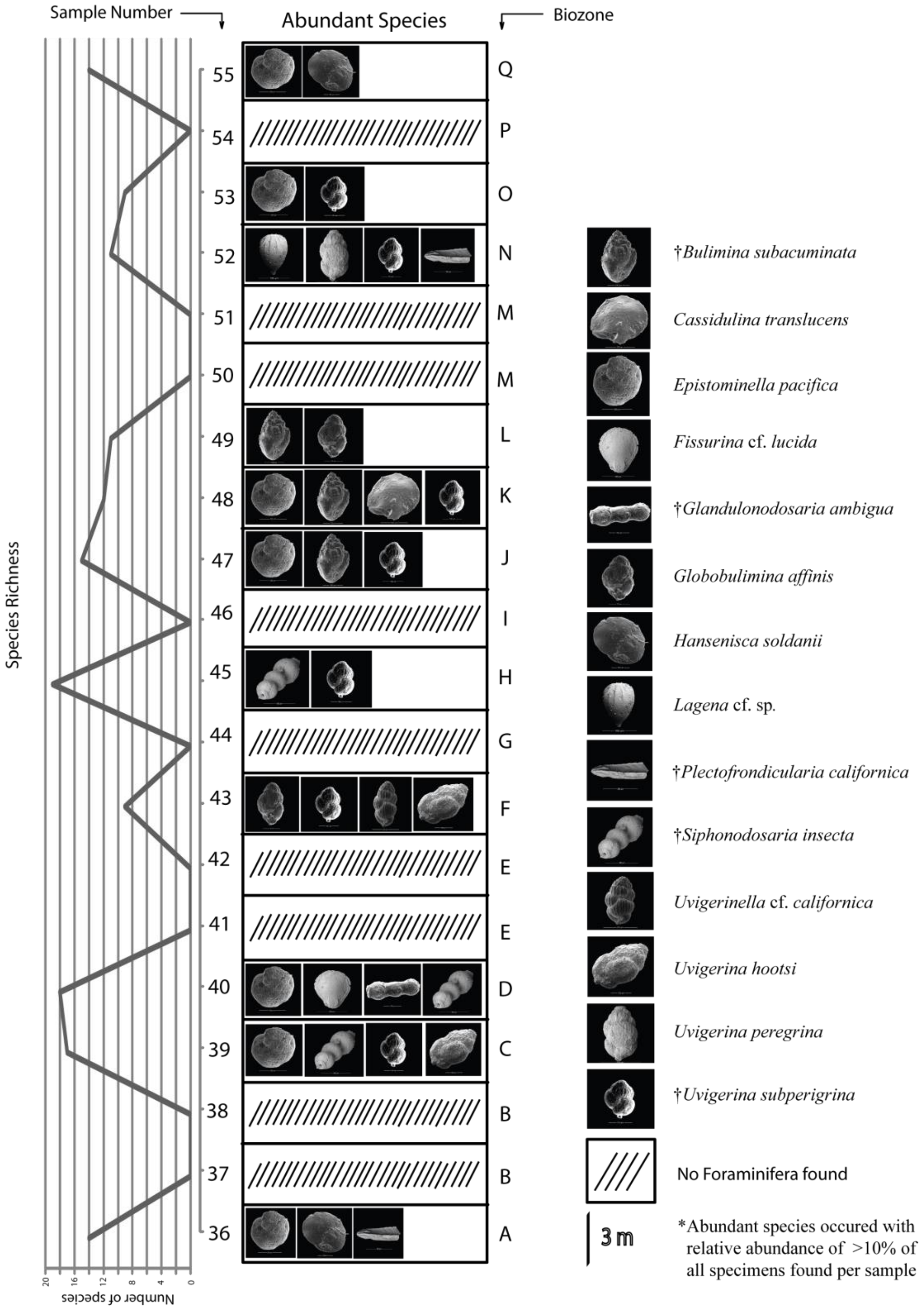


Figure 24 - Diagram showing the various abundant species (>10% of sample specimens) throughout the biozones of the Pullen Formation. The graph on the left shows species richness (number of species) found in each zone.

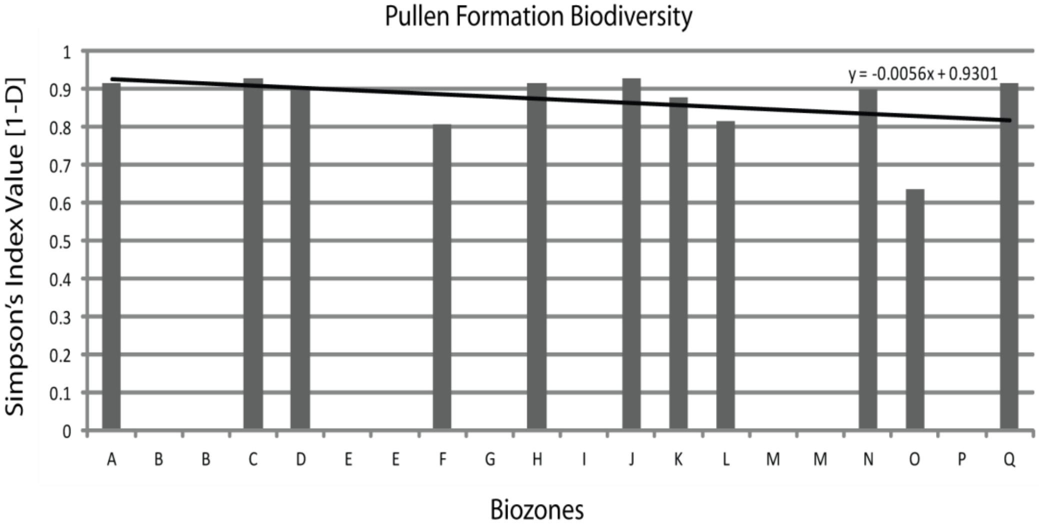


Figure 25 - Bar graph showing biodiversity in the biozones of the Pullen Formation as represented by Simpson's Index 1-D values.

the event, which is possibly due to post-event propagule dispersal from local benthic Foraminifera. This propagule dispersal process could also possibly account for the variation of rare species in the biozones of the Pullen that were deposited after the possible anoxic events. For instance, *Eponides* sp. cf. *E. repandus*, *Pullenia* sp. cf. *P. bulloides*, *Pullenia* sp. cf. *P. subcarinata*, *Glandulonodosaria ambigua*, and *Elphidium* sp. are only found in single biozones, all of which followed biozones that were devoid of Foraminifera. As stated in a previous section however, the stratigraphic resolution (2.6 m) at which samples were taken creates an element of uncertainty in this interpretation. The foraminiferan tests found could be accumulated in a shell pavement created by bottom currents, similar to the mollusks found in the Saint George. Another possibility is that times of rapid deposition created areas within section in which Foraminifera could not live. Since benthic Foraminifera live at or near the sediment water interface, rapid inundation of sediment would make that interface too dynamic for Foraminifera to establish populations.

Temporal Resolution

Pullen Formation

Unlike other eastern Pacific active margin shelves, modern sedimentation rates of the shelf break outward of the mouth of the Eel River are relatively rapid (0.2-0.4 cm/yr) (Sommerfield and Nittrouer, 1999). However, the rates in the southern Eel River Basin during the Miocene-early Pliocene were much lower (Gulick and Meltzer, 2002). The rate of deposition (based on the radiometric dates of interbedded ash deposits) in the lowermost Wildcat Group (Pullen) was 0.46 km/m.y. (Gulick and Meltzer, 2002). If that rate stayed constant, throughout the entire depositional history of the 337 m thick Pullen at Scotia, then the Pullen succession, from bottom to top, represents 732.6 k.y. Every meter of sediment in the Pullen would thus be equivalent to ~2200 years, assuming constant and continuous deposition. Therefore, the 51.4 m of mudstone section that were described in this study could possibly represent 112 k.y. of continuous deposition, assuming a rate of 0.46 km/m.y. However, sediment deposition is not always continuous and can vary greatly, which adds to the ambiguity of this determination. Also, erosive bottom currents can reduce the section via transportation of sediment out of the area.

A temporal signal in strata containing benthic Foraminifera in California can be obtained with the help of foraminiferan guide fossils (Haller, 1980). Using these guide fossils, a series of foraminiferan stages in California were devised and named by geologists and micropaleontologists as a result of intensive work in the petroleum industry during the 1930s to 1960s, stemming from a need to correlate the various formations the different companies investigated (Haller, 1980). The age estimates of the stage boundaries were refined and updated over time with the emergence of new data (Haller, 1980). While these guide fossils tend to vary in importance latitudinally from south to north, a few are relatively consistent in age assignments, regardless of geographic location. *Plectofrondicularia californica* is one such foraminiferan guide fossil. Associations containing *Plectofrondicularia californica* were recognized by numerous micropaleontologists as only occurring in the Repettian Stage in California (Reed, 1933; Kleinpell, 1938; Woodring et al., 1938; Wissler, 1943; Natland, 1952; Holman, 1958). The Repettian Stage was named after the Repetto Formation in southern California and the foraminiferan associations within it (Haller, 1980). *Plectofrondicularia californica* is present in the Pullen in this study at both the lowermost, and uppermost portions of the sampled section. Therefore, the entirety of the sampled section must lie within the Repettian Stage. The Repettian Stage is confined to the lowermost Pliocene, and marks the transition from the late Miocene Delmontian Stage. The occurrence of *Plectofrondicularia californica* in the sampled section of the Pullen gives a temporal signal, although it does not allow small scale temporal resolution, as the Repettian Stage does not have exact beginning and ending dates assigned to it.

Trying to resolve the exact amount of time represented in a stratigraphic section in the absence of absolute radiometric dating data is a daunting task. However, the presence of *Plectofrondicularia californica* in the studied section allows for some general estimates; in this case lower Pliocene. Brett and Baird (2006) point out that temporal resolution based on biozonation tends to be coarse in its accuracy when trying to resolve temporal scales less than 10^6 years, and that most zones have not been calibrated using modern dating methods. This is the case with the Repettian Stage of California. Haller (1980, p. 214) states that "despite all the time-rock terminology, stratigraphic typology, and meticulous biostratigraphy, no biochronologic diagnosis of the Pliocene [foraminiferan] stages has been prepared or presented".

Saint George Formation

In the case of the Saint George Formation the foraminiferan association is monospecific, composed entirely of *Elphidium* sp. Because no foraminiferan guide fossils are found in the Saint George, a foraminferan stage could not be assigned. However, a correlation based on the diatom assemblage of the basal portion of the Saint George was made and provided an age estimate (Robinson et al., 2001). Many of the diatoms in the basal portion of the Saint George have late Miocene-early Pliocene age ranges; an age of 6.4-5.3 Ma was assigned to the basal portion based on the diatom assemblage (Robinson et al., 2001). The numerical age was determined by the occurrence of the age diagnostic diatom species *Delphineis sachalinensis*, *Lithodesmium minusculum*, *Thalassiosira antiqua*, *Thalassiosira temperei,* and *Thalassiosira miocenica* (Robinson et al., 2001). The time frame of 6.4-5.3 Ma was only for the basal portion of the Saint George, and no diatom time correlation was conducted for the overlying strata (Robinson et al., 2001). Thus, rather than foraminiferan biozonation, diatom biozonation indicates that the base of the Saint George is late Miocene-early Pliocene in age. In the absence of radiometric dating for the Saint George strata, the time represented within the studied section is unknown.

Schindel (1980, p. 408) states that “owing to discontinuous or low rates of sedimentation, it is either impossible or impractical to recover a continuous series of discrete life assemblages of fossil populations by collecting microstratigraphic samples from continuous fossiliferous intervals.” The intervals sampled in both the Pullen and Saint George likely record varying rates of sedimentation and periods of nondeposition or erosion. As this study focused on fossil associations at the microstratigraphic level, assigning anything other than a coarse time interval to the sampled section is not possible. For instance, the application of average, modern-day sedimentation rates of the Eel River Basin to the Pullen Formation in order to determine an age interval, does not account for hiatuses in deposition, erosion via bottom currents, compaction, or periods of higher than average deposition. Similarly, using the radiometric dates of ash deposits (Gulick and Meltzer, 2002) only captures the age of the sediment in the particular positions of the strata where the ash is found and the intervals between those ash layers cannot be relied on to represent a recorded period of continuous deposition. This brings up the concept of stratigraphic completeness.

Stratigraphic completeness refers to how much of a stratigraphic section has been preserved, without events of erosion or periods of nondeposition. Sadler (1981, p. 569) states that “continuity of sedimentation is directly linked to the notion of completeness in stratigraphic sections, and it follows that all stratigraphic sections must contain hiatuses at some scale. Although incompleteness is acknowledged, it is less easily quantified.” The assumption of this incompleteness at a microstratigraphic level, in terms of the ideal scale of sampling intervals, has been addressed by Schindel (1980). For instance, in order to determine if a regional extinction or habitat destruction of Foraminifera is apparent in samples from bathyal depths, Schindel (1980) suggests that between 100 mm and 1 m of strata needed to be sampled and studied in their entirety. This level of resolution is still not very precise, as the possible time span can be anywhere from 10^3 to 10^4 years due to variation in sedimentation rates over that time period (Schindel, 1980). Also, calculated average sediment accumulation rates tend to be lower when looking at large time spans, as the effect of periods of nondeposition are cumulative over time, and because the duration and frequency of these periods in a depositional environment are irregular (Sommerfield, 2006). Thus, due to the sampling intervals (3 m) of the Pullen Formation in this study, and the ambiguity in actual sedimentation rates represented in the studied section, it is not possible to know how complete the section is, nor how much time is represented in the studied section.

CONCLUSIONS

The Miocene-Pliocene boundary marks a time of dramatic geologic change in northwestern California. Evidence of a major subsidence event is preserved in the basal portions of the coeval Saint George and Pullen formations in which significant changes in paleobathymetry are apparent. The strata of the Saint George Formation exhibit evidence of a rapid change from a terrestrial, forested regime to a marine setting and the Pullen Formation strata examined in this study record initially shallow marine conditions followed by a rapid deepening to mid-bathyal depths. The main conclusions determined via this study are as follows:

1. The monospecific associations of the Foraminifera and the dominant species of the molluscan fauna of the Saint George Formation provide confirmation that the post-subsidence bulk of the strata in the Saint George was deposited in a shallow, sheltered, and likely brackish bay, rather than in open shelf conditions.

2. The similarity of the fauna in the coeval Wimer Formation could indicate that this bay may have extended well inland and covered a large area.

3. Foraminifera and *Geodia* sterrasters had not been observed in previous studies of the strata of the Saint George Formation. This study shows that, while rare, they are present and greatly aid in eliminating the ambiguity pertaining to the depositional environment of the Saint George Formation.

4. Foraminifera from the lower mudstone beds of the Pullen Formation have been described in previous studies, but with very low sample resolution. This study provided new records of foraminiferan species in the lower mudstones and with much better resolution.

5. The Foraminifera found in this study also provided confirmation of a profound change in bathymetry during the initiation of sedimentation of the Pullen Formation.

6. Foraminiferan data revealed possible periods of prolonged anoxia at bathyal depths during deposition of the Pullen Formation and evidence of a slow overall deepening of the depositional environment subsequent to the rapid change in paleobathymetry.

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Appendix A - Photomicrograph Plates

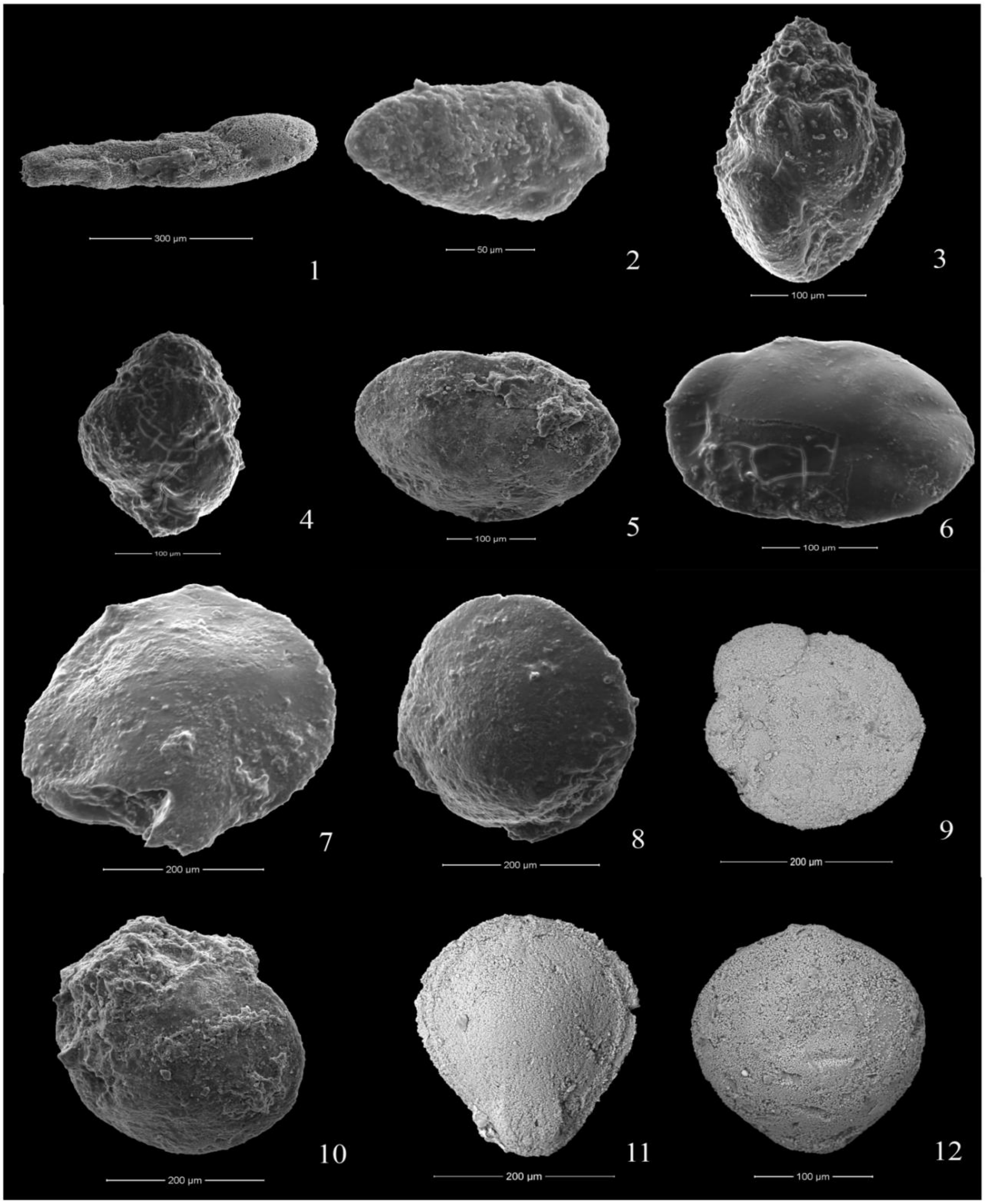

Plate 1 - Foraminifera from the Pullen Formation

Explanation of Plate 1

1) ?*Fursenkoina* sp.

2) *Bulimina* sp.

3) †*Bulimina subacuminata*

4) *Globobulimina affinis*

5) *Valvulineria araucana*

6) *Cassidulina minuta*

7) *Cassidulina translucens*

8) *Cassidulina translucens*

9) *Cibicides mckannai*

10) *Cibicides mckannai*

11) *Fissurina* sp. cf. *F. lucida*

12) ?*Oolina* sp.

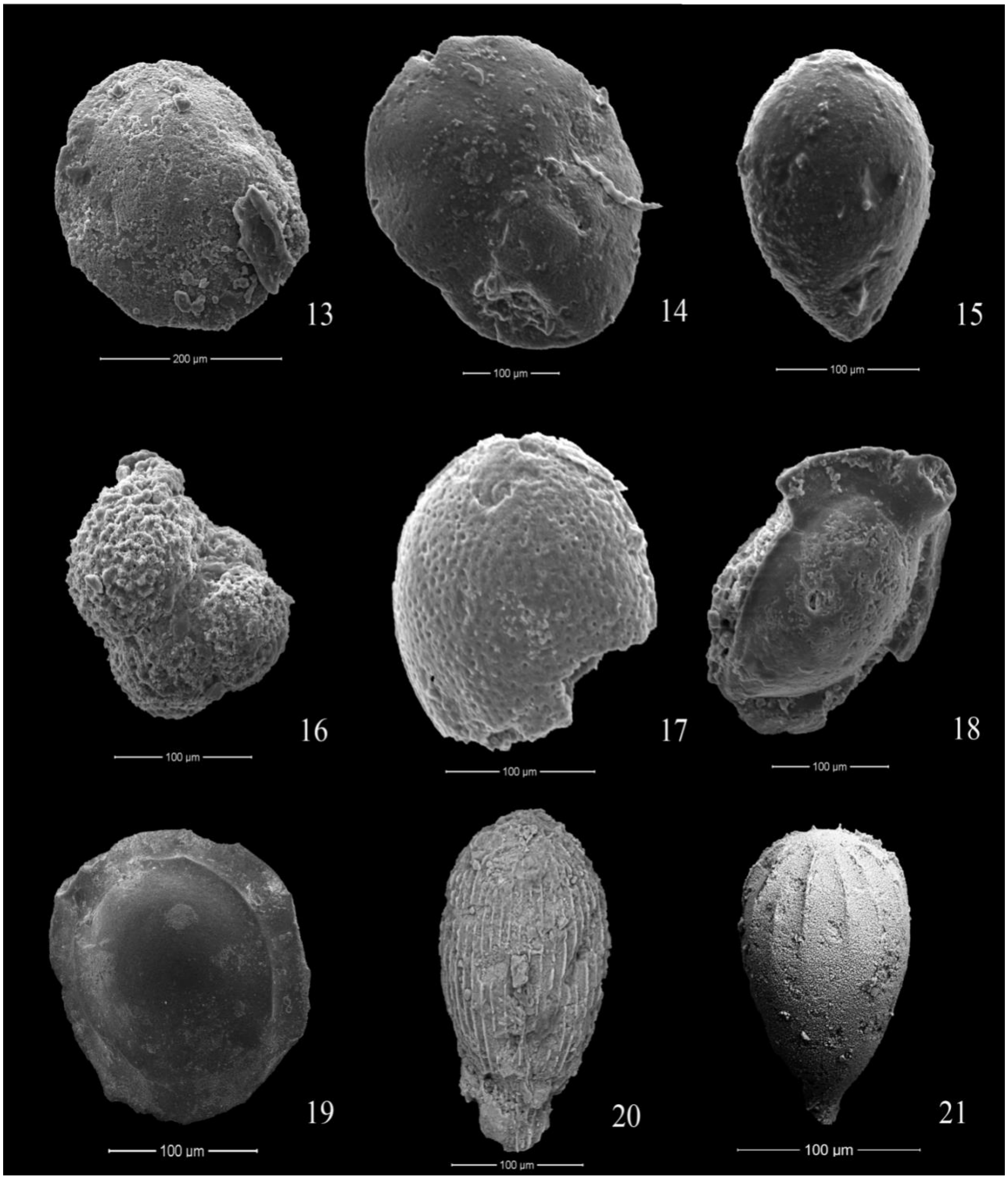

Plate 2 - Foraminifera from the Pullen Formation

Explanation of Plate 2

13) *Eponides* sp. cf. *E. repandus*

14) *Hansenisca* sp. cf. *H. soldanii*

15) *Glandulina* sp. cf. *G. laevigata*

16) *Globigerina bulloides*

17) *Orbulina universa*

18) *Pyrgo* sp. cf. *P. oblonga*

19) *Pyrgo* sp. cf. *P. rotalaria*

20) *Lagena striata*

21) ?*Lagena* sp.

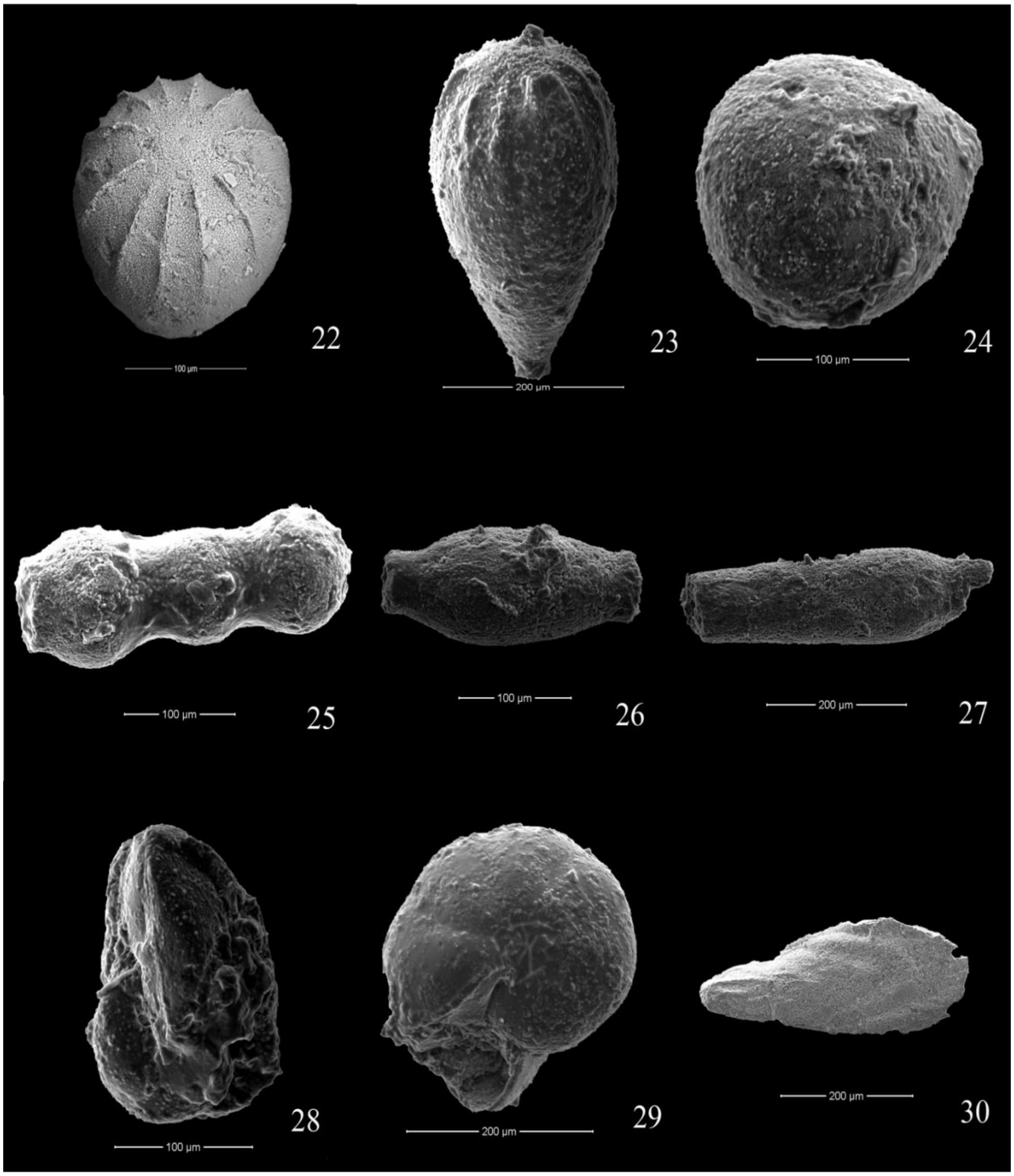

Plate 3 - Foraminifera from the Pullen Formation

Explanation of Plate 3

22) ?*Lagena* sp. (top view)

23) ?*Lagena* sp.

24) ?*Lagena* sp.

25) †*Glandulonodosaria ambigua*

26) †*Nodosaria tympaniplectriformis*

27) †*Nodosaria tympaniplectriformis*

28) *Pullenia* sp. cf. *P. bulloides*

29) *Pullenia* sp. cf. *P. subcarinata*

30) *Plectofrondicularia advena*

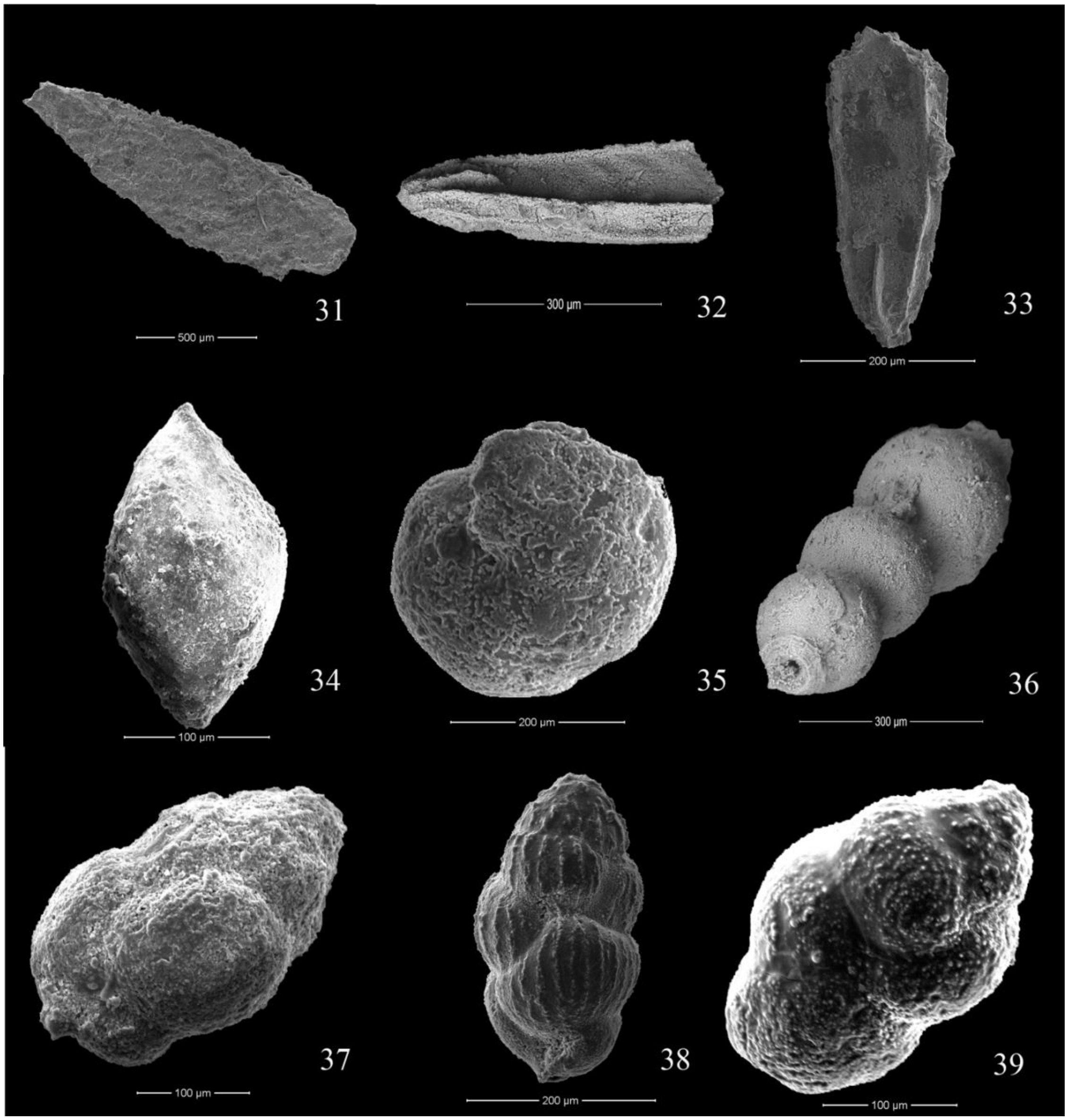

Plate 4 - Foraminifera from the Pullen Formation

Explanation of Plate 4

31) *Plectofrondicularia advena*

32) *Plectofrondicularia californica* (side view)

33) *Plectofrondicularia californica* (dorsal view)

34) *Guttulina* sp. cf. *G. ovata*

35) *Epistominella pacifica*

36) *Siphonodosaria insecta*

37) *Uvigerina hootsi*

38) *Uvigerinella* sp. cf. *U. californica*

39) *Uvigerina subperegrina*

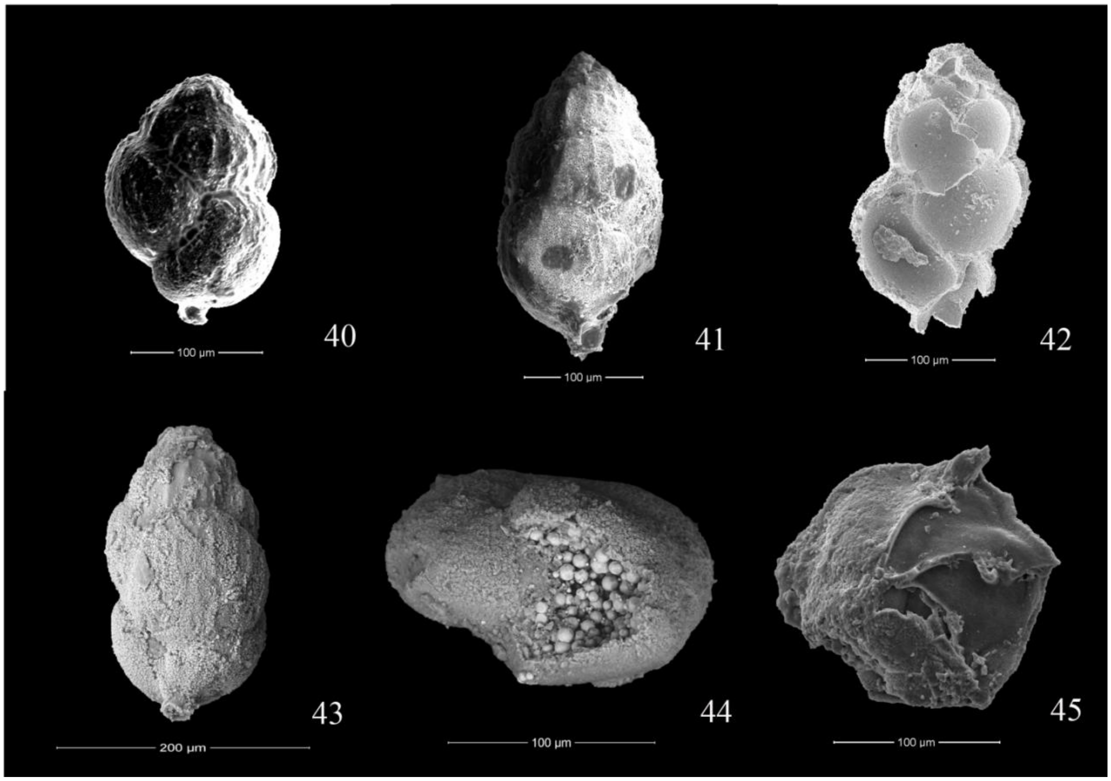

Plate 5 - Foraminifera from the Pullen Formation

Explanation of Plate 5

40) *Uvigerina subperegrina*

41) †?*Uvigerina hannai*

42) *Uvigerina peregrina* (internal view, test broken open)

43) *Uvigerina peregrina*

44)?*Lenticulina* sp.

45) *Lenticulina* sp. cf. *L. calcar*

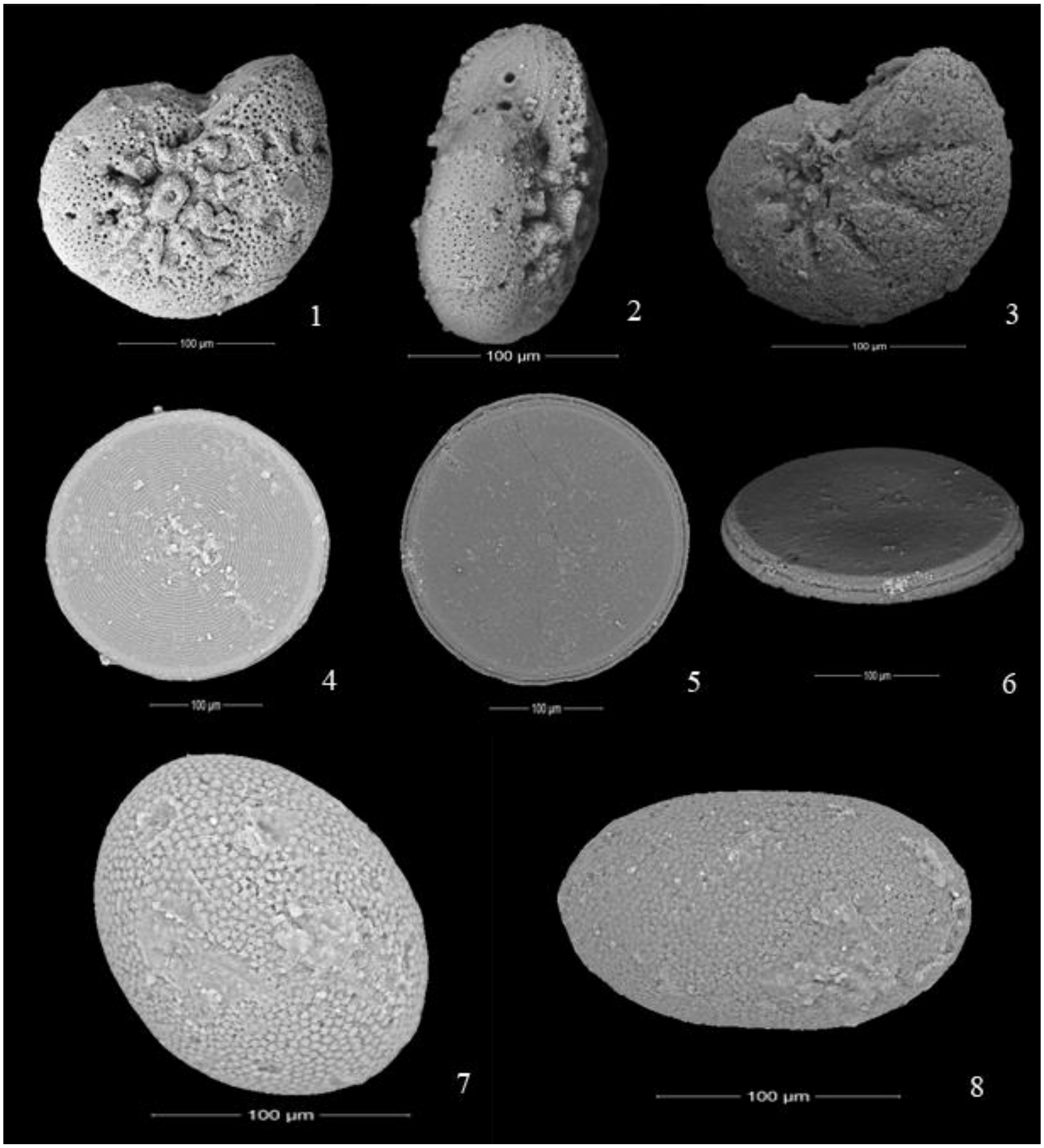

Plate 6 - Foraminifera from the Saint George Formation

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Explanation of Plate 6

1) *Elphidium* sp.

2) *Elphidium* sp. (apertural view)

3) *Elphidium* sp.

4) *Arachnoidiscus japonicus*

5) *Arachnoidiscus japonicus*

6) *Arachnoidiscus japonicus* (side view)

7) Sterraster from the demosponge *Geodia*

8) Sterraster from the demosponge *Geodia*

Appendix B

Systematic Outline of Foraminifera from the Pullen and Saint George Formations

(Classification used here follows the new system proposed by Pawlowski et al. 2013; only species-level taxa determined with confidence are listed, otherwise the classification does not extend beyond genera identified in this study.)

- Phylum Foraminifera
  - Class *Incertae sedis*
    - Order Lagenida
      - Family Ellipsolagenidae
        - Genus *Fissurina* (Reuss, 1850)
          - *Oolina* (Montagu, 1803)
      - Family Glandulinidae
        - Genus *Glandulina* (d'Orbigny, 1826)
      - Family Glandulonodosariidae
        - Genus *Glandulonodosaria* (Silvestri, 1900)
      - Family Lagenidae
        - Genus *Lagena* (Walker and Boys, 1784)
      - Family Nodosariidae
        - Genus *Nodosaria* (Lamarck, 1816)
      - Family Plectofrondiculariidae
        - Genus *Plectofrondicularia* (Liebus, 1902)
      - Family Polymorphinidae

            - Genus *Guttulina* (d’Orbigny, 1826)
        - Family Stilostomellidae
            - Genus *Siphonodosaria* (Schwager, 1866)
        - Family Vaginulinidae
            - Genus *Lenticulina* (Lamarck, 1804)
- Class Globothalamea
    - Order Rotaliida
        - Family Bolivinitidae
            - Genus *Fursenkoina* (Loeblich and Tappan, 1961)
        - Family Buliminidae
            - Genus *Bulimina* (d’Orbigny, 1826)
            - Genus *Globobulimina* (Cushman, 1927)
        - Family Cancrisidae
            - Genus *Valvulineria* (Cushman, 1926)
        - Family Cassidulinidae
            - Genus *Cassidulina* (d’Orbigny, 1826)
        - Family Elphididiidae
            - Genus *Elphidium* (Montfort, 1808)
        - Family Eponididae
            - Genus *Eponides* (Montfort, 1808)
        - Family Gavelinellidae
            - Genus *Hansenisca* (Loeblich and Tappan, 1988)
        - Family Globigerinidae

Genus *Globigernia* (d’Orbigny, 1826)

Orbulina (d’Orbigny, 1839)

Family Nonionidae

Genus *Pullenia* (Parker and Jones, 1862)

Family Pseudoparrellidae

Genus *Epistominella* (Husezima and Maruhasi, 1944)

Family Uvigerinidae

Genus *Uvigerina* (d’Orbigny, 1826)

Uvigerinella (Cushman, 1926)

Class Tubothalamea

Order Miliolida

Family Hauerinidae

Genus *Pyrgo* (DeFrance, 1824)

Appendix C

Counts of Foraminifera from the Pullen Formation by Sample

	FAMILY	**P36**	**P39**	**P40**	**P43**	**P45**	**P47**	**P48**	**P49**	**P52**	**P53**	**P55**	TOTALS
Fursenkoina sp.	Bolivinitidae			1									**1**
Bulimina sp.	Buliminidae			1		1	5		2	1			**10**
Bulimina subacuminata	Buliminidae	7		3		2	7	5	19	3	1	4	**51**
Globobulimina affinis	Buliminidae	5	3	2	8			4	8		1	2	**33**
Valvulineria araucana	Cancrisidae			1									**1**
Cassidulina minuta	Cassidulinidae					2	2	1				1	**6**
Cassidulina translucens	Cassidulinidae	2	2			2	3	9	4		4		**26**
Cibicides mckannai	Cibicididae		4		1	1	1		4		1	2	**14**
Fissurina lucida	Ellipsolagenidae		1										**1**
Oolina sp.	Ellipsolagenidae	14											**14**
Elphidium sp.	Elphidiidae						1						**1**
Eponides repandus	Eponididaae					1							**1**
Epistominella sp.	Eponididae	1	2			3	1		2	3			**12**
Hansenisca. soldanii	Gavelinellidae	11				4	2					6	**23**
Glandulina laevigata	Glandulinidae			1									**1**
Globogerina bulloides	Globogerinidae	9		1		1		1	2	2			**16**
Orbulina universa	Globogerinidae	10											**10**
Pyrgo oblonga	Hauerinidae			1									**1**

	FAMILY	**P 36**	**P 39**	**P 40**	**P 43**	**P 45**	**P 47**	**P 48**	**P 49**	**P 52**	**P 53**	**P 55**	TOTALS
Pyrgo rotalaria	Hauerinidae			1									**1**
Lagena sp.	Lagenidae			1		2	1		1	6	2	3	**16**
Lagena striata	Lagenidae		2		1	2	1				2		**8**
Nodosaria moniliformis	Nodosariidae		1										**1**
Nodosaria sp.	Nodosariidae		1										**1**
Nodosaria tympaniplectriformis	Nodosariidae		3	1		2							**6**
Pullenia subcarinata	Nonionidae				1								**1**
Pullenia bulloides	Nonionidae					1							**1**
Plectofrondicularia advena	Plectofrondiculariidae			1		2	3					1	**7**
Plectofrondicularia californica	Plectofrondiculariidae	13	5							8		1	**27**
Guttulina ovata	Polymorphinidae							1					**1**
Epistominella pacifica	Pseudoparrellidae	12	9	10		3	7	10	5	5	27	9	**97**
Siphonodosaria insecta	Stilostomellidae	8	7	6	3	13	5	1				3	**46**
Uvigerina hannai	Uvigerinidae		1										**1**
Uvigerina hootsi	Uvigerinidae	6	7		16	6	4	8	1	4		4	**56**
Uvigerina peregrina	Uvigerinidae	3	2	1	1	3	2	2	2	7	2	1	**26**
Uvigerina subperegrina	Uvigerinidae	4	3	5	9	9	6	5		9	6	3	**59**
Uvigerinella californica	Uvigerinidae		6	3	8								**17**
Lenticula sp.	Vaginulinidae			1						2		3	**6**
Lenticulina calcar	Vaginulinidae							1					**1**
# of species in sample		14	17	18	9	19	15	12	11	11	9	14	

	FAMILY	**P 36**	**P 39**	**P 40**	**P 43**	**P 45**	**P 47**	**P 48**	**P 49**	**P 52**	**P 53**	**P 55**	TOTALS
Totals		105	59	41	48	60	51	47	50	48	46	40	601