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Using foraminifera in STEMSEAS Site 1 to understand the recent paleoceanographic and paleoclimatic history of Tanner Basin, California Borderland

An Honors College Project Presented to
the Faculty of the Undergraduate
College of Math and Science
James Madison University

By: Michael Stanley Stone

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ABSTRACT

In May of 2016, the STEMSEAS Educational Transit cruise OC1605-tranA collected the STEMSEAS Site 1 core from the Tanner Basin in the California Borderland. This research serves as the first formal survey of the foraminifera preserved within that core. The purpose of this research is to use foraminifera preserved within that core to understand the recent depositional and paleoenvironmental conditions at Site 1, and to place that information into a regional paleoceanographic and paleoclimatic context. In pursuing this purpose, this research aims to answer three questions: 1) Can biostratigraphic markers in the foraminiferal assemblages in STEMSEAS Site 1 core be used to test the hypothesis that a shift in elemental ratio concentrations at 120 cmbsf marks the Pleistocene/Holocene boundary? 2) Is there evidence of turbidity flow deposition at STEMSEAS Site 1? 3) Can the foraminiferal assemblages within STEMSEAS Site 1 core be used to study paleoenvironmental changes in the California Borderland through time? Thirty-four samples of the >63 μm size sediment fraction from the core were analyzed throughout this study, and the data from those samples was compared with lithologic and elemental data collected by the STEMSEAS cruise shipboard party and with regional data. Additionally, radiocarbon dates were obtained to develop an age model for the core, which allowed cored data to be interpreted in a temporal context. In answering the proposed questions, the study found that: 1) The shift in elemental data at 120 cmbsf occurs very close to (~1 kyr following) the Pleistocene/Holocene boundary, and the Pleistocene/Holocene transition represents a period of low dissolved oxygen supply within the Tanner Basin and low surface productivity. 2) A small percentage of benthic foraminifera present at Site 1 were displaced to Site 1 from a shallower depth, suggesting that turbidity flows did impact sedimentation at this location, but were not the dominant sediment transport process. 3) The core records a paleoenvironmental history of semi-regular millennial scale variation in sea surface temperature, upwelling strength, and nutrient influx that may be driven by oscillating and increasing frequency of El Niño/Southern Oscillation events.

PURPOSE AND OBJECTIVES

Summary

The STEMSEAS Site 1 core is a 160-cm sediment core taken from the Tanner Basin in the California Borderland. The purpose of this research is to use foraminifera preserved within the STEMSEAS Site 1 core to develop a paleoceanographic and paleoclimatic history for Site 1. This will allow for a greater understanding of the recent depositional and paleoenvironmental conditions in the Tanner Basin. The research can be divided into two objective categories: research on depositional conditions of Site 1 and research on paleoenvironmental conditions of Site 1. Within those objective categories, the following questions will be addressed:

Objective 1: Research on Depositional Conditions

1) *Can biostratigraphic markers in the foraminiferal assemblages in STEMSEAS Site 1 core be used to test the hypothesis that a shift in elemental ratio concentrations at 120 cmbsf marks the Pleistocene/Holocene boundary?*

2) *Is there evidence of turbidity flow deposition at STEMSEAS Site 1?*

Objective 2: Research on Paleoenvironmental Conditions

3) *Can the foraminiferal assemblages within STEMSEAS Site 1 core be used to study paleoenvironmental changes in the California Borderland through time?*

INTRODUCTION

Geologic Setting

The California Borderland hosts a unique bathymetry that is controlled primarily by the right lateral movement of the San Andres Fault System (Legg et al., 2007). This movement creates accommodation space in the form of a series of submarine basins that are oriented roughly parallel to the fault zone and the coastline (Legg et al., 2007). One such basin is the Tanner Basin, which is located approximately 150 km west of San Diego and extends northwestward (Fig. 1; Hendy and Kennett, 2000). The Tanner Basin has a maximum depth of approximately 1500 mbsl (meters below sea level; Shipboard Scientific Party, 1997a), and an area greater than 1100 km².

A mixture of biogenic and terrigenous sediment coming from the surrounding bathymetric highs enters the Tanner Basin primarily as turbidity flows (downslope submarine mass wasting transport) in the northwestern part of the basin (Shipboard Scientific Party, 1997a). These turbidity flows are often triggered by earthquakes due to regional tectonic activity along the fault system (Legg et al., 2007). Away from these turbidity deposits, the sediment in the Tanner Basin consists of mostly of calcareous nannofossils, foraminifera, and siliciclastic clays (Shipboard Scientific Party 1997a).

Sediment composed of calcareous nannofossils and foraminifera are biogenic in origin. Calcareous nannofossils are microscopic, unicellular, autotrophic, planktic algae, with calcareous hard-parts, which live near the top of the water column (Marsaglia et al., 2015). Foraminifera are sand-sized, unicellular, heterotrophic, testate (shell-bearing) protists that either float in the upper water column (planktic), or live on the seafloor or buried very shallowly in the sediments (epifaunal benthic or infaunal benthic, respectively) (Marsaglia et al., 2015). Upon death, if undisturbed, the hard-parts from both the nannofossils and the foraminifera settle on the seafloor and accumulate. Depending on the species present at a given depth, benthic foraminifera may be autochthonous to the basin or may be attributed to some transport mechanism, such as the turbidity currents (Leckie and Olson, 2003). In addition to biogenic components, the silt and clay size fraction is dominated by terrigenous mud (Shipboard Scientific Party, 1997a).

Oceanographic Setting

The California Current is part of the North Pacific subtropical gyre (Lyle et al., 2000). The strength and position of this current is heavily influenced by seasonal winds and by interannual cycles, such as El Niño/Southern Oscillation (ENSO) events (Lyle et al., 2000). The southward flowing California Current drives the counterclockwise flowing California Countercurrent (Hendy and Kennett, 2000). These two currents are the main surface currents that influence the Tanner Basin (Fig. 1) and are complimented by the northward flowing California Undercurrent; a subsurface current that exists at a depth of 100 to 300 meters below sea level (mbsl; Hendy and Kennett, 2000; Torres and Gomez-Valdes, 2017). Below the California Undercurrent exists the Pacific Intermediate Water (PIW), which has a top depth between 300 and 600 mbsl in this region (Shore-based Scientific Party, 1994; Bray, 1988). The PIW is normally characterized by a salinity minimum (Bray, 1988). The currents and the

wind-driven late-spring (late April through early June) seasonal upwelling influences nutrient and sediment influx, and thus impacts the productivity of the waters above and within the Tanner Basin (Lyle et al., 2000).

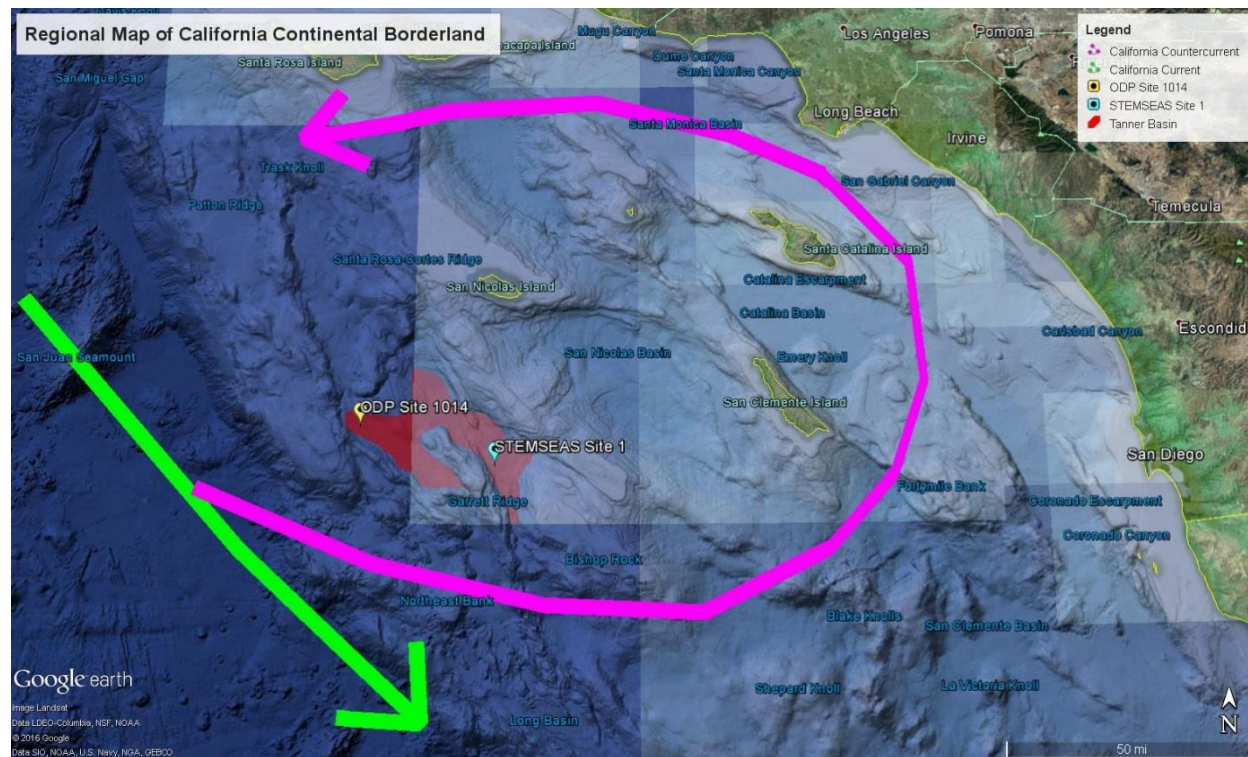


Figure 1: Regional map of the California Borderland. The location of the Tanner Basin is highlighted in red, STEMSEAS Site 1 is indicated by a light blue marker, and ODP Site 1014 is indicated by a yellow marker. The path of the California Current is marked by the green arrow and the path of the California Countercurrent is marked by the purple arrow (Hendy and Kennett, 2000).

The waters of the California Borderland are most strongly stratified during the early part of the summer, following a late-spring seasonal upwelling, and display isothermal conditions during the winter (Sautter and Thunell, 1991). ENSO events cause the waters of the California Borderland to be anomalously warm (Fisler and Hendy, 2008). These warm waters suppress the seasonal upwelling events in the region, and thus lead to greater water column stratification (Jacox et al., 2015).

Site Characteristics

STEMSEAS Site 1 core was collected in May 2016 by members of the STEMSEAS Educational Transit Cruise OC1605-tranA. It was collected aboard the research vessel, *Oceanus*, using the Oregon State University Seafloor Sampling System (OSUSSS), a hydraulically damped gravity corer provided by Oregon State University (D’Andrea et al., 2005; St. John, K., personal communication, 2016). The site location, 32°43’05.3” N, 119°30’43.4” W, is approximately 220 km due west of San Diego in the California Borderland, at the southern end of the Tanner Basin in 1337 m water depth (Fig. 1).

Conductivity, temperature, and depth (CTD) data was collected to create a water column profile at Site 1. Figure 2 shows the profile of dissolved oxygen and fluorescence (a proxy for primary productivity; Garcia-Mendoza and Maske, 1996), and figure 3 shows the temperature and salinity profiles for Site 1. The fluorescence profile shows the majority of primary productivity occurring in

the top 60 m of the water column (Fig. 2). The oxygen profile displays a rapid reduction in dissolved oxygen from around 30 to 300 mbsl, then a gradual reduction to 600 mbsl. Dissolved oxygen begins to gradually increase again around 800 mbsl (Fig. 2).

The surface currents may be captured in the upper portion of the salinity profile, with their lower extent being marked by the shift in concavity direction occurring at 140 mbsl. The shift at 140 mbsl is also being interpreted as the top of the California Undercurrent (Fig. 3). Notably, there are no major reductions in salinity at depth marking the presence of the PIW between 300 and 600 mbsl (Shore-based Scientific Party, 1994; Bray, 1988).

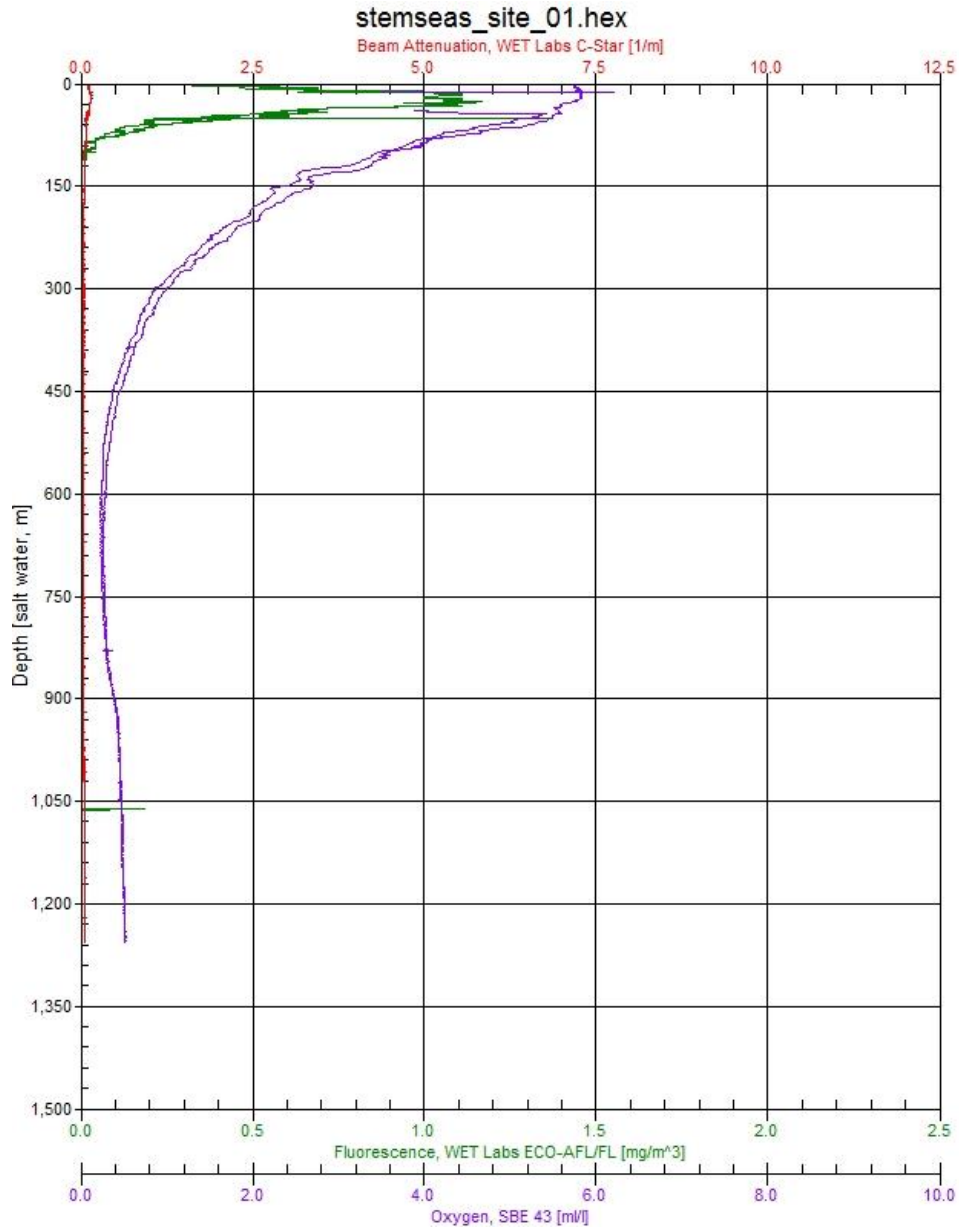


Figure 2: Profile of dissolved oxygen and primary productivity (fluorescence; Garcia-Mendoza and Maske, 1996) produced from CTD data collected by the STEMSEAS Shipboard Party in May of 2016 (taken from St. John and Leckie, 2016, unpublished data).

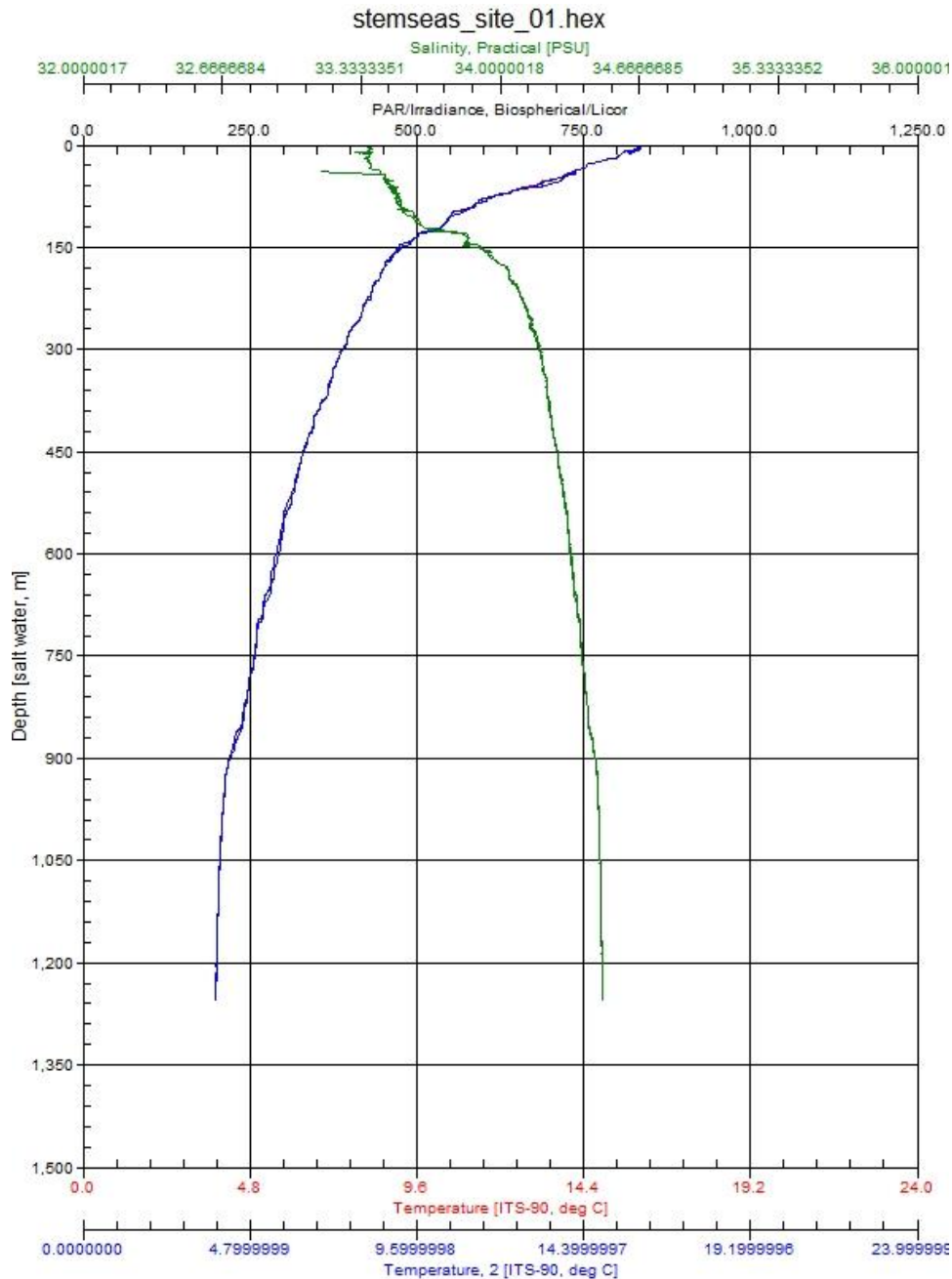


Figure 3: Profile of salinity and temperature produced from CTD data collected by the STEMSEAS Shipboard Party in May of 2016. The California Undercurrent resides beneath the regional surface currents at a suspected top depth of about 140 mbsl, where the salinity profile displays a shift in concavity direction. A salinity minimum below 300 m depth, which would indicate the PIW (Bray, 1988), is notably absent (taken from St. John and Leckie, 2016, unpublished data).

Dr. Kristen St. John (James Madison University) and Dr. Mark Leckie (University of Massachusetts-Amherst) were co-chief scientists on the expedition, and selected the location for coring Site 1. Their rationale for site selection (St. John, K., personal communication, 2016) included Site 1's proximity to Ocean Drilling Program (ODP) Site 1014 (for data referencing; also within the Tanner Basin), and to compare to a deeper and much farther offshore site also drilled during the STEMSEAS cruise. In addition, they used echo-sounder profile data of the seafloor to identify a region in the Tanner Basin

that was relatively flat, and not at the base of a slope to minimize the potential for proximal turbidity flow deposits that could have prevented the penetration of the gravity corer. The water depth at the site is well above the regional carbonate compensation depth (CCD) of approximately 4000 mbsl (meters below sea level; Chen et al., 1988).

Sediment Lithology

The core is 160 cm in length and is composed of sediment described as a nannofossil silty clay, olive gray to olive in color, with foraminifera present throughout (St. John and Leckie, 2016, unpublished data). It is generally homogenous, however St. John and Leckie (2016, unpublished data) note a clay-rich section from 90 to 118 centimeters below sea floor (cmbsf), bioturbation from 145 to 160 cmbsf, layering at 58 and 65 cmbsf, and greater stiffness near the base of the core (Fig. 4).

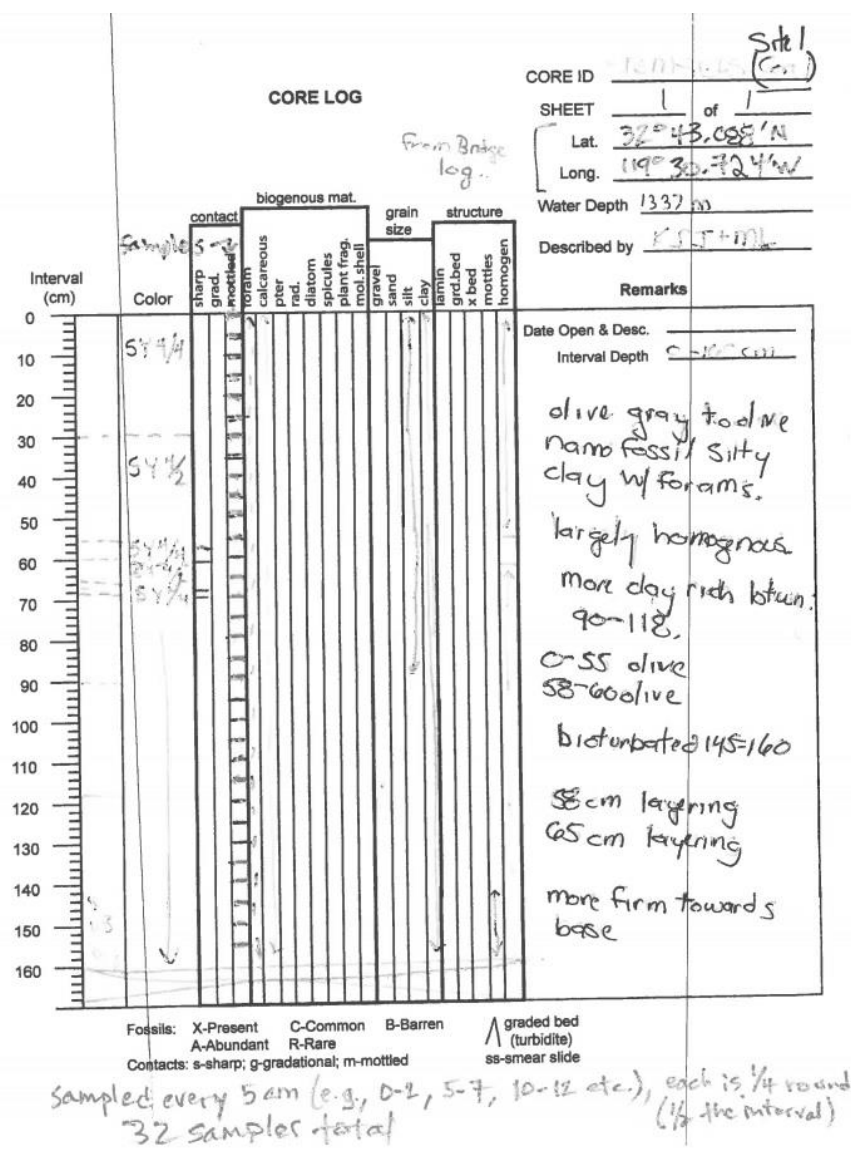


Figure 4: STEMSEAS Site 1 core description, with sampling intervals displayed on the left side of the sheet (taken from St. John and Leckie, 2016, unpublished data).

Foraminifera as Biostratigraphic and Paleoenvironmental Indicators

Foraminifera are an order within the Subphylum Sarcodina, and are close relatives to amoebas (Prothero, 2013, p. 274-275). Their chambered tests grow around their single celled bodies, and are either agglutinated (Suborder Textulariina) or composed of calcium carbonate. The tests of planktic and 'smaller' benthic foraminifera range up to 2 mm (Marsaglia et al., 2015), but the specimens in this study are all <1 mm in size (<1000 μm). Planktic foraminifera (Suborder Globigerina) live in the upper part of the water column in open marine environments. Benthic foraminifera live on the substrate or within the upper 10-cm of the sediments, and the distribution of benthic species approximates water depth in waters shallower than 200 mbsl (Fig. 5; Leckie and Olson, 2003). Benthic species living in depths greater than 200 mbsl, such as those that may be autochthonous to the Tanner Basin, are proposed to be distributed based on bottom water temperature, food supply, dissolved oxygen, and substrate (Bandy, 1953; Leckie and Olson, 2003).

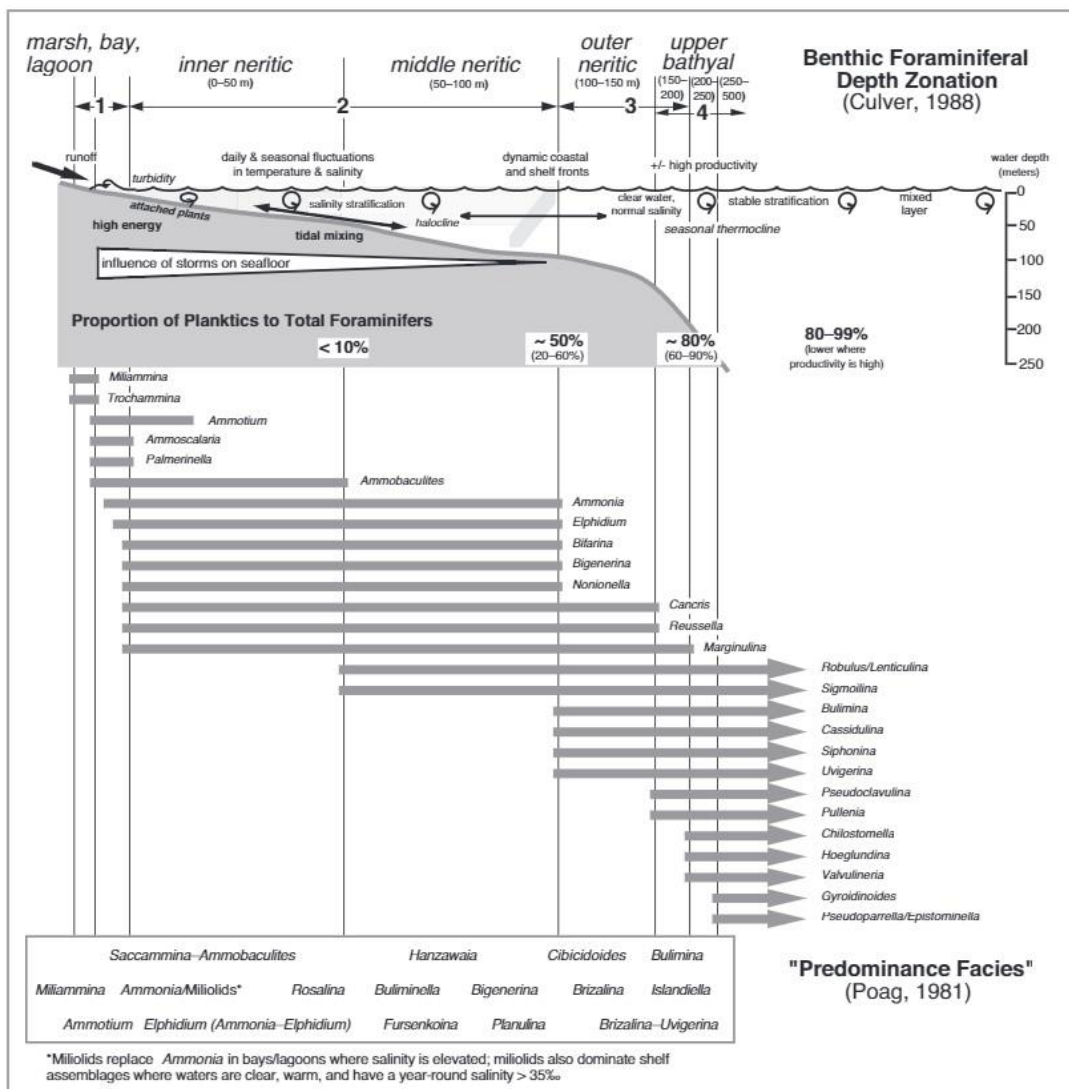


Figure 5: An example of benthic foraminifera correlating to different depth zones due primarily to rapid changes in the physical, chemical, and biological oceanography with increasing distance from shore. Data like these allow for the inference of whether a foraminifera test is allochthonous or autochthonous based on whether or not that test lay within the species given depth range (taken from Leckie and Olson, 2003).

The calcium carbonate tests of foraminifera are useful as proxies for understanding paleoclimatic and paleo-oceanic conditions. At nearby ODP Site 1014, recovered tests were utilized mainly for biostratigraphy by noting the first and last occurrences of different foraminifera species and comparing that data with established time ranges for those species (Shipboard Scientific Party, 1997a). Site 1014 was cored to a depth of 449 mbsf, and data on foraminifera present in the Holocene and uppermost Pleistocene sediment within this part of the core is limited due to sparse sampling by the shipboard scientific party (Shipboard Scientific Party, 1997a; Hendy and Kennett, 2000). Because of the short length (1.6 m) and high frequency of sampling in the STEMSEAS core, this research will produce a much higher resolution biostratigraphic and paleoenvironmental history than at Site 1014 for the short stratigraphic interval of overlap.

Assuming the top of the STEMSEAS core represents modern day and the sedimentation rate at STEMSEAS Site 1 is similar to that of ODP Site 1014 (79.9 m/myr; or, 7.9 cm/kyr), most taxa within the STEMSEAS core should be Holocene to latest Pleistocene in age. Bandy (1953) notes that *Bulimina striata* var. *mexicana*, *B. subacuminata*, *Cassidulina translucens*, and *C. lomitensis* are present in the benthic foraminiferal assemblage autochthonous to depths of 3000 to 6000 feet (900 to 1800 m) in the California Borderland. Based on the 1337 m water depth at Site 1, those species are expected to be present within the core. A preliminary survey of two samples from the STEMSEAS Site 1 core revealed a diverse group of benthic foraminiferal genera: *Brilalina*, *Bulimina*, *Globobulimina*, *Uvigerina*, *Globocassidulina*, *Cassidulina*, *Epistominella*, *Gyroidinoides*, *Cibicidoides*, *Planulina*, *Hoeglundina* (aragonite), *Melonis*, *Nonionella*, *Pyrgo*, *Quinqueloculina*, *Fissurina*, and *Haplophragmoides* (agglutinated) (Leckie R. M., personal communication, 2016). Planktic foraminiferal assemblages include the following species: *Neogloboquadrina pachyderma*, *N. incompta*, *N. dutertrei*, *Turborotalita quinqueloba*, *Globigerina bulloides*, *Globigerinita glutinata*, *G. uvula*, *Globorotaloides hexagonus*, *Globigerinella calida*, *Globorotalia inflata*, *G. scitula*, and *G. theveria* (Kennett et al., 2000; Davis et al., 2016; Leckie R. M., personal communication, 2016).

Research Objectives

It is the intent of this research to determine the diversity and abundance of foraminiferal species in samples taken from the STEMSEAS Site 1 core in order to address a series of research questions concerning the depositional conditions (objective 1) and paleoenvironmental conditions (objective 2) of Site 1.¹

Objective 1: Research on Depositional Conditions

1. *Can biostratigraphic markers in the foraminiferal assemblages in STEMSEAS Site 1 core be used to test the hypothesis that a shift in elemental ratio concentrations at 120 cmbsf marks the Pleistocene/Holocene boundary?*

X-ray fluorescence (XRF) data collected onboard the STEMSEAS cruise shows an elemental shift in Ca/K, Ca/Ti, and Br/Rh ratios all aligning at around 120 cmbsf (Fig. 6; St. John and Leckie, 2016, unpublished data). Kristen St. John (personal communication, 2016) hypothesized shipboard that this elemental-stratigraphic shift could mark a stratigraphic boundary of some significance,

¹ Originally, an additional question was also posed in objective 2 concerning stable isotope ratios. However, stable isotope data was not collected, so that question has been omitted.

perhaps depositional shifts associated with changes in environmental conditions at the Pleistocene/Holocene boundary.

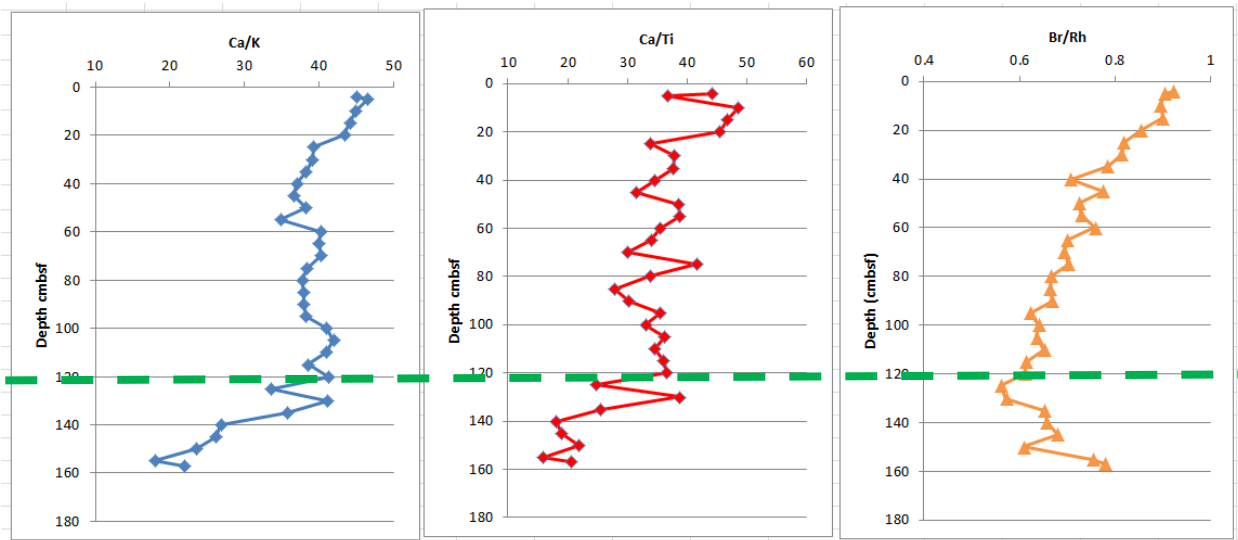


Figure 6: Ca/K, Ca/Ti, and Br/Rh ratio data from the STEMSEAS Site 1 core. Note the shifting in all three ratios which occurs at ~120 cmbsf (taken from St. John and Leckie, 2016, unpublished data).

The Pleistocene/Holocene boundary occurred 11,700 years ago. Paleomagnetic data from ODP site 1014 shows that site to have an average sedimentation rate of approximately 79.9 m/myr, or 7.9 cm/kyr (Shipboard Scientific Party, 1997a). Assuming STEMSEAS Site 1 has a similar sedimentation rate, the STEMSEAS core may contain a temporal record of roughly 20 kyr, placing the Pleistocene/Holocene boundary well within the limits of the core.

If the shift in elemental ratio concentrations truly represents the Pleistocene/Holocene boundary, foraminiferal assemblages should change at around the same depth due to changes in temperature, salinity, nutrient influx, or some other limiting factor (Leckie and Olson, 2003). Changes in nutrient influx are affected by bioproductivity in surface waters. In addition, radiocarbon dating of a mixed-layer planktic foraminifera assemblage can be used to develop an age model for the site.

2. Is there evidence of turbidity flow deposition based on the benthic foraminifera?

While the location of STEMSEAS Site 1 was intentionally chosen to attempt to avoid turbidity flow deposits and no dense sand units were encountered when coring it (St. John, K., personal communication, 2016), turbidity flow deposition has been noted at other sites within the Tanner Basin (Shipboard Scientific Party, 1997a). As such, the potential for at least distal turbidity flow deposits at Site 1 cannot be ruled out. The assemblage of benthic foraminifera within the core may provide evidence for such deposits.

In their study of benthic foraminiferal distribution along the Peru-Chile Trench, Ingle et al. (1980) found that in samples from 500 to 4000 m water depth, as many as 80% of benthic foraminifera present were displaced from shallower water depths. The depth of STEMSEAS Site 1 lies within that range (1337 m water depth), and is thus suspected to also contain a high percentage of displaced foraminifera.

According to Bandy (1953), lower neritic zone (50-200 mbsl) benthic foraminifera assemblages in the California Borderlands may include *Cassidulina californica*, *C. limbata*, *C. quadrata*, *C. tortuosa*, and *Angulogerina angulosa*. The presence of any of these indicator species would indicate some transport mechanism, such as a turbidity flow from the northwest (Shipboard Scientific Party, 1997a), brought these tests into the basin from one of the surrounding banks.

While the lithologic description for Site 1 (Fig. 4) indicated the sediment was largely homogenous, elemental ratio stratigraphic data (Fig. 6; St. John and Leckie, 2016, unpublished data) indicated some regular repeated pattern of elemental relative abundances that may be an indicator of repeated turbidity flow deposition. If re-deposited neritic zone benthic foraminifera are present within the Site 1 core, a correlation between the relative abundance of those foraminifera at different depths and the patterns observed in the elemental relative abundances would provide strong evidence for the influence and timing of turbidity flows at Site 1.

Another foraminiferal indicator of turbidity flow deposition is how well the foraminifera are preserved, as high energy turbidity flows can damage foraminifera tests. Thus, poor preservation of a sample relative to the preservation of the samples above and below it, or poor preservation of benthic tests within a sample relative to the preservation of that sample's planktic tests (of which many within the core would be expected to be autochthonous), may indicate turbidity deposition. Species reworked from shallower depths can be iron-stained due to exposure time on the seafloor prior to downslope transport (Leckie, R. M., personal communication, 2016).

Objective 2: Research on Paleoenvironmental Conditions

3. *Can the foraminiferal assemblages within STEMSEAS Site 1 core be used to study paleoenvironmental changes in the California Borderland through time?*

Foraminifera are commonly used as proxies for paleoenvironmental and paleoclimatological conditions. The relative abundances of left versus right coiling *Neogloboquadrina pachyderma* (hereinafter referred to as *N. incompta* and *N. pachyderma*, respectively) are commonly compared as a proxy for sea surface temperature. *N. incompta* is associated with cooler SST and *N. pachyderma* is associated with warmer SST (Davis et al., 2016; Fislser and Hendy, 2008). In the ocean waters off southern California, the abundance of *Turborotalita quinqueloba* has been used as a proxy for upwelling strength and the abundance of *Globigerina bulloides* has been used as a proxy food availability in the ocean waters off southern California (Fislser and Hendy, 2008).

Benthic foraminifera have been used to understand changes in the dissolved oxygen content in various basins within California Borderland (Cannariato and Kennett, 1999; Cannariato et al., 1999). *Bulimina*, *Cassidulina*, *Nonionella*, *Valvulinaria*, *Cibicides*, *Epsitominella*, and *Fursenkoina* are all associated with more oxic conditions, whereas *Bolivina*, *Buliminella*, *Chilostomella*, *Uvigerina*, and *Globobulimina* are all associated with dysoxic conditions (Cannariato and Kennett, 1999; Cannariato et al., 1999). The presence of any of the mentioned foraminifera will allow for some interpretation to be made of the paleoenvironmental changes which have taken place in the Tanner Basin and in the California Borderland.

The STEMSEAS Shipboard Party did not have the time or funding to do any age analysis on the STEMSEAS Site 1 core. The development of an age model will further aid the interpretation of the paleoenvironmental record of the Site 1 core by allowing that record to be placed within the

context of time. This will allow the magnitude of different paleoenvironmental events to be more easily understood, and could aid in correlations to place those events into a more regional context. If a great enough timespan is captured within the Site 1 core, biostratigraphic markers may be used to develop an age model. This, however, seems unlikely, as the youngest foraminiferal biostratigraphic marker determined by the ODP Leg 167 Shipboard Scientific Party (1997) in the nearby ODP Site 1014 was the first occurrence (FO) of *Neogloboquadrina dutertrei*, which occurs at one million years before present (ma). The most effective method of establishing an age model for STEMSEAS Site 1 is likely radiocarbon dating of the foraminifera.

METHODOLOGY

Sample Recovery and Processing

Thirty-four samples collected from STEMSEAS Site 1 core were analyzed in this project. Thirty-two of the samples were 2 cm thick (stratigraphic thickness), 20 cc quarter round samples taken at intervals of one every 5 cm, with a core depth of 0 cm being the top of the uppermost sample (Fig. 7; St. John and Leckie, 2016, unpublished data). The other two samples came from the sediment on top of the core (hereinafter referred to as core top) and the sediment from the core catcher at the very base of the core (hereinafter referred to as core catcher). The samples were processed by the shipboard party to remove all sediment finer than 63 μm (silts and clays). The sand-sized (63 μm to 2 mm) and larger sediment was retained for foraminiferal analysis as most foraminifera are sand sized (St. John, K., personal communication, 2016).



Figure 7: A shipboard photo of STEMSEAS Site 1 core with the thirty-two 20 cc quarter round samples removed (photo courtesy of Leckie, 2016, unpublished data).

Sample Preparation

Sample preparation consisted of taking the mass of each sample and splitting each sample to a manageable size for picking. A manageable size was defined as a sample size where the sediment could be spread out on a picking tray in a single layer; normally between 0.2 and 0.4 g of sediment. Care was taken to keep splitting to a minimum in order to help ensure picking was random (Leckie, R.M., personal communication, 2017). Samples were split to a manageable size using a microsplitter. The mass of each sample was measured in grams using an electronic balance scale. This was done by finding the mass of a sample and its container together, then subtracting the mass of the container. The mass of each sample is recorded in Appendix 1.

Picking and Foraminifera Identification

Each of the 34 split samples were analyzed on a picking tray under a stereomicroscope. Samples were picked through until approximately 300 foraminifera were removed and placed on a micropaleontology slide. All foraminifera fragments, siliceous microorganisms, sponge spicules, pellets, and terrigenous sediments encountered while picking to the 300 foraminifera mark were counted, and siliceous microorganisms, sponge spicules, and terrigenous sediments were also placed on a sample's micropaleontology slide to serve as reference for future research on the core.

Picking was done systematically, beginning with picking all of the sediment in the upper-left most square of the picking tray before moving diagonally (down and to the right) three squares and picking that square. Once that square was picked, picking again moved diagonally three squares following the pattern in figure 8. If a square was not empty when the minimum 300 foraminifera had been picked, picking continued until all of the specimens in the given square were picked. This method of picking was selected to help ensure picking was random (Leckie, R.M., personal communication, 2017).

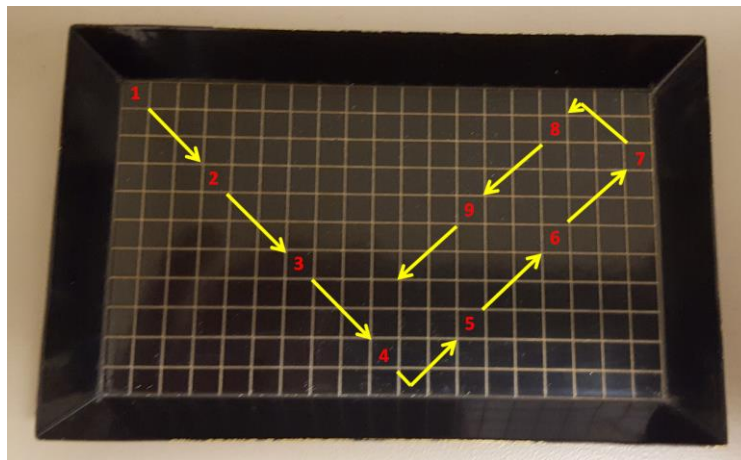


Figure 8: A picking tray with the picking strategy labeled. Numbered boxes were picked sequentially until a minimum of 300 foraminifera were picked from each sample. The arrow extending beyond box number 9 implies that the pattern continues as long as was necessary to reach 300 foraminifera.

The foraminifera on each sample's micropaleontology slide were identified as either planktic or benthic dwelling. For every other sample starting at 0-2 cmbsf, and for the core top, core catcher, and 115-117 cmbsf samples, planktic and benthic foraminifera were identified to the genus and (where possible) species level. Identification was aided by two example slides from the core top and core

catcher provided by Dr. Mark Leckie, planktic foraminifera identified by Dr. Mark Leckie in 115-117 cmsbf sample, and the resources listed in table 1. Additionally, three days of instruction and supervised specimen identification were provided by Dr. Leckie at the University of Massachusetts-Amherst during the summer of 2017.

Table 1: Resources with plates used to aide in the identification of planktic and benthic foraminifera.

Planktic Foraminifera	Cifelli, 1973; Eynaud, 2011; Kennett et al., 2000; Olsson, 1974; Parker, 1962; Raynolds and Thunell, 1986; Williams and Johnson, 1974
Benthic Foraminifera	Bandy, 1953; Bernhard et al., 2001; Ingle et al., 1980; Mohan et al., 2011; Phipps et al., 2012; Setoyama and Kaminski, 2015; Uchio, 1960

Planktic foraminifera were identified and counted in place on their given micropaleontology slide. Benthic foraminifera were identified and grouped accordingly on their given micropaleontology slide (Fig 9). A sample card was produced for each micropaleontology slide where benthic foraminifera were identified and grouped.

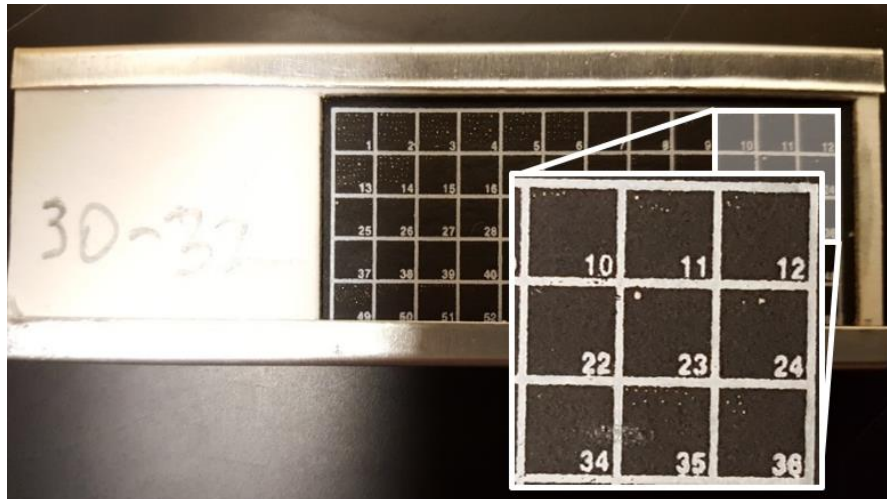


Figure 9: An example micropaleontology slide (for sample 30-32 cmsbf). Boxes 1 through 6 and 13 through 15 contain a mixture of planktic foraminifera species. Each benthic genus and/or species was placed into a specific box. On the example slide shown, the benthic foraminifera are organized as follows: box 8. *Cassidulina quadrata*, 9. *Bolivina/Brazilina*, 10. *Uvigerina*, 11. *Globocassidulina*, 12. *Islandiella*, 20. *Cassidulina tortuosa*, 21. *Globobulimina*, 22. *Fursenkoina*, 23. *Pyrgo*, 24. *Cassidulina sp.*, 33. *Miliolid*, 34. *Nonionella*, 35. *Alabaminella weddellensis*, 36. *Epistominella*, 47. *Valvulinaria*, and 48. *Ehrenbergina*.

Sample Calculations and Analysis

A number of ratios were produced to aid in data analysis. Many of these ratios normalized a given type of data (for example pellets or terrigenous sediment) to the total number of foraminifera in a given sample. Other ratios were comparative, such as the ratio of planktic foraminifera to benthic foraminifera or, following the method of Fisler and Hendy (2008), the ratio of *N. incompta* to *N. pachyderma*.

Foraminifera identified to the level of genus or species were converted to a percentage of the total planktic or benthic foraminiferal community in a given sample, respective to whether the identified foraminifera was planktic or benthic.

In some cases, the numbers of multiple genera and/or species of foraminifera were added together under a certain category, and that category was either used as part of a ratio or converted to a percentage of some larger community. Those categories and how they were measured are presented in table 2.

Species richness and diversity were calculated for each sample. Species richness was calculated by adding the total number of species present in a sample. Species diversity represents the number of individuals of each species present, and was calculated using the Shannon-Wiener Diversity Index, $H(s)$ as outlined by Williams and Johnson (1974). The Shannon-Wiener index was calculated as follows:

$$H(s) = - \sum_{i=1}^s p_i \log p_i$$

where s = species richness, and p_i = the number of foraminifera of a single species divided by the total number of foraminifera within the sample (Williams and Johnson, 1974).

Graphs were produced from each of the above calculations for analysis.

Table 2: Various measurements made for different categories of foraminifera.

Measurement	Category(s)
Percent of displaced benthic foraminifera relative to total benthic foraminifera	Displaced benthics (Bandy, 1953): <i>Cassidulina quadrata</i> , <i>C. tortuosa</i> , <i>C. limbata</i> , <i>C. californica</i> , and <i>Angulogerina angulosa</i> .
Ratio of oxic to dysoxic benthic foraminifera	Oxic benthic foraminifera (a combination of the genera of the oxic and suboxic II foraminifera referenced in Cannariato and Kennett, 1999, and oxic foraminifera referenced in Cannariato et al., 1999): <i>Bulimina</i> , <i>Cassidulina</i> , <i>Nonionella</i> , <i>Valvulinaria</i> , <i>Cibicides</i> , <i>Epsitominella</i> , and <i>Fursenkoina</i> . Dysoxic benthic foraminifera (a combination of the genera of the suboxic I and dysoxic foraminifera referenced in Cannariato and Kennett, 1999, and the dysoxic foraminifera referenced in Cannariato et al., 1999): <i>Bolivina</i> , <i>Buliminella</i> , <i>Chilostomella</i> , <i>Uvigerina</i> , and <i>Globobulimina</i> .
Ratio of upwelling associated planktic foraminifera to total planktic foraminifera	Upwelling associated planktic foraminifera (Fisler and Hendy, 2008): <i>Turborotalita quinqueloba</i> and <i>Globigerina bulloides</i> .

Radiocarbon Dating and Calibration

The 120-122 cmbsf and 155-157 cmbsf samples were selected for radiocarbon dating based on the shift in STEMSEAS Site 1 XRF data around 120 cmbsf and the 155-157 cmbsf sample's proximity to the base of the core (Fig. 6). Samples were prepared for radiocarbon analysis by first dry sieving each sample to isolate the >250 μm fraction and avoid juvenile foraminifera (St. John, K., personal communication, 2017). Next, the >250 μm fraction was rinsed with deionized (DI) water to remove debris, then set aside until completely dry. Finally, 8 mg of mixed upper water column planktic foraminifera was picked from each sample and shipped to the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) laboratory at Woods Hole Oceanographic Institution for radiocarbon analysis. The following species were excluded from this picking based on where they reside in the water column: *Pulleniatina obliquiloculata*, *Globorotalia inflata*, *Globorotalia truncatulinoides*, *Globorotalia hirsute*, *Globorotalia scitula*, *Globorotalia menardii*, and *Globorotalia tumida* (St. John, K., personal communication, 2017; Kucera, 2007).

The radiocarbon data received from the NOSAMS laboratory was calibrated with the MARINE 13 curve using online Calib 7.10 software (Stuiver et al., 2017), and the output ages (in calibrated years BC, calBC) were converted to calibrated years before present (calBP) by adding 1950, the standard modern age for radiocarbon analysis (Ramsey, 2017).

Age Model and Linear Sedimentation Rates

The calibrated radiocarbon ages were plotted versus depth to create a linear age model for the core. The following calculation was done to determine the cores different linear sedimentation rates (LSR), which are equivalent to the slope of the lines in the age model (St. John et al., 2012, p. 121-126):

$$\text{sedimentation rate, } \left(\frac{\text{cm}}{\text{kyr}}\right) = \frac{\Delta \text{ depth}}{\Delta \text{ age}}$$

The sedimentation rate was then used to convert sample top depths to ages using the following formula (St. John, personal communication, 2016):

$$y_f = y_i + \frac{(d_f - d_i)}{r}$$

where y_f is the age of the given sample in kyr calBP, y_i is the age of the sample above the given sample in kyr calBP, d_f is the depth of the given sample in cmbsf, d_i is the depth of the sample above the given sample in cmbsf, and r is the appropriate LSR for the given sample's depth in $\frac{\text{cm}}{\text{kyr}}$.

RESULTS

Foraminifera Identifications

Several genera of benthic, and several species of planktic and benthic foraminifera were identified throughout the core. Representative images of the planktic species in STEMSEAS Site 1 are displayed on plate 1. Representative images of benthic genera and species in STEMSEAS Site 1 are displayed on plates 2, 3, and 4. Occurrence and abundance data are in Appendix 1.

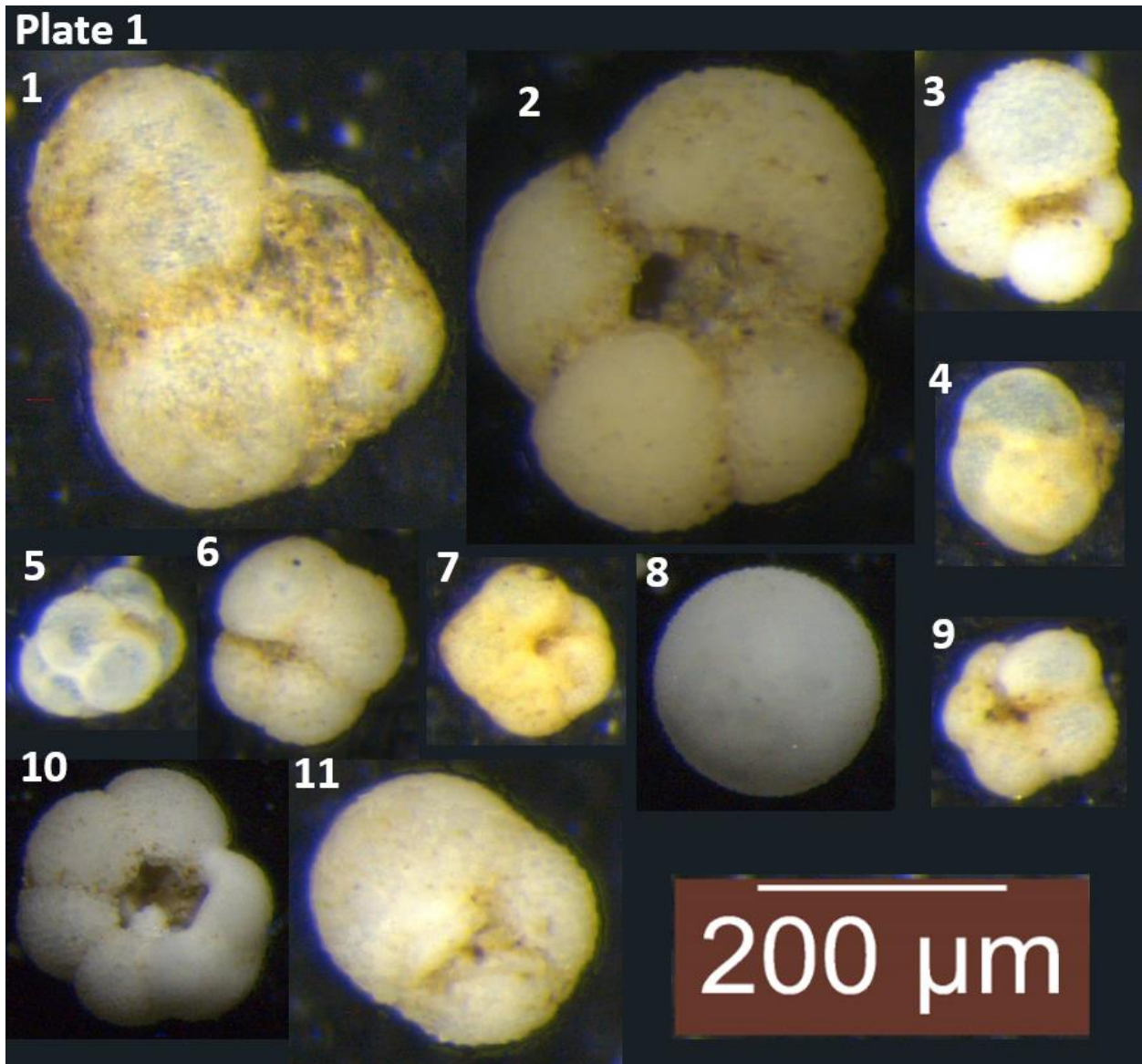


PLATE 1: Planktic foraminifera: (1) *Globigerinella aequilateralis*, (2) *Globigerina bulloides*, (3) *Globigerinita glutinata*, (4) *Globorotalia scitula*, (5) *Globigerinita uvula*, (6) *Neogloboquadrina incompta*, (7) *Neogloboquadrina pachyderma*, (8) *Orbulina universa*, (9) *Turborotalita quinqueloba*, (10) *Neogloboquadrina dutertrei*, (11) *Globigerinoides sacculifer*

Plate 2

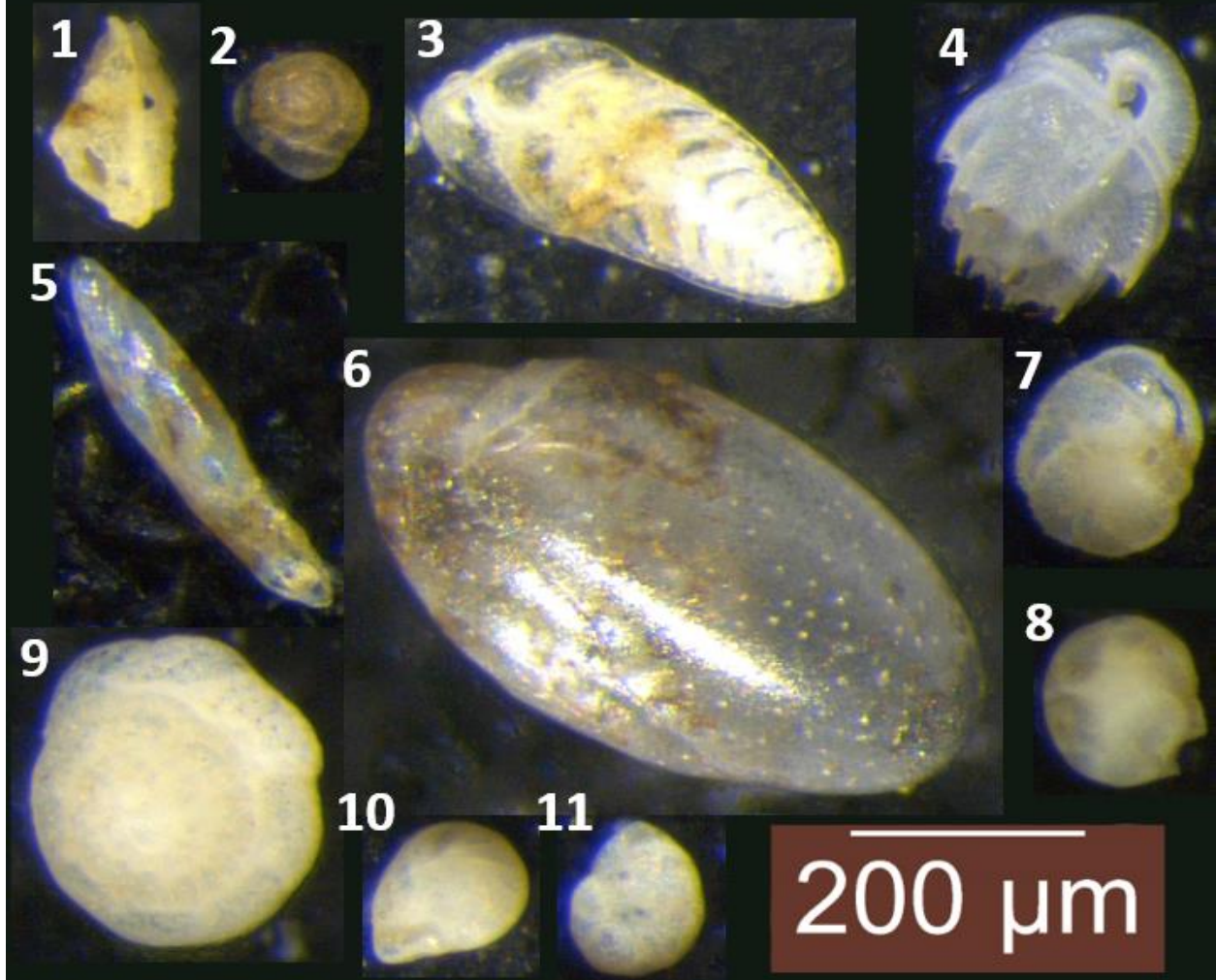


PLATE 2: Benthic foraminifera: (1) *Angulogerina angulosa*, (2) *Alabaminella weddellensis*, (3) *Bolivina* sp., (4) *Bulimina* sp., (5) *Buliminella* sp., (6) *Chilostomella* sp., (7) *Cassidulina* sp., (8) *Cassidulina tortuosa*, (9) *Cibicides* sp., (10) *Cassidulina limbata*, (11) *Cassidulina quadrata*

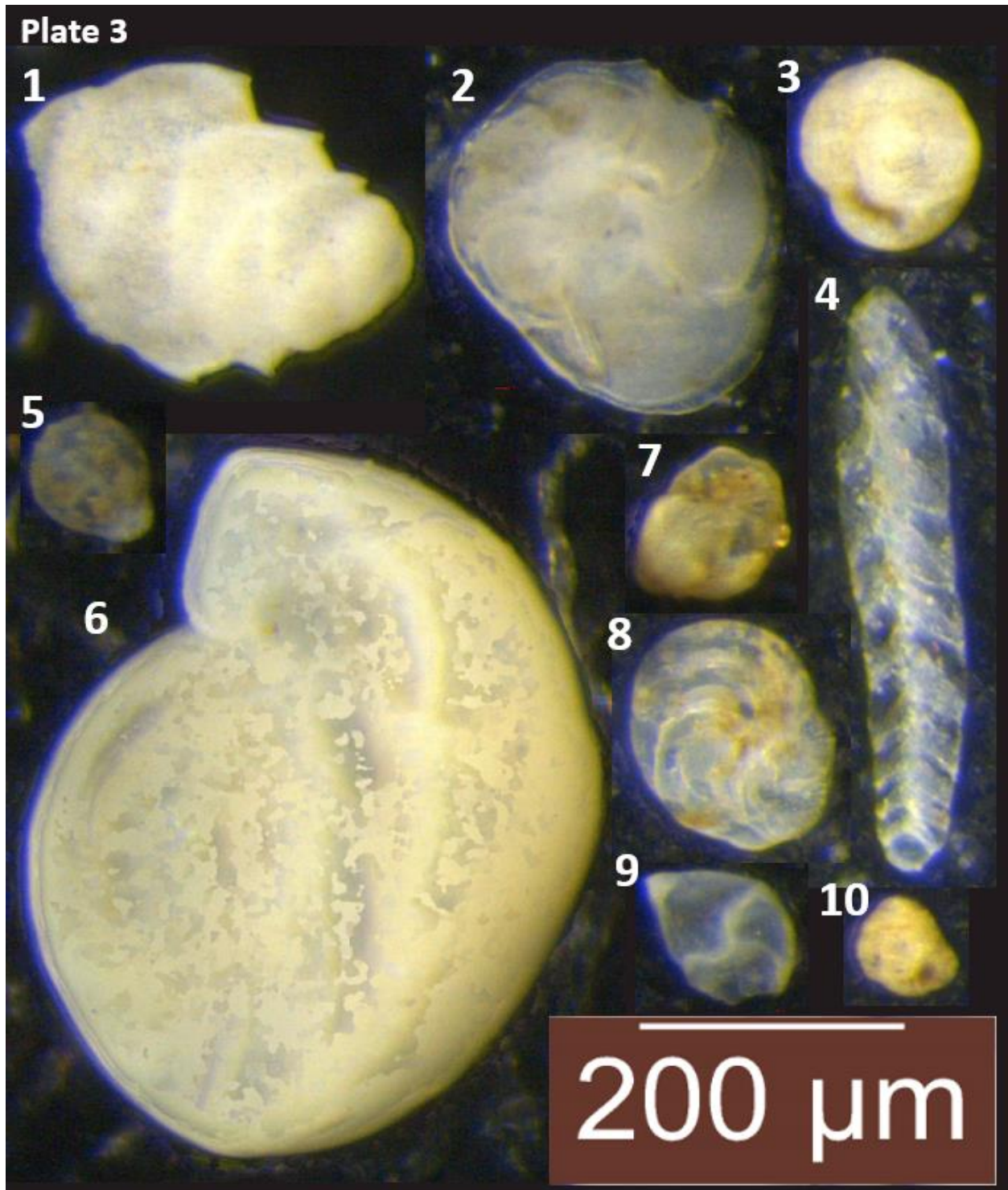


PLATE 3: Benthic foraminifera: (1) *Ehrenbergina* sp., (2) *Epistominella* sp., (3) *Globocassidulina* sp., (4) *Fursenkoina* sp., (5) *Fissurina* sp., (6) *Gyroidinoides soldanii*, (7) *Globobulimina* sp., (8) *Islandiella* sp., (9) *Lenticulina* sp., (10) *Haplophragmoides* sp.

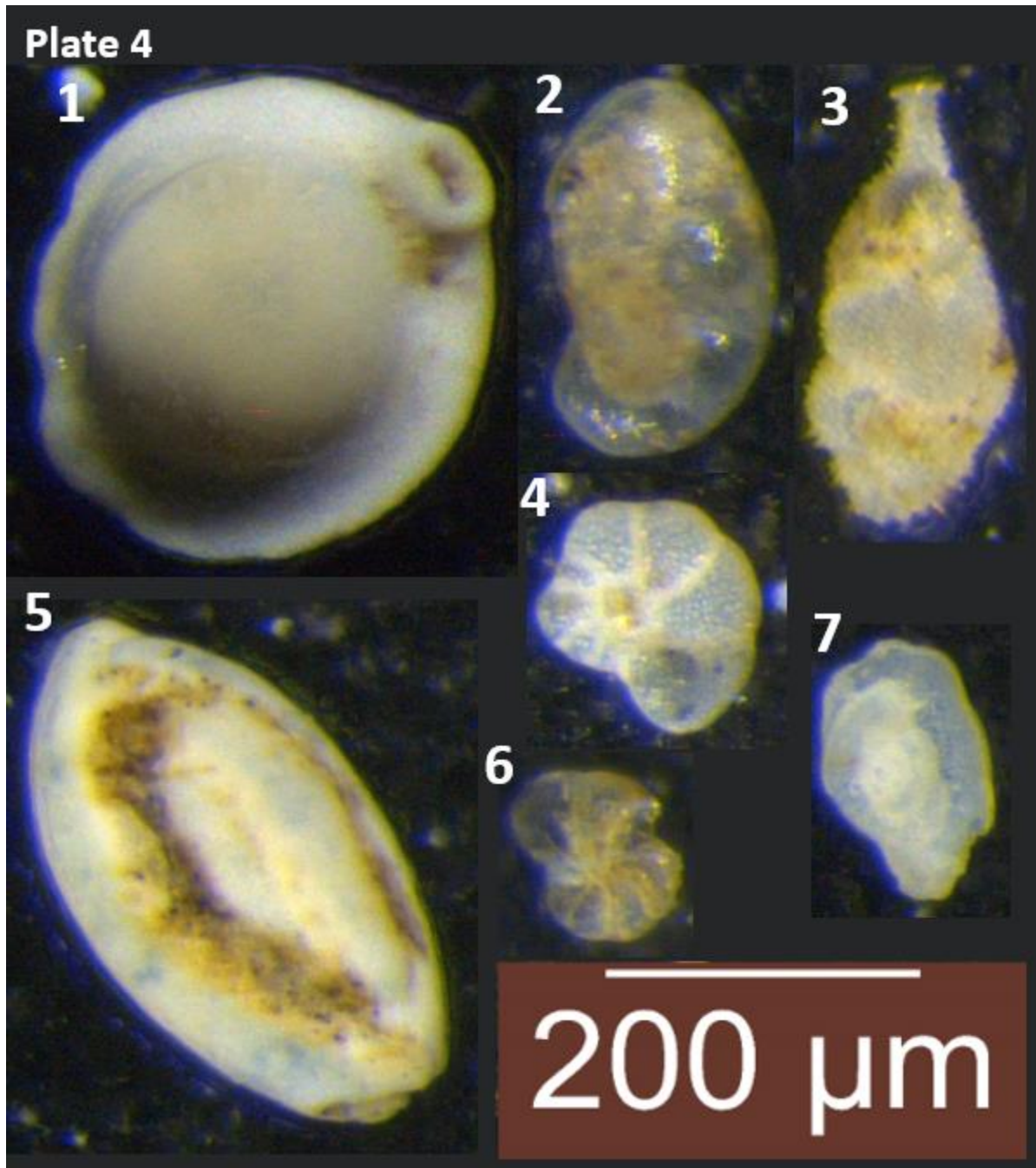


PLATE 4: Benthic foraminifera: (1) *Pyrgo* sp., (2) *Nonionella* sp., (3) *Uvigerina* sp., (4) *Valvulinaria* sp., (5) *Quinqueloculina* sp., (6) *Nonionella fragilis*, (7) *Miliolid* sp.

Age Model

The uncalibrated radiocarbon dates received from the NOSAMS laboratory were 9.74 ± 0.025 ka for the 120-122 cmbsf sample, and 11.05 ± 0.035 ka for the 155-157 cmbsf sample. These dates were calibrated to 10.648 ± 0.091 kyr calBP and 12.602 ± 0.082 kyr calBP, respectively. Using the

calibrated radiocarbon dates, the LSR was calculated as $17.9 \frac{cm}{kyr}$ between 155 and 120 cmbsf, and $11.3 \frac{cm}{kyr}$ between 120 cmbsf and the present (Fig. 10).

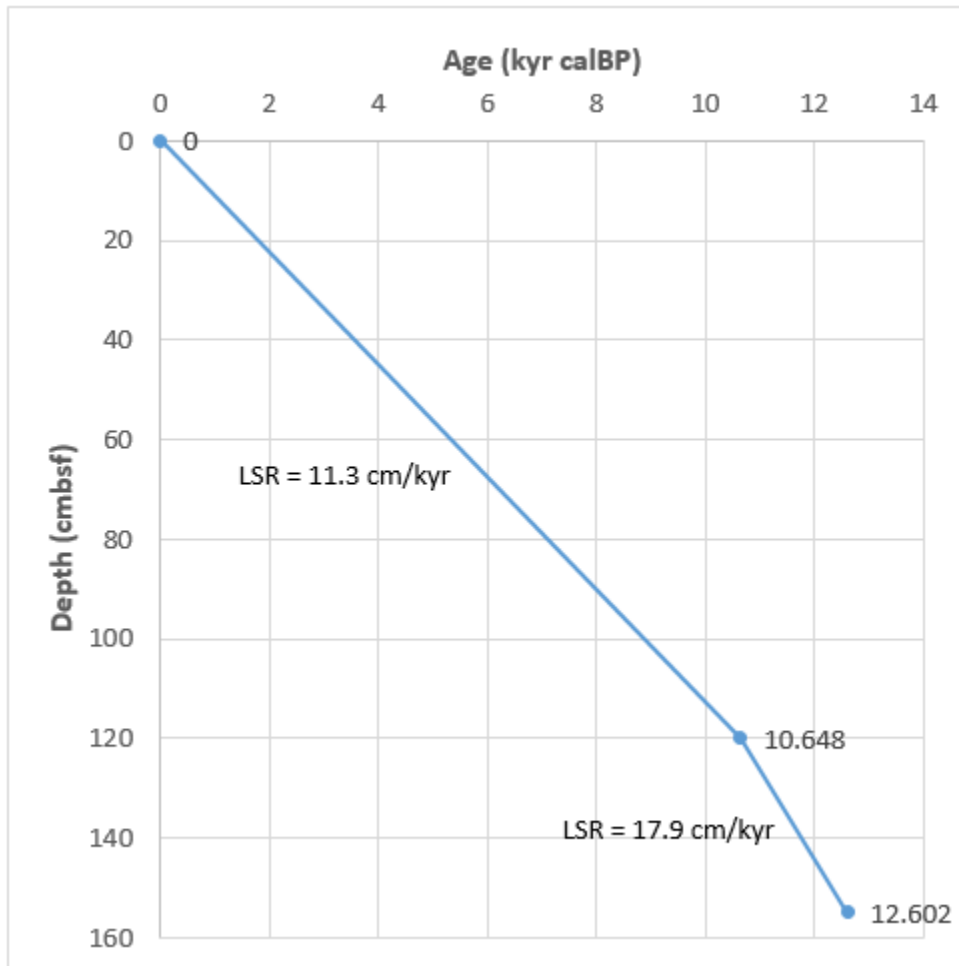


Figure 10: Age model for STEMSEAS Site 1 core.

Shift at 120 cmbsf

Figure 11 shows that many of the types of data collected during this project display a shift at (or near) 120 cmbsf; similar to what is seen in some of the XRF data collected during the STEMSEAS cruise (Fig. 6; St. John and Leckie, 2016, unpublished data). The LSR is much higher from 155 to 120 cmbsf than it is from 120 cmbsf to the core top. The ratios of pellets to foraminifera, foraminifera fragments to whole foraminifera, and siliceous organisms to foraminifera all decrease slightly from the base of the core to 120 cmbsf, then increase from 120 cmbsf to the top of the core.

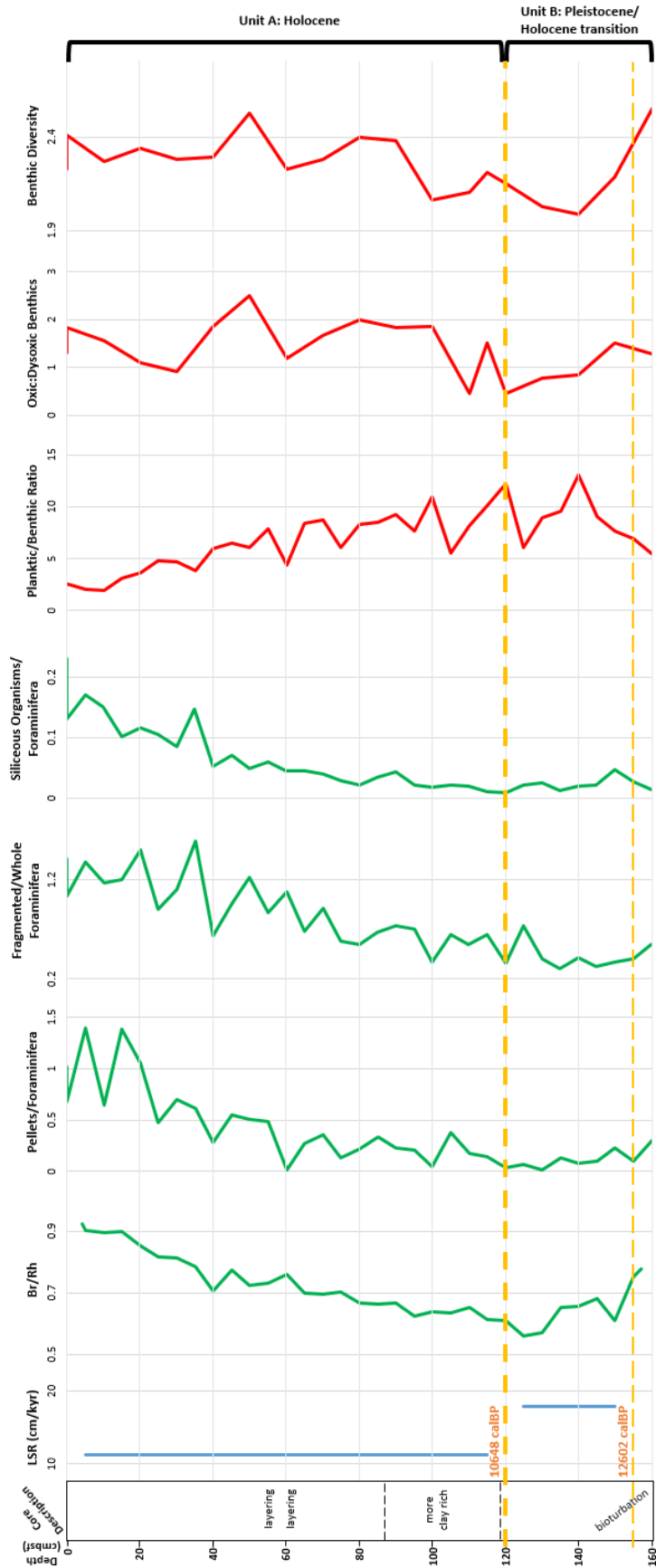


Figure 11: Selection of data displaying a distinctive shift around 120 cmbsf. Data is divided into three groups distinguished by line color: blue, green, and red. Blue: linear sedimentation rate derived from the calibrated radiocarbon dates. Green: Br/Rh ratio (St. John and Leckie, 2016, unpublished data) and other ratios relating to marine organic matter (Ziegler et al., 2008). Red: ratios and data relating to benthic foraminifera.

Much of the data concerning planktic foraminifera does not indicate any notable changes around 120 cmbsf (Fig. 14). The shift is instead more prominent in data concerning benthic foraminifera. The ratio of planktic to benthic foraminifera shows the amount of benthic foraminifera decreasing toward 120 cmbsf, then increasing from 120 cmbsf to the top of the core. This decrease then increase in the number of benthics correlates with a decrease then increase in the benthic Shannon-Weiner Diversity Index, and a decrease then increase in the ratio of benthic foraminifera which are indicators of oxic conditions to dysoxic indicating benthic foraminifera.

Displaced Foraminifera

Displaced lower neritic and upper bathyal zone benthic foraminifera were found in varying abundances throughout the core (Fig. 12; Bandy, 1953). There was a higher percent of displaced species in the upper 120 cm of the core than in the lower core, with the greatest percentages occurring between 30 and 60 cmbsf. The most commonly displaced species was *Cassidulina quadrata*, followed by *C. tortuosa*, *Angulogerina angulosa*, and *C. limbata*, respectively (Bandy, 1953). *C. quadrata* was the only displaced foraminifera recognized at or below 120 cmbsf. No *C. californica* were observed anywhere in the core.

The higher numbers of displaced foraminifera in the upper 120 cm of the core occur alongside that part of the core's low sedimentation rates (relative to the sedimentation rate between 155 and 120 cmbsf; Fig. 12). The presence of displaced foraminifera in a sample weakly correlates with the abundance of terrigenous sediment >63 μm relative to foraminifera in that sample (Fig. 12 and 13a). However, the presence of displaced foraminifera does not correlate with a sample's pellet to foraminifera ratio, foraminifera fragment to whole foraminifera ratio, or its Cl/Rh elemental ratio (Fig. 12 and 13b-d; St. John and Leckie, 2016, unpublished data).

Planktic Proxies

Planktic foraminifera are common proxies for assessing a range of climate related variables (Fisler and Hendy, 2008; Davis et al., 2016). Figure 14 plots a selection of planktic foraminifera data against age in order to more easily search for and interpret temporally based climate patterns and events.

The percentages of *T. quinqueloba* and *G. bulloides* relative to the total number of planktic foraminifera behave similarly from about 9 kyr calBP through the present (Fig. 14). Both oscillate on an approximately 1 kyr cycle from around 9 kyr calBP to around 5 kyr calBP, then decrease until around 1.8 kyr calBP, and finally increase towards the present. Prior to 9 kyr calBP, the percentages of the two species behave differently (Fig. 14). *T. quinqueloba* makes up anywhere between 19 and 28 % of the total number of planktic foraminifera in a sample, whereas *G. bulloides* makes up only 0 to 5% of the planktics foraminifera in a sample.

The ratio of *N. incompta* to *N. pachyderma* shows two short-lived high peaks at around 10.2 and 2.7 kyr calBP, and a more long-term high interval from 8.9 to 6.2 kyr calBP. This ratio does not correlate with the percentages of *T. quinqueloba* and *G. bulloides*, however it does show some oscillation on an approximately 1 kyr cycle.

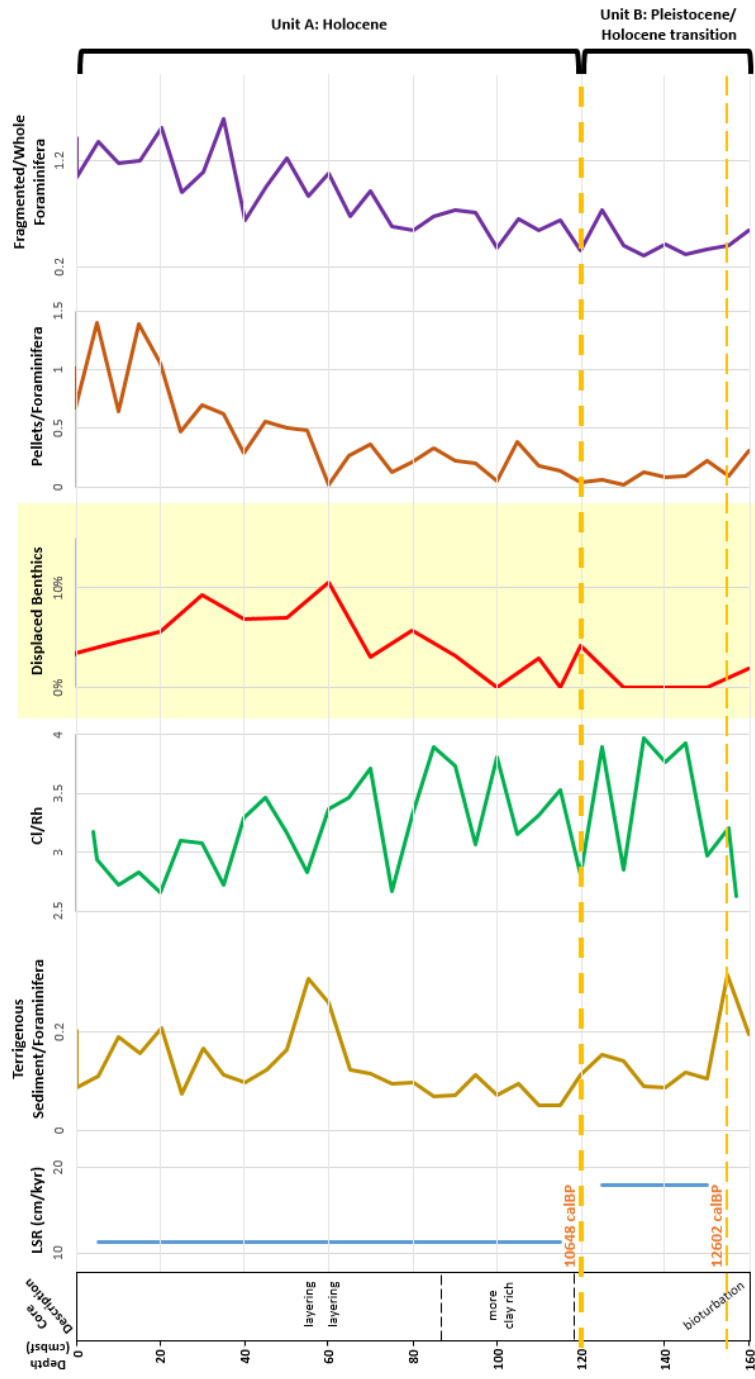


Figure 12: The percent of benthic foraminifera that have been redeposited at STEMSEAS Site 1 from a shallower depth (Bandy, 1953), along with other data that could support various hypotheses as to how the displaced benthic foraminifera were transported to Site 1 if a correlation is found between that data and the displaced benthic foraminifera data. No such correlation is readily observable.

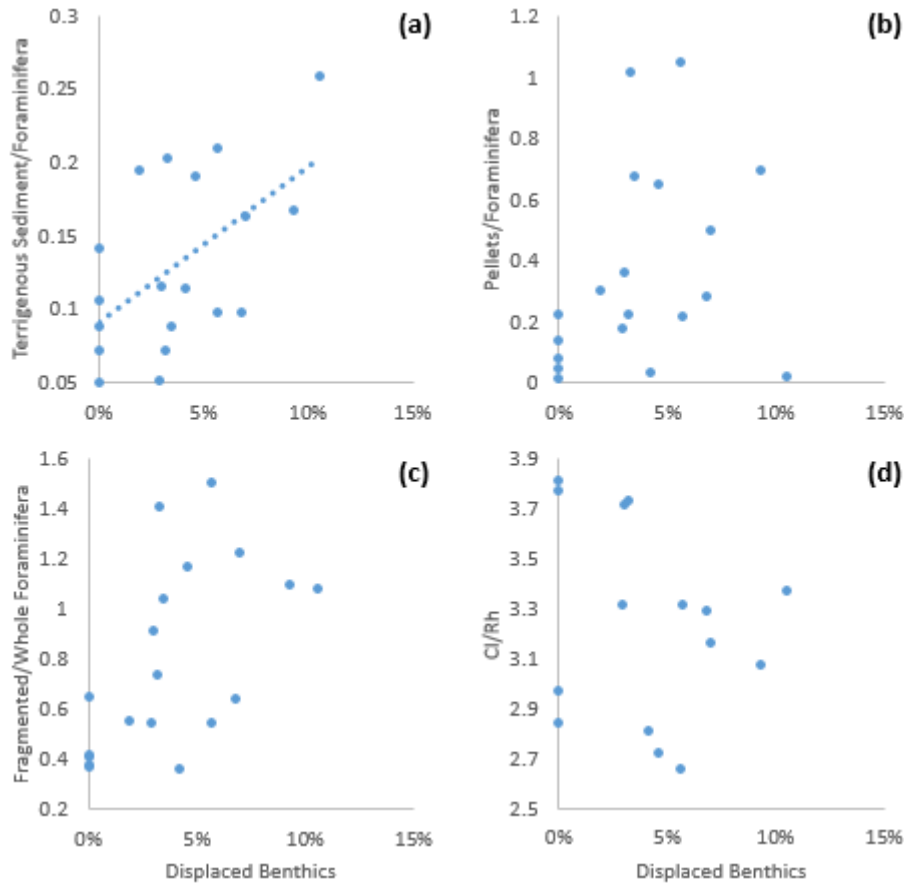


Figure 13: (a) A weak correlation between displaced benthic foraminifera and terrigenous sediment. (b) No correlation between displaced benthic foraminifera and fecal pellets. (c) No correlation between displaced benthic foraminifera and foraminifera fragments. (d) No correlation between displaced benthic foraminifera and the Cl/Rh ratio (St. John and Leckie, 2016, unpublished data).

DISCUSSION

A Note on Benthic Data

This project served as an initial survey of STEMSEAS Site 1 core. Picking yielded relatively low numbers of benthic foraminifera compared to planktic foraminifera; in one sample only 22 of the 308 foraminifera picked were benthic. These low numbers do not provide a statistically accurate representation of the actual composition and diversity of the benthic community. However, some trends within the sparse benthic data were notable and are mentioned in the discussion below.

Shift at 120 cmbsf

The age model shows that the shift in elemental ratios at 120 cmbsf occurs at 10.6 kyr calBP, approximately one thousand years after the Pleistocene/Holocene boundary (Fig. 10). However, much of the elemental data collected throughout this project also displays some shift happening around 120 cmbsf (Fig. 11). Within the foram data, the event which caused the changes at 120 cmbsf seems to be largely constrained to the benthic community (Fig. 12). Notable changes in planktic

foraminiferal proxies for temperature and nutrient influx to the surface waters are not apparent at this boundary (Fig. 14).

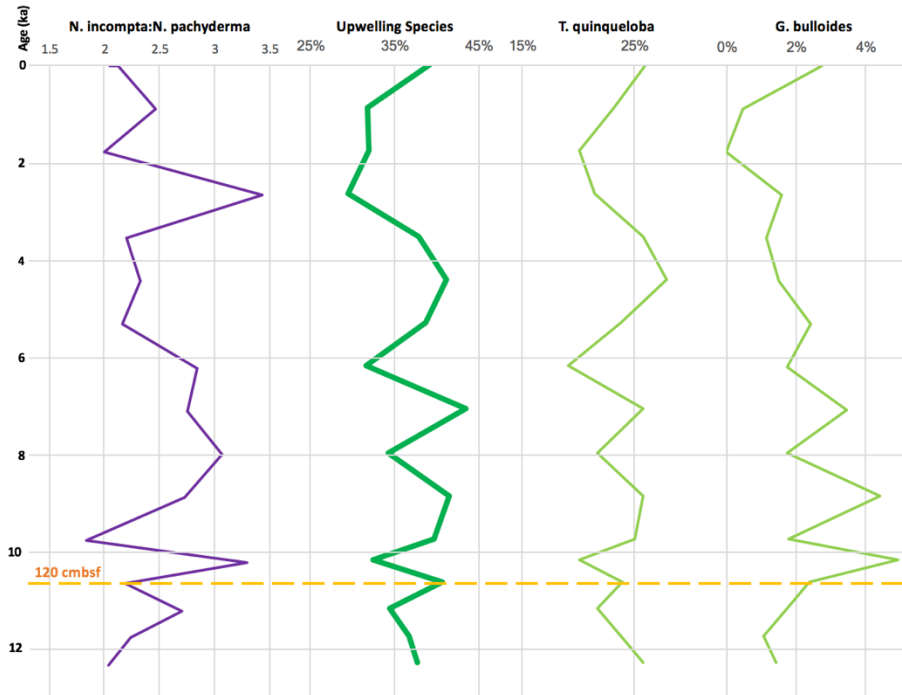


Figure 14. Planktic foraminiferal proxies for sea surface temperature (SST; *N. incompta*:*N. pachyderma*), upwelling conditions (Upwelling Species: *T. quinqueloba* plus *G. bulloides*; *T. quinqueloba*), and food availability (*G. bulloides*; Fislser and Hendy, 2008). An increased ratio or percentage indicates warmer SST, strong upwelling conditions, or abundant food availability.

Based on the distinct differences above and below 120 cmbsf in much of the data from STEMSEAS Site 1, the core is interpreted as two different units: Unit B and Unit A (Fig. 11). Unit B is composed of all of the sediment from the base of the core through 120 cmbsf. Barring an unconformity, the Pleistocene/Holocene boundary (11.7 ka) is captured within Unit B. Unit A is composed of all of the sediment above 120 cmbsf. All of the sediment in Unit A was deposited during the Holocene.

In figure 11, the data are color coded into three groups. The blue group consists only of the LSR. The green group consists of the Br/Rh ratio (St. John and Leckie, 2016, unpublished data), the pellet to foraminifera ratio, the fragmented to whole foraminifera ratio, and the siliceous organism to foraminifera ratio. According to Ziegler et al. (2008), bromine can be used as a proxy for marine organic matter, such as fecal pellets. The fecal pellets may have been responsible for trapping the finer grained foraminifera fragments and siliceous organisms and depositing them at Site 1. This could explain why all of the data in the green group follow an overall similar trend. It also suggests that there was overall greater bioproductivity in the surface waters and transfer of organic matter to the deep sea in the Holocene than during the Pleistocene/Holocene transition.

The red group consists of data dealing directly with the abundance and diversity of benthic foraminifera: the planktic to benthic foraminifera ratio, the ratio of oxic to dysoxic indicator benthic foraminifera, and the benthic diversity. In their study of oxygen deficient marine settings, Gooday et al. (2000) observed that low dissolved oxygen results in decreased species richness and diversity

among benthic foraminiferal communities. Figure 11 supports Gooday et al.'s observations, showing benthic diversity and the oxic to dysoxic ratio following similar trends. In Unit B, the oxic to dysoxic ratio is generally lower than in Unit A, which is interpreted as the basin having lower dissolved oxygen during the Pleistocene/Holocene transition than it did for much of the Holocene. The low dissolved oxygen during the Pleistocene/Holocene transition correlates with a low benthic diversity relative to Unit A.

This inferred dissolved oxygen data from Site 1 correlates with data from ODP Site 893 in the nearby Santa Barbara Basin. There, the presence or absence of laminations in the Site 893 core is used as a proxy for low or high dissolved oxygen, respectively (Kennett and Ingram, 1995; Shore-based Scientific Party, 1994). The ODP Leg 146 Shore-based Scientific Party (1994) attribute changes in dissolved oxygen in the Santa Barbara Basin to glacioeustatic driven depth changes of the impinging Oxygen Minimum Zone (OMZ) relative to the depth of the surrounding sills, changes in the oxygen content of the PIW, and changes in productivity in the surface waters. As the STEMSEAS Site 1 core does not capture any history prior to 13 kyr calBP, it is unlikely that glacioeustatics play a role in the trends of the dissolved oxygen data.

Alternatively, changes in the PIW dissolved-oxygen levels maybe driven by larger-scale changes in the global ocean conveyor (i.e., thermohaline circulation). For example, Kennett and Ingram (1995) hypothesized that the most likely influence on dissolved oxygen at ODP Site 893 during the Late Quaternary was changes in North Atlantic Deep Water (NADW) production related to variation in surface water salinity driven by changes in global climate (e.g., increased or decreased ice melt). This could explain changes in oxic and dysoxic conditions at the two sites.

It is notable that the low bioproductivity recorded during the 120 cmbsf shift occurs at the same time as a period of lower dissolved oxygen at Site 1 (Fig. 11). In contrast, increased bioproductivity has been shown to cause a decrease in the amount of dissolved oxygen in the lower regions of other California Borderland basins due to available oxygen being consumed by decay of the organic materials that settle on the basin floor (Shore-based Scientific Party, 1994). This relationship between bioproductivity and dissolved oxygen is only readily apparent in the core top, where dissolved oxygen is shown to decrease at the same time as pellets, siliceous organisms, and foraminifera fragments increase (Fig. 11). The increased bioproductivity in this sample is likely due the sample representing the present at the time of Site 1 core's collection, which was during the spring upwelling.

Gooday et al. (2000) note that the population size in benthic foraminiferal communities is limited more by food availability than by dissolved oxygen. Figure 11 supports Gooday et al.'s observations. When marine organic matter (the Br/Rh ratio) is generally lower during the Pleistocene/Holocene transition (relative to the Holocene) the planktic to benthic ratio shows that the abundance of benthic foraminifera is also low relative to Holocene abundances (Fig. 11).

In summary, Unit B shows marine organic matter deposition at STEMSEAS Site 1 decreasing through time during the transition period between the Pleistocene and Holocene. The reduction in organic matter resulted in a reduction in the population size of the benthic foraminiferal community at Site 1. The reduction in organic matter correlates with a reduction in dissolved oxygen, which is perplexing. The shift toward dysoxic conditions resulted in a reduction of diversity in the benthic foraminiferal community. Following 120 cmbsf, or 10.6 kyr calBP, Unit A shows the deposition of marine organic matter increasing, which resulted in an increase in the population of benthic

foraminifera. The increase in marine organic matter corresponds to an increase in dissolved oxygen, which resulted in an increase in benthic foraminifera diversity.

Evidence for Turbidity Flow Deposition

The presence of displaced benthic foraminifera indicates some transport mechanism from shallower water depths to STEMSEAS Site 1 in the Tanner Basin. However, the percentage of displaced benthic foraminifera displayed in figure 12 is in reference to the total number of benthic foraminifera in a sample, not the total number of all foraminifera in a sample. The actual number of displaced foraminifera found in any sample was very low, not exceeding 2% of the total foraminifera picked from that sample. Since the majority of the foraminifera in any given sample were either autochthonous benthic foraminifera or planktic species that settled out of the water column, there is little evidence supporting turbidity flow deposition as the dominant sediment transport process at Site 1.

It is expected that turbidity flows would lead to high sedimentation rates. Yet the majority of displaced foraminifera occur above 120 cmbsf, and the sedimentation rate above 120 cmbsf is much lower than the sedimentation rate below that depth (Fig. 12). Also, the high energy of turbidity flows may lead to the fragile foraminifera tests being damaged and fragmented. However, there is no correlation between the number of foraminifera fragments in a sample and the abundance of displaced benthic foraminifera in that sample (Fig. 12 and 13c). Finally, it was hypothesized shipboard (St. John, 2016, personal communication) that stratigraphic changes in elemental ratios (Cl/Rh in particular because Cl is a proxy for increased pore water; Tjallingii et al., 2007) may correspond to turbidity flow deposits. However, the presence of displaced foraminifera does not correlate with changes in the elemental ratios (Fig. 12 and 13d).

The presence of sand sized terrigenous sediment in a core primarily composed of silt and clay sized sediments may indicate pulses of higher than normal energy. This increase in energy could be the result of turbidity flows. Aside from the displaced foraminifera themselves, the only evidence supporting the presence of turbidity flow deposits is the weak correlation between those foraminifera and the ratio of terrigenous sediment >63 μm to the total number of foraminifera picked from each sample (Fig. 12 and 13a). A grain size analysis of bulk samples from the core may provide more conclusive evidence on whether there is a correlation between grain size and displaced foraminifera.

Another possible transport mechanism for the displaced benthic foraminifera is the deposition of the foraminifera in the fecal matter of organisms which feed at shallower depths, then defecate into the basin. However, while both the percentage of displaced benthic foraminifera and the ratio of fecal pellets to foraminifera increase above 120 cmbsf (Fig. 12), there is no apparent correlation between the two (Fig. 13b). Even where pellets are absent, the fragments of foraminifera tests that were consumed by larger organisms, then shattered during digestion could also provide evidence for the displaced foraminifera being redeposited in fecal matter. However, no correlation between the number of foraminifera fragments in a sample and the abundance of displaced foraminifera in a sample was observed (Fig. 12 and 13c).

Planktic proxies

Upwelling events are often associated with an influx of food and nutrients to the surface waters, and because the trend of *G. bulloides* follows so closely with the trend of *T. quinqueloba* (Figure 14), both

species are being associated with upwelling in this discussion. The varying percent of these upwelling species throughout STEMSEAS Site 1 core record periods of relatively strong upwelling at 12.3 kyr calBP, 9.8 to 8.9 kyr calBP, 7.1 kyr calBP, 4.4 to 3.5 kyr calBP, and near the present (Fig. 14). The *G. bulloides* data records a similar history for food and nutrient availability at Site 1. Nutrients were most abundant at 10.2 and 8.9 kyr calBP, and also were relatively abundant at 7.1 kyr calBP and near the present (Fig. 14). In addition to the upwelling record, the ratio of *N. incompta* to *N. pachyderma* records two short-lived warm SST periods at around 10.2 and 2.7 kyr calBP, and a more long-term warm period from 8.9 to 6.2 kyr calBP (Fig. 14).

In the context of the age model, the sampling frequency of the STEMSEAS Site 1 core provides a higher resolution record of the latest Pleistocene and Holocene age sediment in the Tanner Basin than was produced for the nearby ODP Site 1014 by the ODP Leg 167 Shipboard Scientific Party (1997a). However, the STEMSEAS Site 1 resolution is relatively low when compared with Fisler and Hendy's (2008) high resolution study of the paleoenvironmental history of ODP Site 893 in the nearby Santa Barbara Basin (Fig. 15). Fisler and Hendy (2008) observed millennial-scale climate variability recorded in the Holocene sediment at ODP Site 893. Despite the differences in resolution, the planktic foraminifera present throughout the STEMSEAS Site 1 core also record a history of semi-regular cycling of temperature, upwelling strength, and nutrient availability on a roughly millennial-scale (Fig. 14 and 15).

Millennial-scale variability is also observed in the elemental data from the STEMSEAS Site 1 core (e.g., Fig. 6 Ca/Ti ratio; St. John and Leckie, 2016, unpublished data), suggesting that millennial oscillations are a characteristic feature of latest Pleistocene and Holocene deposition at Site 1. In addition, the trends of *T. quinqueloba* and *G. bulloides* at Site 1 correlate decently with the data of the same species at ODP Site 893 (Fig. 15; Fisler and Hendy, 2008). The most obvious exception to this is near present, where the high resolution study of Fisler and Hendy (2008) finds the percentage of *G. bulloides* to remain relatively low at ODP Site 893, while the STEMSEAS Site 1 data shows the percentage of *G. bulloides* increasing. This deviation may be due to differences in currents and/or upwelling strength between the two locations, or is an artifact of the relatively low sampling frequency for the STEMSEAS Site 1 core.

In contrast, despite it also displaying a roughly millennial-scale variability, the pattern of the ratio of *N. incompta* to *N. pachyderma* from STEMSEAS Site 1 does not match well with the pattern of that ratio recorded by Fisler and Hendy (2008) at ODP Site 893 (Fig. 15). This may be due to differences in latitude, differences in how currents affect the two sites, or is an artifact of the relatively low sampling frequency or distribution of sampling within the STEMSEAS Site 1 core.

Holocene-age millennial-scale variability (millennial oscillations; MOs) similar to what is observed at STEMSEAS Site 1 has been noted in a number of studies from the California Borderland (Fisler and Hendy, 2008; Masters, 2006; Jacox et al., 2015) and the eastern Pacific (Moy et al., 2002). To a varying extent, those studies all attribute MOs to ENSO variability (e.g., intensity and frequency) through time. Jacox et al. (2015) note that along the California margin ENSO years are marked by decreased upwelling strength (and occasionally downwelling), which results in a decrease in nutrient availability. ENSO years should thus be marked by low numbers of *T. quinqueloba* and *G. bulloides* (Fisler and Hendy, 2008). The low numbers of those species should be complimented by a high *N. incompta* to *N. pachyderma* ratio, reflecting the warm SST also associated with ENSO (Fisler and Hendy, 2008; Jacox et al. (2015).

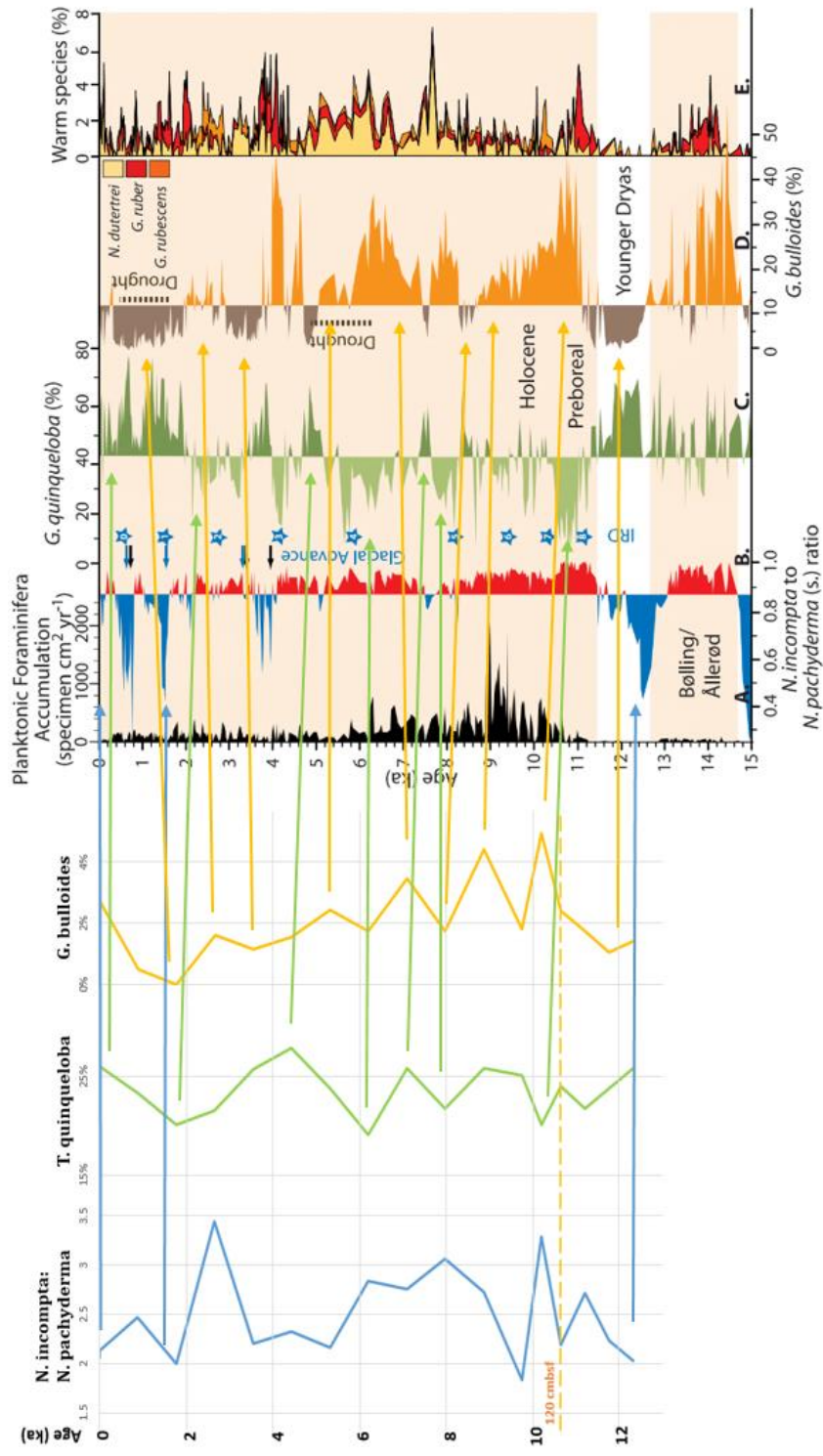


Figure 15: Correlation of STEMSEAS Site 1 planktic foraminifera proxy data (left) to ODP Site 893 data (right). Various colored arrows represent strong correlations between datasets. Arrows are color-coded to match the color used to represent their given species/ratios data (modified from [Fisler and Hendy, 2008](#)).

The frequency and intensity of ENSO events can change through time (Moy et al., 2002), and as such, in the California Borderland periods of high frequency should be marked by generally warmer SST and low productivity and nutrient availability. In the STEMSEAS core, these high frequency periods should thus manifest as low numbers of upwelling species and a high *N. incompta* to *N. pachyderma* ratio. Moy et al. (2002) used lacustrine sediment to track ENSO frequency through time, and found that the number of ENSO events per 100 years has generally increased from around 12 ka to the present. While the SST record from the STEMSEAS Site 1 core does not support Moy et al.'s findings, the upwelling and nutrient records from STEMSEAS Site 1 do support Moy et al.'s findings, showing an overall decrease in *T. quinqueloba* and *G. bulloides* through time (Fig. 14).

CONCLUSION

The STEMSEAS Site 1 core records a complex depositional and paleoenvironmental history for its locality in the Tanner Basin. That record allows Site 1 to be placed within the context of the California Borderland's diverse paleoceanographic and paleoclimatic history. Answering the questions posed within each of the initial objectives of this study provides a good summary of the STEMSEAS Site 1 history.

Objective 1: Research on Depositional Conditions

1) *Can biostratigraphic markers in the foraminiferal assemblages in STEMSEAS Site 1 core be used to test the hypothesis that a shift in elemental ratio concentrations at 120 cmbsf marks the Pleistocene/Holocene boundary?*

The age model developed for the STEMSEAS Site 1 core shows that the shift at 120 cmbsf occurs around the time of (~1 kyr following) the Pleistocene/Holocene boundary (Fig. 10 and 11). 120 cmbsf therefore represents a shift from a Pleistocene/Holocene transitional period (Unit B) to the Holocene (Unit A; Fig. 10 and 11).

The benthic foraminifera and other biostratigraphic data in the Site 1 core reveal different patterns above and below 120 cmbsf, similar to what is seen in the core's elemental ratio concentrations (Fig. 11). Based on that data, the Pleistocene/Holocene transition is hypothesized to have been a period of low dissolved oxygen within the Tanner Basin. This period of inferred low dissolved oxygen in the basin correlates with the dissolved oxygen record of ODP Site 893 (Kennett and Ingram, 1995) and is tentatively attributed to low dissolved oxygen in the PIW.

The data also reveal a period of low productivity during the Pleistocene/Holocene transition (Fig. 11). This seems counterintuitive as normally surface water productivity is contrary to dissolved oxygen in basins (Shore-based Scientific Party, 1994; Kennett and Ingram 1995). A more in depth investigation of the changes in the benthic foraminiferal community above and below 120 cmbsf may provide a better understanding as to why the general behavior of productivity mimics the behavior of inferred dissolved oxygen during the Pleistocene/Holocene transition and during the Holocene (Fig. 11).

2) *Is there evidence of turbidity flow deposition at STEMSEAS Site 1?*

The presence of displaced benthic foraminifera in certain Site 1 core samples indicates some transport mechanism from shallower depths to Site 1 (Fig. 12). They provide some evidence for

turbidity flow deposition, however their low numbers suggest that it is not the dominant sediment transport process at Site 1. The displaced foraminifera show, at best, only weak correlations with other sediment types that might also be attributed to turbidity flow deposition (Fig. 12 and 13a, c, and d). Also, the majority of displaced foraminifera occur at depths that fall within the cores lowest sedimentation rate (Fig. 12). However, evidence for other transport mechanisms for these foraminifera, such as their redeposition in fecal pellets, is even more lacking. The displaced foraminifera show no correlation with sediment types that could be associated with fecal deposition (Fig. 12 and 13b and c).

The low numbers of benthic foraminifera picked from each sample do not provide a statistically accurate representation of the benthic assemblages throughout the Site 1 core. Therefore, a more in depth study of the benthic foraminifera in STEMSEAS Site 1 could provide greater evidence for turbidity deposition at that location. A grain size analysis of Site 1's bulk samples may reveal further evidence for turbidity deposits.

Objective 2: Research on Paleoenvironmental Conditions

3) Can the foraminiferal assemblages within STEMSEAS Site 1 core be used to study paleoenvironmental changes in the California Borderland through time?

The foraminiferal assemblages within STEMSEAS Site 1 reveal a paleoenvironmental history that spans from the latest Pleistocene through the present day. Relative to high resolution paleoenvironmental data from the Santa Barbara Basin (Fisler and Hendy, 2008), the STEMSEAS Site 1 history is low resolution (Fig. 15). Regardless, this history indicates semi-regular millennial scale variations of upwelling strength, nutrient influx, and SST at Site 1 (Fig. 14). These variations mostly correlate with the regional record of MOs (Fig. 15), which could be driven by ENSO events. The increase in the frequency of ENSO events in the last 12 ka correlate with the overall decreasing trend in upwelling strength and nutrient influx observed at Site 1 (Fig. 14).

SST data from STEMSEAS Site 1, however, do not display the overall increase in water temperature that is expected to go along with the increased frequency of ENSO events (Jacox et al., 2015; Fisler and Hendy, 2008). The SST data also do not correlate with other records of SST from the California Borderland (Fig. 15). A higher sampling frequency and a higher number of picks per sample may help refine the SST record at STEMSEAS Site 1 and provide a greater understanding as to how that record fits into the regional context of the California Borderland and the context of the increase in ENSO events through time.

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APPENDIX 1: DATA

General Data

Sample Depth (cmbfsf)		Sample Weight (g)	Number of Splits	Foraminifera				Siliceous Organisms	Sponge Spicules	Pellets	Terrigenous Sediment
Top	Bottom			Planktics	Benthics	Total	Fragments				
Top Sample	0	1.59	6	224	92	316	446	49	24	321	64
	0	2.47	4	219	86	305	317	36	4	206	27
	5	1.37	6	221	108	329	455	35	21	459	36
	10	1.46	5	211	109	320	375	36	12	208	61
	15	3.31	6	237	77	314	378	24	8	435	49
	20	3.10	6	254	71	325	489	30	8	342	68
	25	2.18	6	260	54	314	285	25	8	148	23
	30	2.01	6	251	54	305	335	12	14	212	51
	35	2.19	6	254	66	320	510	20	27	198	36
	40	2.07	5	264	44	308	197	13	3	88	30
	45	2.16	6	283	44	327	315	10	13	181	40
	50	1.89	6	262	43	305	373	4	11	153	50
	55	2.36	6	267	34	301	262	11	7	145	93
	60	0.79	3	248	57	305	330	6	8	6	79
	65	1.20	5	278	33	311	211	3	11	83	38
	70	1.65	6	288	33	321	293	7	6	116	37
	75	1.57	6	271	45	316	185	6	3	41	30
	80	2.72	4	290	35	325	177	4	3	71	32
	85	3.12	7	288	34	322	216	4	7	108	22
	90	4.03	6	286	31	317	234	9	5	72	23
	95	2.33	6	298	39	337	239	5	2	70	38
	100	2.81	5	294	27	321	121	2	4	15	23
	105	2.28	6	268	48	316	206	2	5	121	30
	110	2.87	6	279	34	313	171	4	2	56	16
	115	3.22	6	324	32	356	230	3	1	50	18
	120	4.85	5*	292	24	316	113	1	2	12	36
	125	6.17	6*	286	47	333	247	1	6	21	51
	130	5.52	6*	285	32	317	129	4	4	5	45
	135	3.27	6	306	32	338	103	1	3	44	30
	140	3.42	5	286	22	308	128	3	3	25	27
	145	3.30	6	299	33	332	107	2	5	33	39
	150	3.43	6	283	37	320	118	7	8	72	34
	155	1.96	6	297	43	340	136	4	5	33	108
	160	Core Catcher	6	281	52	333	183		5	102	65

*Received as a split

Planktic Foraminifera Data

Sample Depth (cmbsf)		Globigerina bulloides	Globigerinita glutinata	Globigerinita uvula	Globigerinella aequilateralis	Globigerinoides sacculifer	Globorotalia scitula	Neogloboquadrina dutertrei	Neogloboquadrina incompta	Neogloboquadrina pachyderma	Orbulina universa	Turborotalita quinqueloba	Unknowns	TOTAL PLANKTICS
Top	Bottom													
Top Sample	0	6	7	68		1			37	18		63	24	224
	0	2	6	9	42	1	3		49	23		57	29	219
	10	12	1	5	83	1	1		42	17		49	12	211
	20	22		10	81	1	1		60	30		51	20	254
	30	32	4	9	75	1	2	2	55	16	1	54	32	251
	40	42	3	6	72	2		3	64	29		68	17	264
	50	52	4	8	63		2	1	72	31		73	8	262
	60	62	6	7	67		1		67	31	1	59	8	248
	70	72	5	7	87		2	2	88	31		55	11	288
	80	82	10	7	31	2	1	1	113	41		75	9	290
	90	92	5	11	70		2		95	31		62	9	286
	100	102	13	6	61		1	2	90	33	2	76	10	294
	110	112	5	2	93	1			66	36		70	6	279
	115	117	16	5	64	1	1	2	79	24		65	67	324
	120	122	7	10	66		1		92	42	1	70	3	292
	130	132	5	4	80	1	2	1	84	31	1	62	14	285
	140	142	3	9	81		1	2	76	34	1	68	11	286
	150	152	4	5	85				61	30		73	25	283
	160	Core Catcher	7	6	105	1		2	62	23		69	6	281

Benthic Foraminifera Data

Top Sample	Sample Depth (cmbsf)		Alabaminella weddellensis	Angulogerina angulosa	Bolivina/Brizalina	Bulimina	Buliminella	Cassidulina	Chilostomella	Cibicides	Ehrenbergina	Epistominella	Fissurina	Fursenkoina	Globobulimina	Globocassidulina	Gyroidinoides soldanii	Haplophragmoides	Islandiella	Lenticulina	Miliolid	Nonionella	Pyrgo	Quinqueloculina	Uvigerina	Valvulinaria	Unknown Benthics	TOTAL BENTHICS		
	Top	Bottom																												
0	0	2	6	8	20	1	4	13	14	2	1	11	9	1	2	10	1	1	7	1	1	5	1	2	1	1	6	1	6	86
10	12	14	1	1	17	1	1	12	6	3	2	6	1	2	4	16	4	1	16	7	5	3	1	3	3	6	5	109		
20	22	13	16	1	16	1	1	6	3	3	1	6	2	2	4	4	1	7	7	4	3	2	3	2	3	4	0	71		
30	32	12	6	6	6	6	7	7	7	1	5	5	2	2	1	7	2	1	4	4	2	1	2	5	1	0	54			
40	42	8	1	5	5	2	7	2	2	2	2	2	2	1	2	2	1	1	7	7	1	3	3	5	1	2	44			
50	52	8	3	2	3	2	3	3	3	1	2	3	4	4	3	3	3	3	3	3	2	3	3	3	2	1	43			
60	62	6	3	8	8	8	8	8	8	2	1	4	1	4	4	4	4	4	13	4	2	3	3	3	3	2	57			
70	72	6	3	2	3	3	3	3	3	1	1	2	1	1	2	2	2	2	4	4	3	3	3	3	3	3	33			
80	82	1	5	1	5	1	6	1	1	3	5	5	1	1	2	2	2	4	4	4	1	1	1	1	2	1	35			
90	92	2	3	3	3	2	2	3	3	3	4	4	1	1	4	4	4	4	4	4	2	1	1	1	2	1	31			
100	102	2	4	4	4	1	1	2	2	2	8	8	1	1	1	1	1	3	3	2	2	1	1	2	1	1	27			
110	112	9	7	7	7	2	2	2	2	1	1	1	1	3	3	3	3	3	2	2	1	2	2	2	2	2	34			
115	117	5	5	5	5	2	1	1	1	1	6	6	4	4	4	4	4	4	4	4	3	3	3	3	1	1	32			
120	122	3	5	5	5	1	1	3	3	2	1	1	2	2	2	2	2	2	3	3	3	3	3	3	3	1	24			
130	132	5	6	6	6	4	4	4	4	2	2	2	2	1	1	1	1	6	6	6	3	2	2	3	1	2	32			
140	142	3	4	4	4	3	3	3	3	2	2	2	2	3	3	3	3	3	3	3	2	2	2	2	1	4	22			
150	152	1	6	6	6	1	1	3	3	3	4	4	2	3	3	3	3	3	8	8	3	3	3	2	1	4	37			
160	Core Catcher	4	7	7	2	2	1	1	1	3	1	1	1	3	3	6	1	1	11	1	1	2	1	1	1	3	52			