2014

Low Resolution Examination of Cool-water Carbonate Foraminifera around Tasmania during the Pleistocene

Sara Jane Hughes

Eastern Illinois University

This research is a product of the graduate program in Natural Sciences at Eastern Illinois University. Find out more about the program.

Low Resolution Examination of Cool-water Carbonate Foraminifera

around Tasmania during the Pleistocene

(TITLE)

BY

Sara Jane Hughes

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

Master of Science in Natural Science

IN THE GRADUATE SCHOOL, EASTERN ILLINOIS UNIVERSITY
CHARLESTON, ILLINOIS

2014

YEAR

I HEREBY RECOMMEND THAT THIS THESIS BE ACCEPTED AS FULFILLING
THIS PART OF THE GRADUATE DEGREE CITED ABOVE

███████████ 7/3/14	███████████ 7/7/14	
THESIS COMMITTEE CHAIR DATE	DEPARTMENT/SCHOOL CHAIR DATE OR CHAIR'S DESIGNEE	
███████████ 3 July 2014	███████████ 7/8/14	
THESIS COMMITTEE MEMBER DATE	THESIS COMMITTEE MEMBER DATE	
THESIS COMMITTEE MEMBER DATE	THESIS COMMITTEE MEMBER DATE	

Abstract

Benthic foraminifera from nine sediment samples recovered during Ocean Drilling Program (ODP) Leg 189: The Tasman Gateway were examined to determine how changing Southern Ocean conditions affect benthic foraminiferal populations. All samples come from Site 1168 situated 70km from the coast of Tasmania on the western continental slope (2463 m below the surface) and are spaced at roughly 150,000 years apart. Identifications of benthic foraminifera were done with a dissecting microscope and several reference books. Foraminifera were correlated with environmental proxy data obtained from Brughmans (2003) (total organic carbon, carbonate, siliciclastics, coarse fractions, chlorin, barium, aluminum, iron, and titanium) and The Scientific Shipboard Party (2001) (density, magnetic susceptibility, and lightness).

The data demonstrates that benthic foraminifera responded to large-scale changes in the ocean surface waters caused by the movement of the subtropical convergence during glacial and interglacial periods. Genera such as *Uvigerina*, *Cibicidoides*, *Cibicides*, and *Notoralia* tend to be more successful during glacial periods when there is greater abundance of wind-blown terrigenous metals delivered to the ocean; whereas genera *Pyrgo* and species *Epistominella elegans* and *Hansenisca soldanii* seem to thrive under interglacial conditions when there is higher productivity in the surface waters. This research also adds to the growing knowledge base of cool-water carbonate environments and provides further evidence of a mid-Pleistocene extinction event affecting the genus *Siphondosaria* and others.

Dedication

I dedicate this project to my family (past, present, and future), for I have known

nothing but love and support from them. Mom and Dad, I want you to know how much I

appreciate all of the sacrifices you made to lift me up in the world. I know that sending

me to private school could not have been an easy decision for you given your financial

situation, but you believed in the power of education and passed that attitude on to me. It

also must have been difficult giving up that second paycheck so mom could be at home to

raise Gary and me. Mom – it was worth every penny having you there to care for us when

we were sick, walk us back and forth to school, chaperone our trips, read to us every

night, and be there for us no matter what. I love you both more than words can express.

Aunt Nancy, I will never forget all the fun we have together going on little

adventures and watching documentaries and musicals on the couch. Your influence on

my life has been priceless. I hope that living through me vicariously has been everything

you wanted it to be.

To my future husband, Patrick, where would I be without you? You picked up

where my family left off, nurturing my mind, body, and soul to help me grow into the

woman that I am today. I have loved every moment with you over the last nine years and

am so excited to see what other adventures our life takes us on. I am truly, madly, deeply

yours.

Acknowledgements

Dr. Katherine Lewandowski has been a patient and devoted advisor, I would not have been able to finish this project without her guidance. I know it couldn't have been easy dealing with my panic moments, but I hope I made you proud. I must also give a special thanks to my friend Michelle Friel-Kaylor, for convincing me to get a master's degree and Fran Hirshfelder and Dena Guptill for all the moral support.

Table of Contents

List of Figures and Tables

I. Introduction

The Earth and all its myriad components are constantly shifting and changing. One of the most dynamic and influential of these components is the ocean with its complex array of tides, deep water masses, surface currents, eddies, and gyres. The ocean, arguably, has the greatest impact on life on this planet, as it is the only habitat and food source for countless species and a major factor in regional and global climate. In order for us to better understand the actions of the modern ocean and their implications, we must understand how the ocean behaved in the past. The purpose of this research is to use benthic foraminifera and environmental proxies to make inferences about Southern Ocean conditions and global climate at 150,000 year time intervals during the Pleistocene (ranging from 16,000 – 1,370,000 years ago).

II. Literature Review

A. Foraminifera

Foraminifera are a phylum of protozoa on the taxonomic tree of life. They are characterized as complex, single-celled creatures that build tests (shells) and use pseudopodia to feed. Foraminifera first evolved during the Cambrian and are currently found within marine environments. Most foraminiferal species are benthic with calcium carbonate shells, but planktonic species and other shell types, such as aragonite and foreign particle conglomerates, also exist. There are thousands of existing foraminiferal species that are classified in a variety of ways, including, but not limited to, test shape, test composition, habitat, and mode of life (Gupta, 2002).

Foraminifera have been used in the past by researchers for a variety of reasons. Commonly, the carbonate tests of foraminifera are used to analyze oxygen isotope ratios ($\delta^{18}O$) for dating and for the purpose of paleoclimatic information (Brughmans, 2003). The oxygen isotope ratio investigated when using $\delta^{18}O$ is the proportion of ^{18}O to ^{16}O. The lighter isotope, ^{16}O, is preferentially evaporated from the ocean surface. The heavier isotope, ^{18}O, is preferentially precipitated out of the atmosphere during rain or snow events. This process is called fractionation. The oceans are generally enriched in the heavier oxygen isotope during periods of colder temperatures and more ice volume. During periods of warmer temperatures and lower global ice volume, the oceans are relatively more depleted in ^{18}O or enriched in ^{16}O. Thus, the oxygen isotope ratio, $\delta^{18}O$, changes with temperature and global ice volume. Because some species of foraminifera secrete their tests in equilibrium with the ocean, foraminifera can be used as a proxy for past ocean temperatures. For those species which do not secrete their tests in equilibrium with seawater, transfer functions have been developed to calculate corrections in order to estimate past temperatures.

Productivity is a term used in ocean ecology to describe how much photosynthesis and other biochemical processes are taking place. The more organic life that is present, the higher the productivity of the ocean will be. Certain foraminiferal species have also been shown to be highly correlated to ocean productivity (Nees, 1997). That is to say, the more productive the ocean is, the more abundant those species of foraminifera will be. Moreover, some foraminiferal species show preferences for particular environments related to ocean chemistry, substrate, current velocity, oxygen content, etc., so looking at

a certain species in the rock record could also be indicative of environmental conditions in the ocean or at the seafloor in that location at that time. This information can be extrapolated to infer the influencing ocean currents and periods of glaciation operating during the interval (Gupta, 2002).

B. Setting

The foraminiferal samples analyzed are from seafloor sediment core samples obtained by The Ocean Drilling Program (ODP), during Leg 189: The Tasmanian Gateway. Specifically, these samples were taken from Site 1168, Hole A, located at a depth of 2463 meters below the surface and 70 km from the western Tasmanian coast in the Southern Ocean, see Figure 1 (Shipboard Scientific Party, 2001). The site is on the continental margin on a 4° slope in a strike-slip basin that experienced uplift during the late Paleocene and early Eocene. The bedrock is composed of continental basement rock overlain by sandstone, siltstone, and mudstone with the most recent layers being carbonate sediments, specifically nannofossil ooze (Shipboard Scientific Party, 2001). Seismic data suggests Site 1168 has a history of gravity flows. Though historically the site is known for having a continuous sediment record, the current rate of deposition is very low (Shipboard Scientific Party, 2001).
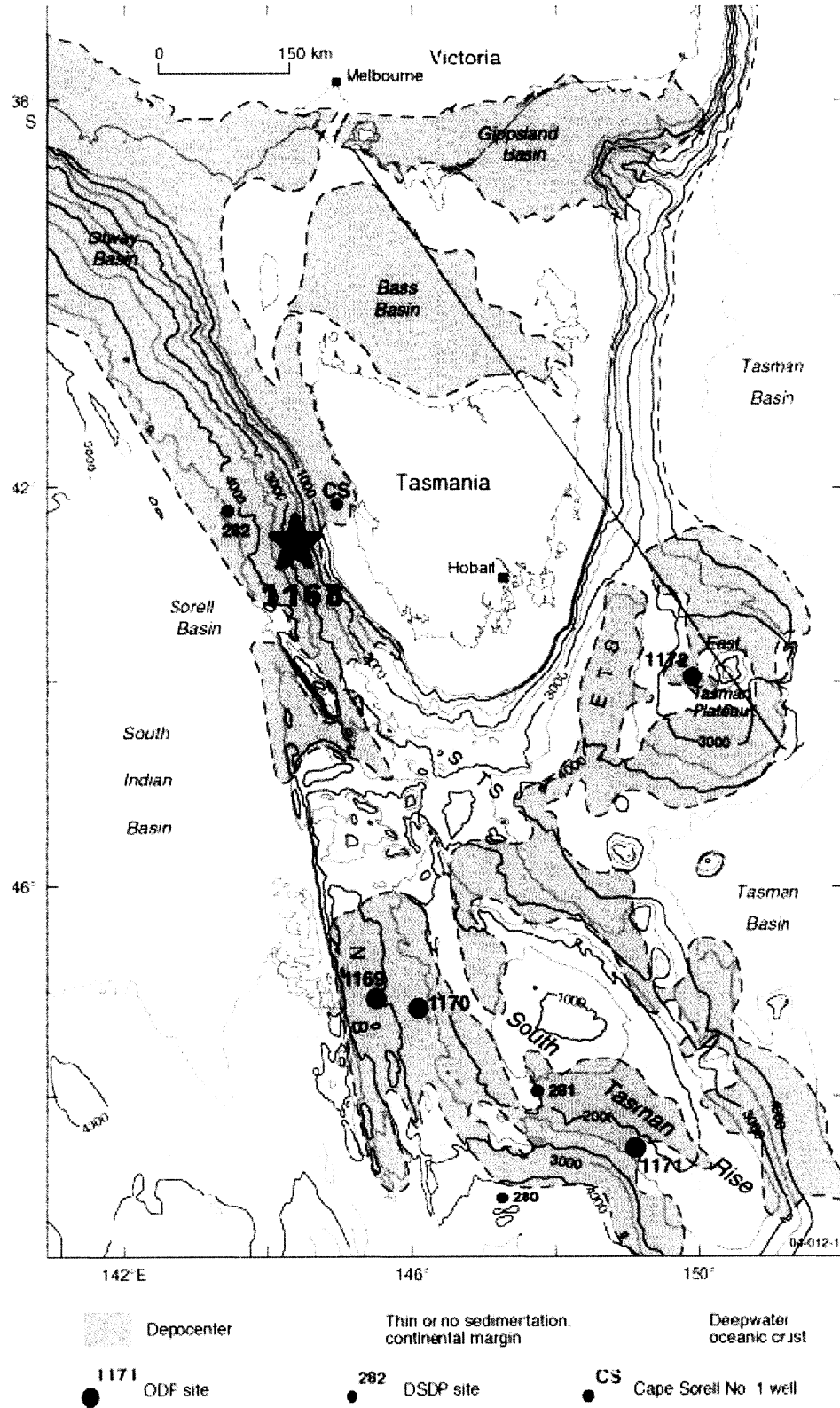
Figure 1: Location of ODP Leg 189 core sites, outlining the sedimentary rock basin and general topography of the ocean around Tasmania (Exon, Kennett, and Malone., 2004).

4

The current climate of Tasmania and the Tasmanian region are classified as cool temperate with four distinct seasons (Climate and Weather). The weather is greatly influenced by ocean currents, most notably the subtropical convergence (STC) where warm, nutrient rich water called Subtropical Surface Water (STSW) meets cold, nutrient poor water called Subantarctic Surface Water (SASW) (Rea & Bloomstine, 1986). The location of the STC shifts seasonally, contributing to the seasons of the area, but it also shifts with glacial maxima and minima (Klinck & Smith, 1993). In 2003, Brughmans defended her dissertation which consisted of a high resolution environmental analysis of ODP sites 1168, 1169, 1170, and 1171 to determine to the location of the STC relative to these sites over the last 500,000 years. She concluded that during glacials the STC shifted south of site 1168 and during interglacials it shifted north of site 1168 (Brughmans, 2003).

Tasmania's modern setting can also be described as a cool-water carbonate environment. Cool-water carbonate environments are places where carbonate sediments, which may later become limestone, are formed in shallow, cool marine environments. This contrasts with the classical carbonate depositional setting, where carbonates form at low latitudes in tropical, warm, shallow waters. Given Site 1168's current location in a shallow, cool marine environment, the carbonates currently being formed and accumulated here could someday lithify into a cool-water limestone, as is currently happening in nearby New Zealand. Research by Noel P. James (1997), suggests that our current interpretation of limestone always being formed in warm environments has skewed our perception of paleoclimate. James (1997) found that while foraminifera are

present in all ocean environments, warm-water carbonate environments were dominated by corals whereas cool-water carbonate environments were dominated by foraminifera and molluscs. Since Site 1168 has been in a cool-water carbonate environment for the last several million years and the Pleistocene biota are dominated by foraminifera, calcareous nannofossils, and bryozoan fragments, core data from the site could add to our growing understanding of carbonate rocks and their depositional environments.

Given that Site 1168 is on the slope of a continental margin and has been under the influence of gravity flows, relict sediments play a major role in the interpretation of data for this research. Relict sediments are loosely defined as sediments, biogenic or otherwise, that are no longer in their environment of deposition (Rivers, James, Kyser, and Bone, 2007). For example, a gravity flow could bring the shallow marine type foraminifer tests down to deep marine environments. The foraminifer test from the species living in shallow waters is no longer in its environment of deposition, thus it is a relict sediment. Relict sediments could also accumulate as a result of greater rates of erosion than deposition and dramatic sea level changes (Rivers et al, 2007).

Lastly, this site is in the ocean and carbonate material is being analyzed, which means the carbonate compensation depth and the lysocline can potentially affect the data. The carbonate compensation depth (CCD) is the depth where all carbonate material completely dissolves. The lysocline is the depth in the ocean where carbonate material will begin to dissolve. The precise depth of the lysocline and the CCD are mostly a function of pressure, temperature, and dissolved carbon dioxide concentration, but other

factors can contribute as well. Due to this, the location of both the lysocline and CCD are highly variable, though the lysocline in the Southern Ocean south of Australia is thought to occur at about 3.4 km below sea level (Takahashi, Broecker, Bainbridge, and Weiss 1980). Carbonate dissolution increases with depth once the lysocline is reached as a result of increased pressure and decreased temperature. Other factors that will increase the rate of carbonate dissolution is a decrease in temperature, or a decrease in dissolved carbon dioxide.

C. Proxies

When studying paleo-settings, it is not possible to take direct measurements of the environment as those environments no longer exist. Instead, researchers rely on proxies to take indirect measurements. A proxy is a measureable remnant of a situation, environment, or event that can be used to indicate that that situation, environment, or event happened. Proxies are not perfect and are often based on correlations, not causations. For example, a puddle can be a proxy for rain fall, but it could also be a sign that your neighbor was watering the grass. The proxies used in this study are lightness, total organic carbon (TOC), carbonate, chlorin, barium, siliciclastics, coarse fractions, iron, aluminum, titanium, and magnetic susceptibility.

Let us begin with a discussion of lightness. Lightness is a unit-less measure of how pale or dark the color of the drill core is compared to a panel of colors. Each color on the color panel is assigned a number where the lower the number, the darker the color. Therefore, to find lightness, one must only compare the color of the sediment to the color

panel to find the best match. Spectrophotometers are often used to enhance the accuracy

of these measurements. The color of the cores is important, as it can be a surprisingly

accurate proxy for TOC (which is composed of dark, organic matter) and carbonate

(which is composed of white, carbonate based sediments).

Total organic carbon (TOC) is the carbon in the sediment derived directly from

organic sources, most commonly pelagic organisms that have died and drifted down the

water column. TOC is usually measured as a percent weight and is an accepted proxy for

surface productivity, as the more pelagic life there is, the more pelagic life will

accumulate on the ocean floor. However, oxygen content both at the surface and at the

ocean floor can affect how much TOC actually gets preserved in sediment cores.. High

TOC is also associated with interglacial periods, where we would expect temperatures to

be warmer and thus encouraging pelagic life (Creaney and Passey, 1993). Carbonate is

TOC's counterpart – a sediment with a high lightness value (high carbonate, low TOC),

can be indicative of low surface productivity – which would be expected during glacial

periods – or and/or high oxygen content in the seawater.

Other indicators of surface productivity are chlorin and barium. Chlorin is a

byproduct of photosynthesizing pelagic organisms and barium results from the

degradation of organic matter as it settles to the ocean floor, thus these substances may be

a reflection of surface productivity (Harris, et al., 1996; Schroeder, Murray, Leinen,

Pflaum, and Janecek, 1997). These proxies are somewhat controversial in that both

substances have a tendency to degrade and decompose as they descend the water column

8

(Schönfeld, 2001; Francois, Honjo, Manganini, and Ravizza, 1995). The general abundance of planktonic foraminifera, usually referred to as sand, on the sea floor is an additional way to quantify surface productivity.

In this context, the word sand is used to represent sediments larger than 150 μm and usually consists mostly of foraminiferal shells. The sand content of bathyal and abyssal ocean sediments are often a dependable reflection of carbonate dissolution where less sand equates to more dissolution (Haug & Tiedemann, 1998). Many researchers use the term coarse fraction when referring to sediments larger than 150 μm instead of sand to reduce ambiguity. In this study, Brughmans' (2003) coarse fraction measurements were found according to the following calculation:

$$\% \text{ coarse fractions} = \frac{\% \text{ coarse material}}{\% \text{ carbonate}} \times 100$$

Whatever percentage of the sediment remains after coarse material and TOC are accounted for were deemed siliceous, or siliciclastic, material coming from land as continental rocks are composed of primarily silica based compounds

The elements iron, aluminum, and titanium are also materials that originate from the land. These elements are from minerals found within the continental crust, but are blown into the sea when sea-level is low and/or erosion rates are high. As such, they are considered proxies for terrigenous input, sea-level, and erosion rates, but can also reach the ocean via rivers (Duce & Tindale, 1991). As Fe, Al, and Ti are metals, magnetic susceptibility is often used in place of running tests to measure actual iron, aluminum, and titanium concentrations. Magnetic susceptibility is a unit-less assessment of how

strongly the sediments are affected by a magnet and is performed by running the core

through a Multi Sensor Track (MST) and taking measurements at regular intervals

(Shipboard Scientific Party, 2001). Magnetic susceptibility has been found to be a

reliable proxy for terrigenous input as long as the analysis site is not under the influence

of active volcanism or magnetotatic bacteria (Tarduno, Mayer, Musgrave, and Shipboard

Scientific Party, 1991). Neither of these factors applies to Site 1168.

III. Methodology

The sediment samples being analyzed are from Ocean Drilling Program Leg 189, Site 1168. They were drilled from the seafloor in the spring of 2000 with a 98% recovery rate (See Figure 2 (Shipboard Scientific Party, 2001). The sediment samples used in this thesis were requested from the Gulf Coast Repository of ODP at Texas A&M University in 2004 by Dr. Lewandowski as part of her dissertation work. Ultimately, the samples from this location were excluded from her dissertation as she decided to focus her research only on the Southern Kerguelen Plateau in the Southern Indian Ocean.
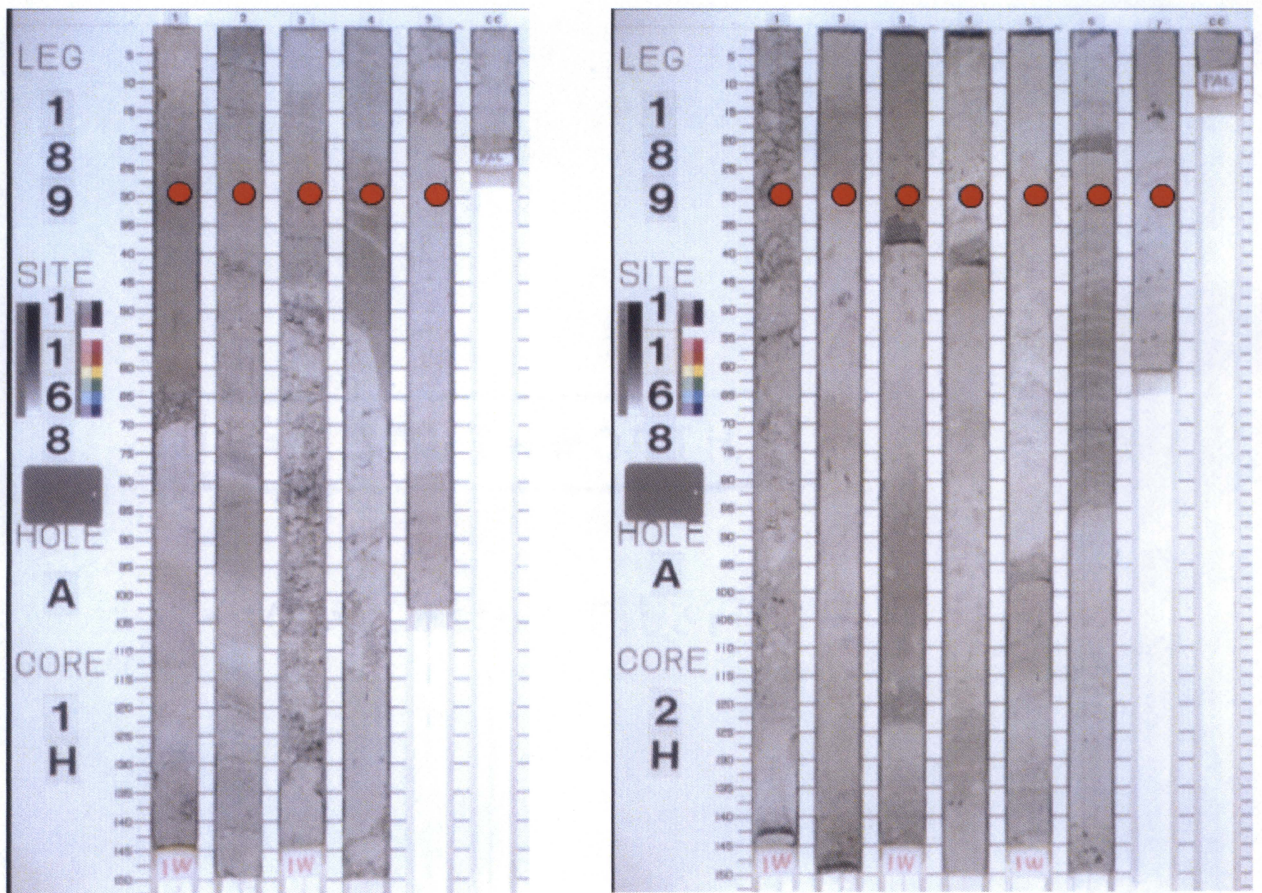
Figure 2: Images of the cores extracted from site 1168 by the Shipboard Scientific Party in 2001. The red dots indicate the came from within the core.

Once the samples were sent to Ohio State University, under the care of Dr. Lewandowski, they were weighed, washed and sieved. The samples were washed in tap water to separate the sediment into different size fractions. They were then sieved into smaller than 63 micron (mostly nannoplankton), 63-125 micron (juveniles and small foraminifera), and greater than 125 microns size fractions. After washing, the samples were allowed to air dry. They were then put in vials for later study.

The samples do have a history of study before this project. Some of the samples were studied by Betsy Zunk, an undergraduate at Muskingum College in 2005-2006, under the supervision of Dr. Shelley Judge, a faculty member there at the time. Zunk performed a sedimentology study on the samples (Zunk, Johnson, and Judge, 2006)..
Undergraduate students (Kara Kooken in the fall of 2010, and Brandy Guerrettaz in the fall of 2011 and 2012) at Eastern Illinois University used the samples, as part of their independent study projects. Their main task was to pick out all biogenic material (excluding the numerous planktonic foraminifera) and glue them onto faunal slides. Gum tragacanth was used as the adhesive. While those students made efforts to identify the material, they did not identify to species level.

For this project, only Pleistocene-aged (ranging from16,000-1,370,000 years ago) sediment samples were investigated. Nine sediment samples provide the basis of this study. Focusing on individuals greater than 125 microns, which are easier to identify due to their larger size, nine samples spaced at approximately 150,000 year intervals were

used to catalogue the benthic foraminifera and describe other biogenic components of each sample (e.g., coral pieces, bryozoans, etc.) (Lewandowski et al., 2013).

The goal of this thesis is to identify those individual foraminifera, in nine faunal slides, to the species level using a variety of sources such as Cushman1968, Barker1960, Loeblich and Tappan 1988, Hayward, Grenfell, Reid, and Hayward,1999, Hayward, Grenfell, Sabaa, Neil, and Buzas, 2010, Holbourn, Henderson, and MacLeod, 2013, and the World Register of Marine Species (WoRMS) (see Appendix A). Identifications were performed with a dissecting microscope provided by Eastern Illinois University. Species names were checked with WoRMS to determine the most current and up-to-date taxonomy. Oxygen isotopes, sedimentation rates, and the shipboard chronostratigraphic scheme were utilized to determine the age of the samples (Shipboard Scientific Party, 2001; Brughmans, 2003). Other sources helped in determining the global, tectonic, and geochemical setting (ODP Janus database), and sedimentological setting (Zunk et al., 2006).

After identification, statistics were run on the community to better understand the paleoecology. The following questions were asked: What is the species diversity? Does the abundance of benthic foraminifera vary from sample to sample? How good is the preservation? What would the living community (biocoenosis) look like vs. this thanatocoenosis (death assemblage)? Are there any correlations between foraminiferal species or groups and the examined environmental proxies? In addition, analysis of the paleocommunity included efforts to compare this location with previously studied cool-

water carbonate locations. Benthic foraminifera can often be used to infer paleobathymetry and an effort towards categorizing species that are *in situ* vs. allochthonous was made

IV. Results

Data collected from the Shipboard Scientific Party (2001) and Brughmans (2003), shown in Figure 3 and 4, show fluctuations in the ocean environment over the last 1.37 million years. The data received from the ODP Janus database also had some outliers that were removed to improve the clarity and resolution of the graphs. Four density values were negative or below 1 and the peak in magnetic susceptibility seen at about 7.5 meters below seafloor (mbsf) actually extends to nearly 200. These extreme outliers are likely due to errors in data collection and not actual values. Peaks and valleys in each figure are consistent within the various environmental proxies. For example, lightness (L*) is used as a proxy for carbonate and TOC where high TOC creates low lightness or high carbonate creates high lightness. These relationships can also be seen in Table 1. This data is consistent with this proxy and many others. It is worth noting however that magnetic susceptibility does not appear to correlate with Al, Fe, and Ti as predicted (metals are magnetic so this should be a high positive correlation) and chlorin and barium have a negative correlation when a positive correlation was expected (since they are both indicators of surface biochemistry). The Shipboard Scientific Party (2001) indicated that the magnetic signal from this core was so low that it was near the detection limit of the

instrument used and explains why the magnetic susceptibility measurements may be unreliable. Barium's moderate correlation to Al, Fe, and Ti may indicate the barium in these samples are of terrestrial origin and not from surface productivity. A complete correlation coefficients table can be found in Appendix B.
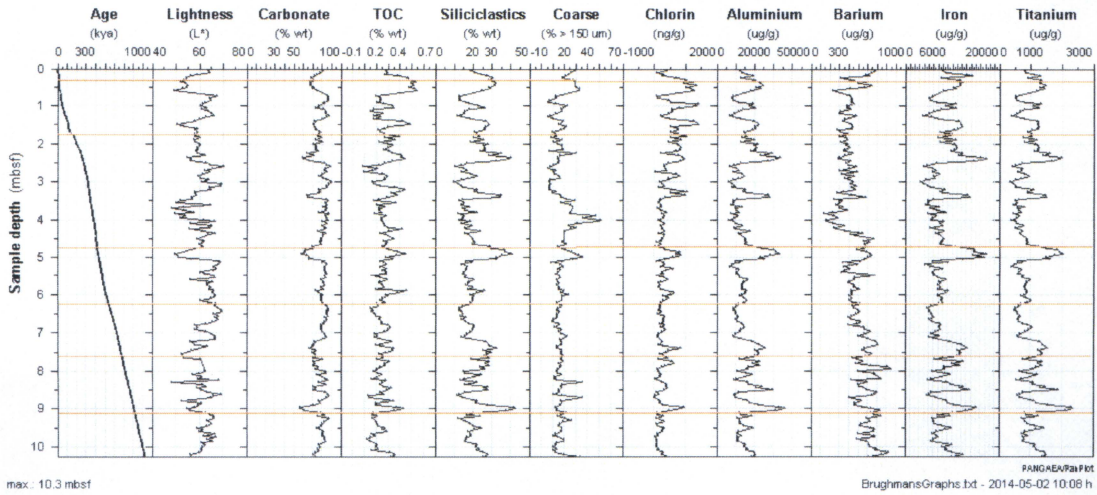
Figure 3. Age model (kya) , lightness (L*), carbonate weight percent, TOC weight percent, siliciclastics weight percent, coarse fractions over 150 μm weight percent, chlorin (ng/g), aluminum (μg/g), barium (μg/g), iron (μg/g), and titanium (μg/g) as compared to depth (mbsf). Data obtained from Brughmans (2003). The parts of the graph highlighted in orange indicate where the samples examined in this project fall.
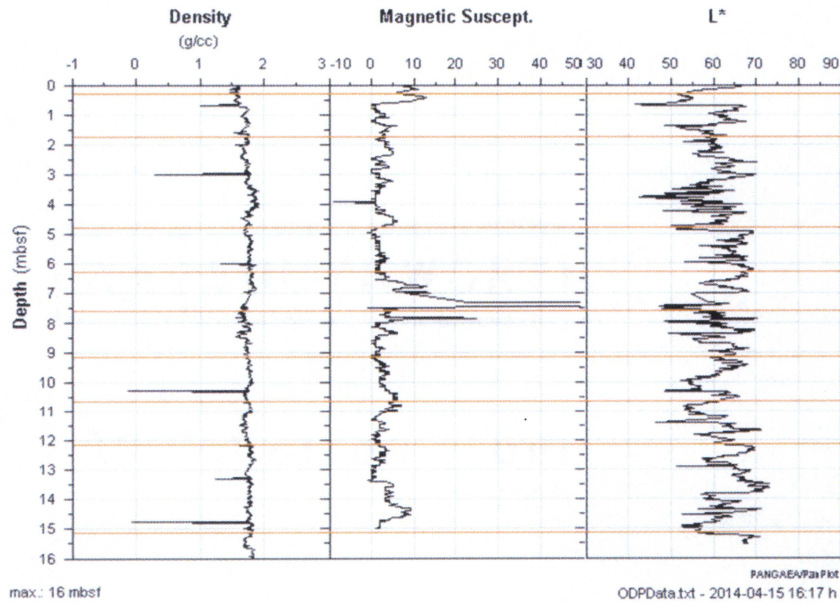
Figure 4. Density (g/cc), magnetic susceptibility, and lightness (L*) compared to depth (mbsf). Data obtained from ODP Janus database.   The parts of the graph highlighted in orange indicate where the samples examined in this project fall.

	Mag. Sus.	Lightness	Carbonate	TOC	Chlorin	Aluminum	Barium	Iron
Mag. Sus.								
Lightness	-0.51945							
Carbonate	-0.27244	0.82028						
TOC	0.11957	-0.72547	-0.42007					
Chlorin	-0.06312	-0.49663	-0.049004	0.83285				
Aluminum	0.20533	-0.5257	-0.8502	-0.0796	-0.3083			
Barium	0.21117	0.022786	-0.34095	-0.5636	0.7656	0.57726		
Iron	0.34907	-0.72028	-0.89788	0.11768	-0.0871	0.96173	0.45681	
Titanium	0.32678	-0.68647	-0.90458	0.09509	-0.139	0.97643	0.45836	0.99495

Table 1. Table of correlation coefficients for the proxies magnetic susceptibility, lightness, carbonate, TOC, chlorin, aluminum, barium, iron, and titanium. Grey = unexpected correlation between Magnetic susceptibility and terrigenous sediment. Yellow = expected correlations for lightness as an indicator of glacial versus interglacial periods. Purple = expected correlation between carbonate and terrigenous sediment. Blue = unexpected correlations between barium, chlorin, and terrigenous sediment. Green = expected correlations among terrigenous sediment.

Depth (mbsf)	0.28	1.78	4.78	6.28	7.58	9.08	10.58	12.08	15.08
Taxa_S	17	8	25	5	35	10	38	26	14
Individuals	46	22	49	7	79	18	112	57	37
Dominance	0.104	0.2066	0.07372	0.2245	0.04727	0.1235	0.05405	0.05879	0.2169
Fisher_alpha	9.75	4.523	20.44	7.824	24.06	9.264	20.25	18.47	8.203

Table 2. Absolute number of taxa, absolute number of individuals, and Fisher's alpha diversity index for each sample.

The complete table of the absolute abundance of benthic foraminifera can be found in Appendix C. There is wide variation in the abundance and diversity of foraminifera in the samples analyzed. The number of individual foraminifera ranges from 7 to 112 while the number of distinct species ranges from 5 to 38. The values for Fisher's alpha show the disparities in diversity between samples as well. In none of the samples analyzed was there clear dominance by any one taxon. Other diversity indices were run, such as Simpson's and the Shannon index. These indices were excluded as they did not provide any additional information about the data.

No single species of benthic foraminifera dominated in the samples, making evaluation of individual species unrealistic. To more easily interpret the data, common and relatively abundant genera with multiple species were grouped, such as *Cibicides* spp., as displayed in Figure 5 (complete abundance by depth table is available in Appendix C).
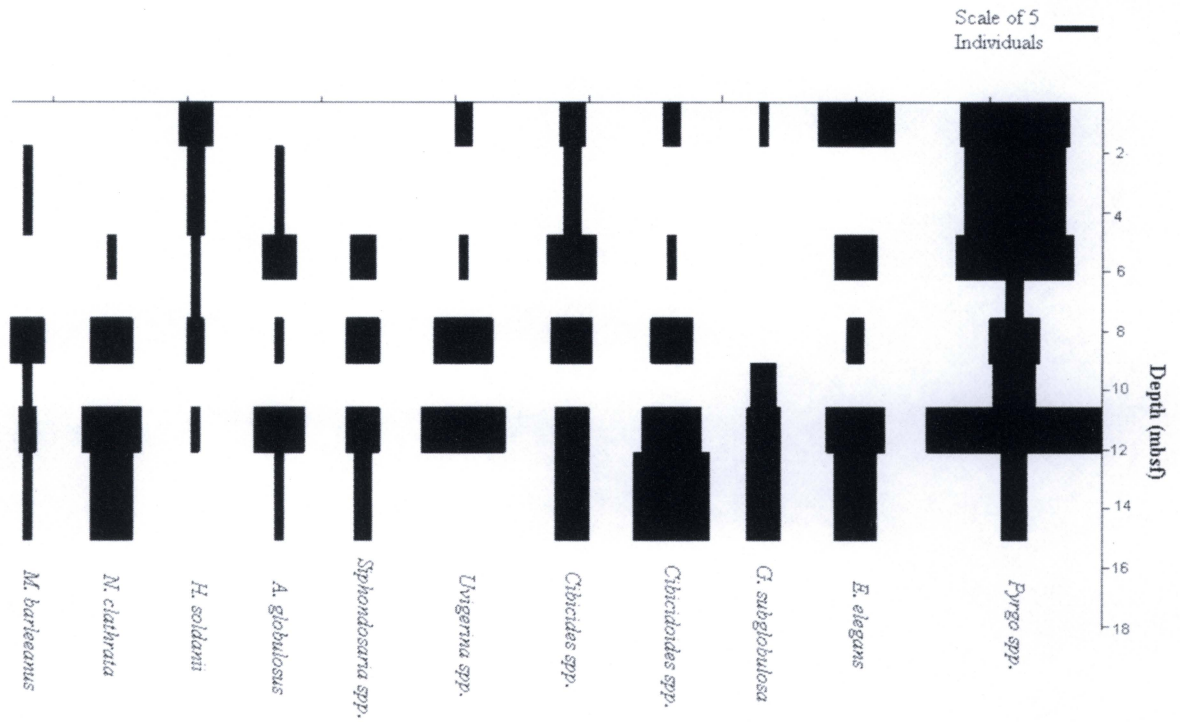
Figure 5. Stratigraphic records of the absolute abundance of the most abundant species and genus groups compared to depth.

Table 3 demonstrates that the relative abundance data of various biota and the mineral quartz remain fairly steady throughout the parts of the core examined. Note the variation in bryozoans and the decrease in both benthic and planktonic foraminifera in the 6.28 mbsf and 9.08 mbsf samples.

Depth (mbsf)	Benthic foraminifera	Planktonic foraminifera	Shells	Ostracods	Echinoderm Spines	Quartz	Fish material	Bryozoan fragments
0.28	3	4	1	1	1	1	1	1
1.78	3	4	1	2	2	0	0	2
3.28	3	4	0	1	1	0	0	0
4.78	4	4	1	2	2	0	0	3
6.28	2	3	1	1	1	1	0	3
7.58	3	4	1	1	1	1	1	3
9.08	2	3	1	0	1	0	0	1
10.58	3	4	1	1	1	1	1	3
12.08	4	4	1	1	1	0	1	3
13.58	3	4	1	2	2	0	0	2
15.08	3	4	1	2	2	0	1	2

Table 3. Table showing relative abundances of different types of grains in the samples (benthic forams, planktonic forams, mollusk shells, ostracode valves, echinoderm spines, quartz, fish material, bryozoans). 0 = absent, 1 = very rare, 2 = occasional, 3 = common, 4 = abundant. (Lewandowski, unpublished data)

V. Discussion

In an effort to gain a deeper understanding of the data collected, the most common and abundant foraminifera represented in Figure 5 were further grouped into two general assemblages based on commonalties in the data: a productivity assemblage and a terrigenous assemblage (Figure 6). The first assemblage consists of *Uvigerina* spp., *Cibicidoides* spp., *Cibicides* spp., *Anomalinoides globosus*, *Notoralia clathrata*, *Melonis barleeanus*, and *Siphondosaria* spp. These groups were clumped together based on their correlations to high terrigenous input and thus glacial periods, as dictated by the positive correlations with aluminum, iron, and titanium, and each other (Table 4). As a result this group was dubbed the "Terrigenous Assemblage." This assemblage dominated at 1) 683,000, 2) 956,000, 3) 1,090,000, and 4) 1,370,000 years ago (7.58 mbsf, 10.58 mbsf,

12.08 mbsf, and 15.08 mbsf, respectively) and ranges in bathymetry from middle neritic to abyssal.

The second assemblage (Figure 6) contains *Pyrgo* spp., *Epistomina elegans*, and *Hansenisca soldanii*. Each taxon in this group is positively correlated to TOC, chlorin, and coarse fractions (planktonic foraminifera) (Table 5). This suggests they are correlated to high surface productivity, thus causing them to be grouped together under the name "Productivity Assemblage." This group dominated at 16,000, 165,000, and 428,000 years ago (0.28 mbsf, 1.78 mbsf, and 4.78 mbsf, respectively) and ranges in ocean habitat from middle neritic to abyssal.
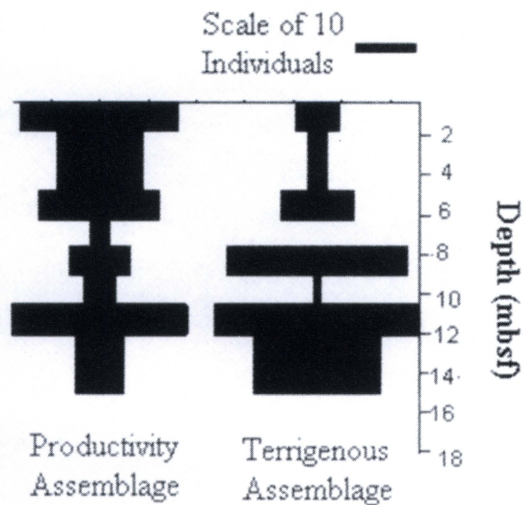
	Al	Fe	Ti	Cibicidoides spp.	Cibicides spp.	Uvigerina spp.	Siphondosaria spp.	A. globosus	N. clathrata
Cibicidoides spp.	0.225	0.340	0.329						
Cibicides spp.	0.642	0.712	0.736	0.430					
Uvigerina spp.	0.217	0.320	0.305	0.514	0.428				
Siphondosaria spp.	0.652	0.643	0.667	0.634	0.773	0.771			
A. globosus	0.751	0.690	0.737	0.344	0.623	0.638	0.735		
N. clathrata	0.336	0.385	0.376	0.848	0.597	0.759	0.838	0.623	
M. barleeanus	0.194	0.281	0.233	0.469	0.315	0.697	0.647	0.164	0.661

Table 4. Table of correlation coefficients between Al, Fe, Ti, *Cibicidoides spp.*, *Cibicides spp.*, *Uvigerina spp. Siphondosaria spp.*, *A. globosus*, *N. clathrata*, and *M. Barleeanus*. Yellow is used to highlight the correlations between these groups and terrigenous sediment, leading them to be clustered into an assemblage.
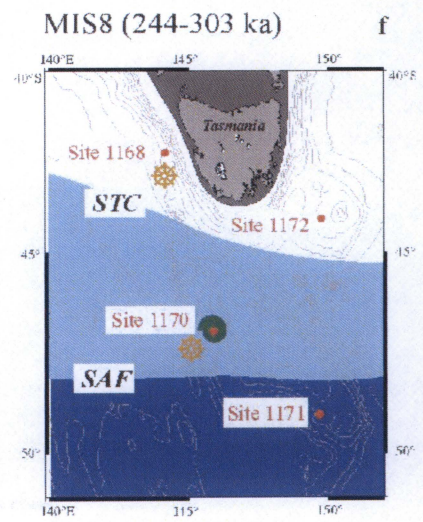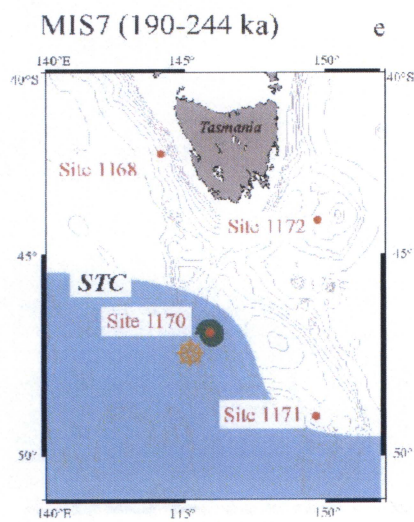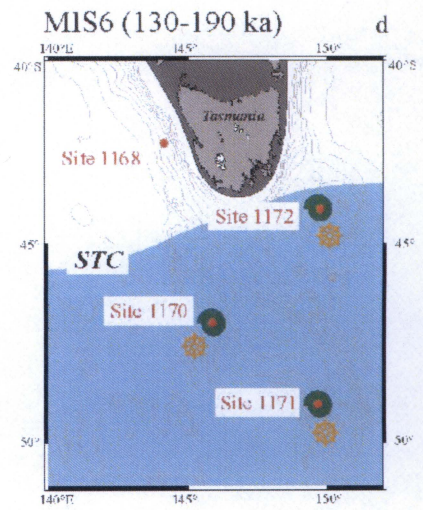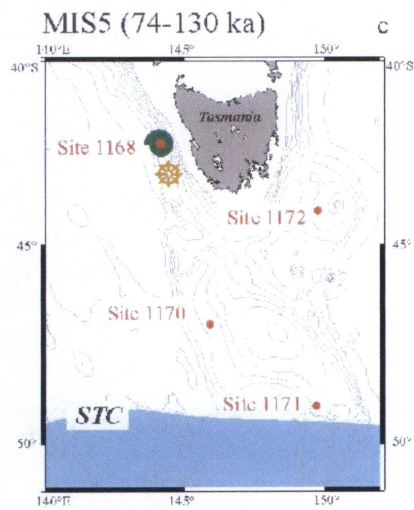
	Lightness	Carbonate	TOC	Coarse Fraction	Chlorin
Pyrgo spp.	-0.7017	-0.60088	0.73297	0.36679	0.6763
E. elegans	-0.51088	-0.58868	0.80818	0.90829	0.4054
H. soldanii	-0.49768	-0.052818	0.79156	0.4848	0.7042

Table 5. Table of correlation coefficients between lightness, carbonate, TOC, siliciclastics, coarse fractions, chlorin, *Pyrgo spp., E. elegans, and H. soldanii.* Green is used to highlight the correlations between these groups and surface productivity proxies, leading them to be clustered into an assemblage.

The differences between these two assemblages become clearer once it is noted that there is a cyclical nature to them, as illustrated in Figure 6. When one assemblage has a high abundance, the other assemblage is in low abundance. Not only does this demonstrate variable ocean conditions over the period of the study, these cycles are directly linked to the movement of the subtropical convergence (STC) during glacial and interglacial periods as described by Brughmans (2003). Figure 7 outlines the movement of the STC over 13 Marine Isotope Stages (MIS). Interglacials are odd numbered MIS's and glacial periods are evenly numbered MIS's. During interglacial periods, when the surface productivity assemblage dominated, the STC shifted to higher latitudes, meaning that the warm, nutrient rich subtropical surface water (STSW) was over site 1168, allowing plankton to prosper, thus increasing the amount of TOC present in the cores. Conversely, the STC shifted to lower latitudes during glacial periods, placing the cooler, nutrient poor subantarctic surface water (SASW) over site 1168. Brughmans (2003) was also able to show, using Al/Ti and Fe/Al ratios, the metals detected were of windblown origins as opposed to turbidity current sediments in both glacial and interglacial periods. These details provide support for the success of the terrigenous assemblage during these periods.

Figure 6. Stratigraphic records of the absolute abundance of two assemblage groups compared to depth. "Terrigenous Assemblage" contains *Uvigerina spp.*, *Cibicidoides spp.*, *Cibicides spp.*, *A. globosus*, *N. clathrata*, *M. barleeanus*, and *Siphondosaria spp.* "Productivity Assemblage" contains *Pyrgo spp.*, *E. elegans*, and *H. soldanii.*

MIS1 (0-12 ka)   a

MIS2-4 (12-74 ka)   b

MIS5 (74-130 ka)   c

MIS6 (130-190 ka)   d

MIS7 (190-244 ka)   e

MIS8 (244-303 ka)   f

MIS9 (303-333 ka) g

140°E   145°   150°
40°S   40°S
Tasmania
Site 1168
Site 1172
45°   45°
Site 1170
STC
Site 1171
50°   50°
110°E   145°   150°

MIS10 (333-364 ka) h

140°E   145°   150°
40°S   40°S
STC   _Tasmania_
Site 1168
Site 1172
45°   45°
Site 1170
SAF
Site 1171
50°   50°
110°E   145°   150°

MIS11 (364-427 ka) i

110°E   115°   150°
40°S   40°S
Tasmania
Site 1168
Site 1172
45°   45°
Site 1170
STC
Site 1171
50°   50°
140°E   145°   150°

MIS12 (427-473 ka) j

110°E   145°   150°
40°S   40°S
STC   _Tasmania_
Site 1168
Site 1172
45°   45°
Site 1170
no data
SAF
Site 1171
50°   50°
140°E   145°   150°

MIS13 (473-527 ka) k

140°E   145°   150°
40°S   40°S
Tasmania
Site 1168
Site 1172
45°   45°
Site 1170
no data
STC
Site 1171
50°   50°
140°E   115°   150°

Legend

⚙ high terrigenous supply

● high marine productivity

Subtropical Surface Water (STSW)
Subtropical Convergence (STC)
Subantarctic Surface Water (SASW)
Subantarctic Front (SAF)
Circumpolar Surface Water (CSW)

25

Figure 7. (the previous 2 pages) Summary diagram of the how the Subtropical Surface Water (STSW) , the Subtropical Convergence (STC) the Subantarctic Surface Water (STSW), the Subantarctic Front (SAF), and the Circumpolar Surface Water (CSW) change latitude with respect ODP Leg 189 Sites 1168, 1170, 1171, and 1171 during glacials and interglacials from 0- 527 kya) as put forth by Brughmans in 2003.

Samples from 550 kya (6.28 mbsf), 820 kya (9.08 mbsf), and 1.370 million years ago (15.08 mbsf) have exceptionally low abundance and diversity of benthic foraminifera and relatively low abundance of planktonic foraminifera (Table 3). Many of the rare foraminifera found in these samples were badly broken or were especially difficult to identify due to the faintness of their features. These facts are likely a sign of carbonate dissolution indicating the waters of these time periods had decreased temperatures, increased pressures, and/or a higher concentration of dissolved carbon dioxide. Coarse fraction data from Zunk at al. (2006) supports dissolution at 820,000 years ago, but not at the other time periods. It is unknown what could be causing the noted dissolution of carbonate samples, but it may be linked with increases in sea-level or STC front movement occurring during transitions between glacials and interglacials.

Work completed by Zunk, et al. (2006) proposed that gravity flows occurred at 16,000, 428,000, 550,000, 956,000, and 1,090,000 years ago (0.28 mbsf, 6.28 mbsf, 10.58 mbsf, and 12.08 mbsf, respectively). The presence of potential shallow water foraminifera, as documented by Holbourn (2013), *Heronallenia lingulata, Notoralia clathrata, Laevidentalina filiformis,* and possibly *Evolvocassidulina orientalis* in this data support Zunk's findings (Table 6). There is no foraminiferal data from this study to support a gravity flow at 16 kya. However, the wide depth range of benthic foraminifera habitats makes knowing whether these species are *in situ* or allochthonous impossible given current information. Even so, her data helps to shed light on the

uncertainty of the data, especially that data which appears to be in transition. However, Zunk's grain size analysis could have been skewed by the rather large planktonic foraminiferal tests contained in many of the samples. What Zunk describes as evidence of a gravity flow may actually be evidence of surface productivity.

Species	Depth (mbsf)	Absolute Abundance								
		0.28	1.78	4.78	6.28	7.58	9.08	10.58	12.08	15.08
L. filiformis		0	0	0	0	0	0	1	0	0
E. orientalis*		1	0	0	0	0	3	4	4	0
H. lingulata		0	0	1	0	0	0	0	0	0
N. clathrata		0	0	1	0	5	0	7	5	0

Table 6. Absolute abundance of potential shallow water foraminifera by depth. *Some of the species identified as *Globocassidulina subglobosa* may actually be *Evolvocassidulina orientalis*. See *Globocassidulina subglobosa* in Appendix A for more information.

Previous work done by Hayward (e.g. Hayward et al. 2012; Johnson, Hayward, Holbourn, 2011) determined that certain species of foraminifera went extinct near the end of the Cenozoic era and dubbed this event the Last Global Extinction (LGE). This event preferentially affected certain families and genera of foraminifera, such as those presented in Table 7. One of the more accepted hypotheses for the LGE is that the species that went extinct were remnants of the last true greenhouse time period. As the Earth transitioned to a cooler environment, ocean currents and food sources were altered in a way that selectively eliminated those species (Thomas, 2007). The work done here supports the extinction of the genera *Mucronina, Pleurostomella, Ellipsoglandulina, Ellipsoidina, Siphondosaria,* and *Stilostomella* during the LGE as those genus almost completely disappear after 683 kya (7.58 mbsf) and are completely gone after 428 kya (4.78 mbsf) as shown in Table 7.

Species	Depth (mbsf)	Absolute Abundance								
		0.28	1.78	4.78	6.28	7.58	9.08	10.58	12.08	15.08
Mucronina compressa		0	0	0	0	2	0	0	0	0
Pleurostomella incrassata		0	0	0	0	1	0	0	0	0
Ellipsoglandulina labiata		0	0	0	0	0	0	1	0	0
Ellipsoidina ellipsoides		0	0	0	0	0	0	1	0	0
Siphonodosaria bradyi		0	0	0	0	3	0	3	1	1
Siphonodosaria campana		0	0	0	0	1	0	0	1	0
Siphonodosaria consobrina		0	0	0	0	0	0	1	0	0
Siphonodosaria lepidula		0	0	3	0	0	0	0	0	0
Stilostomella fistuca		0	0	0	0	0	0	1	0	0

Table 7. Absolute abundance of extinct foraminifera by depth.

Nonetheless, the complete absence of coral or coral fragments, even in possible

gravity flow sediments, and the presence of ostracods, bryozoans, and echinoderms,

provides evidence that the area surrounding the site is a cool-water carbonate

environment and has been for at least 1.37 million years.

VI. Conclusions

An examination of benthic foraminifera on the continental slope off the coast of

Tasmania occurred herein. Multiple proxies were studied for correlations between the

proxies themselves and foraminifera present. This project used data from dissertation

research previously completed by Brughmans (2003) to fill in gaps between samples and

relate the foraminifera found to the ocean environment. The data strongly suggests that

benthic foraminifera responded to large scale changes in the ocean surface waters caused

by the movement of the subtropical convergence during glacial and interglacial periods.

A deeper knowledge base was also established for the cool-water carbonate environments. The mid-Pleistocene extinction of the genus *Siphondosaria* and others indicates changes must have taken place in the source and/or abundance of food for benthic foraminifera.

In order to draw more solid conclusions, this project needs to be done with much higher resolution. Identifying and evaluating the benthic species found in Brughmans' (2003) samples would greatly increase the correlations between her environmental data and foraminifera populations. This data would also benefit from a more in depth analysis of the planktonic foraminifera in the sediment, as it might then be clear whether the changes in grain sizes are the result of gravity flows or surface productivity. Investigation into benthic foraminifera in the nearby ODP sites (Sites 1170, 1171, and 1172) at the same time intervals would similarly add depth to our understanding.

References

Barker. W. R. (1960). *Taxonomic Notes on the Species Figured by H. B. Brady in his Report on the Foraminifera Dredged by H.M.S. Challenger During the Years 1873-1876.* Tulsa, OK: Society of Economic Paleontologists and Mineralogists. 238.

Brughmans, N. (2003). *Marine Productivity and Terrigenous Matter Supply: The Variability of the Subtropical Convergence around Tasmania during the last 500 ka.* Kiel, Germany: Christian-Albrechts-University. Unpublished dissertation. 125.

Climate and Weather (n.d) *Discover Tasmania.* Retrieved on 6/19/14 from: http://www.discovertasmania.com.au/about/climate-and-weather

Creaney, S. & Passey, Q. R. (1993) *Recurring Patterns of Total Organic Carbon and Source Rock Quality Within a Sequence Stratigraphic Framework.* The American Association of Petroleum Geologists Bulletin, 77, 386-401.

Cushman, J. A. (1968). *Foraminifera their classification and economic use.* (4th ed). London, England: Harvard University Press. 588.

Duce, R. & Tindale, N.(1991). *Chemistry and biology of iron and other trace metals.* Limnological Oceanography, 36, 1715-1726.

Exon, N.F., Kennett, J.P., and Malone, M.J. (2004) Leg 189 synthesis: Cretaceous– Holocene history of the Tasmanian Gateway. *In* Exon, N.F., Kennett, J.P., and Malone, M.J. (Eds.), *Proc. ODP, Sci. Results,* 189: College Station, TX (Ocean Drilling Program), 1–37. doi:10.2973/odp.proc.sr.189.101.2004

Francois, R., Honjo, S., Manganini, S. & Ravizza, G. (1995) *Biogenic barium fluxes to the deep-sea: Implications for paleoproductivity reconstruction.* Global Biochemical Cycles, 9, 289-303.

Gupta, B. K. S. (2002). *Modern Foraminifera.* Dordrecht, The Netherlands: Kluwer Academic Publishers. 371.

Harris, P., Zhao, M., Rosell-Melé, A., Tiedemann, R., Sarnthein, M. & Maxwell, J.(1996). *Chlorin accumulation rate as a proxy for Quaternary marine primary production.* Nature, 383, 63-65. doi:10.1038/383063a0

Haug, G. & Tiedemann, R. (1998) *Effects of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation.* Nature, 393, 673-676.

Hayward, B. W., Grenfell, H, R., Reid, C. M., and Hayward, K. A. (1999). *Recent New Zealand shallow-water benthic foraminifera: Taxonomy, ecologic distribution, biogeography, and use in paleoenvironmental assessments.* Institute of Geological & Nuclear Sciences Monograph 21: Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Limited. 264.

Hayward, B. W., Grenfell, H, R., Sabaa, A. T., Niel, H., and Buzas, M. A. (2010). *Recent New Zealand deep-water benthic foraminifera: Taxonomy, ecologic distribution, biogeography, and use in paleoenvironmental assessments.* GNS Science Monograph 26: Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Limited. 363.

Hayward, B. W., Kawagata S., Ashwaq, S., Grenfell, H., Van Kerckhoven, L., Johnson, K., Thomas, E. (2012). *The Last Global Extinction (Mid-Pliestocene) of Deep-Sea Benthic Foraminifera (Chrysalogoniidae, Ellipsoidinidae, Glandulonodosariidae, Plectofrondiculariidae, Pleurostomellidae, Stilostomellidae), Their Late Cretaceous-Cenozoic History and Taxonomy.* (Cushman Foundation for Foraminiferal Research Spec. Pub. 43). Lawrence, KS: Allen Press. 408.

Holbourn, A., Henderson, A. S., MacLeod, N. (2013) *Atlas of Benthic Foraminifera.* West Sussex, United Kingdom. Wiley-Blackwell. 641.

James, N. P. (1997). *The cool-water carbonate depositional realm.* In: James, N.P., Clarke, J.A.D., eds., Cool-Water Carbonates, SEPM Special Publication 56: Tulsa, OK Doi: 10.2110/pec.97.56.0001

Johnson, K., Hayward, B.W., and Holbourn, A. (2011). *Impact of the Middle Miocene climate transition on elongate, cylindrical foraminifera in the subtropical Pacific.* Marine Micropaleontology, 78, 50-64. DOI: 10.1016/j.marmicro.2010.09.008

Klinck, J. and Smith, D. (1993) *Effect of wind changes during the last glacial maximum on the circulation in the Southern Ocean.* Paleoceanography, 8(4): 427-433.

Lewandowski, K., Judge, S., Hughes, S., Zunk, B., Guerrettaz, B., & Kooken, K (2013). *Pleistocene Cool-Water Carbonates: Forams and Bryozoans of West Tasmania Slope Sediments (ODP Leg 189, Site 1168).* Geological Society of America Abstracts with Programs, 45, 332.

Loeblich, A.R., Tappan, H. (1988). *Foraminiferal Genera and their Classification.* V. 1-2. Van Nostrand Reinhold Company, New York. 970.

Nees, S. (1997). *Late Quaternary palaeoceanography of the Tasman Sea: the benthic foraminiferal view*. Amsterdam: Elsevier: Palaeogeography, Palaeoclimatology, Palaeoecology, *131*, 365-389. Doi: 10.1016/S0031-0182(97)00012-6.

Rea, D. & Bloomstine, M. (1986) *Neogene history of the south Pacific tradewinds: evidence for hemispherical asymmetry of atmospheric circulation*. Paleogeography, Paleoclimatology, Paleoecology, 55, 55-64.

Rivers, J. M., James, N. P., Kyser, T. K., and Bone, Y. (2007). *Genesis of Palimpest Cool-Water Carbonate Sediment on the Continental Margin of Southern Australia*. Journal of Sedimentary Research, *77*, 480-494. doi: 10.2110/jsr.2007.046.

Schönfeld, J. (2001) *Benthic foraminifera and pore-water oxygen profiles: a re-assessment of species boundary conditions at the western Iberian margin*. Journal of Foraminiferal Research, 31, 86-107.

Schroeder, J., Murray, R., Leinen, M., Pflaum, R. & Janecek, T. (1997). *Barium in equatorial Pacific carbonate sediment: Terrigenous, oxide, and biogenic associations*. Paleoceanography, 12, 125-146.

Shipboard Scientific Party (2001) Site 1168. *In* Exon, N.F., Kennett, J.P., Malone, M.J., et al., *Proc. ODP, Init. Repts.,* 189: College Station, TX (Ocean Drilling Program), 1–170. doi:10.2973/odp.proc.ir.189.103.2001

Takahashi, T., Broecker, W., Bainbridge, A. &Weiss, R. (1980) *Carbonate chemistry of the Atlantic, Pacific and Indian Oceans: the results of the GEOSECS expeditions, 1972-1978., Technical Reports 1*. Lamont Doherty Earth Observations, Palisades.

Tarduno, J.A., Mayer, L.A., Musgrave, R., and Shipboard Scientific Party (1991) High-resolution, whole-core magnetic susceptibility data from Leg 130, Ontong Java

plateau. *In* Kroenke, L.W., Berger, W.H., Janecek, T.R., et al., *Proc. ODP, Init.*
Repts., 130: College Station, TX (Ocean Drilling Program), 541–548.
doi:10.2973/odp.proc.ir.130.111.1991

Thomas, E. (2007). Cenozoic mass extinctions in the deep sea: What perturbs the largest
habitat on earth? In: Monecchi, S., Coccioni, R., Rampino, M.R. (Eds.), *Mass*
extinctions and other large ecosystem perturbations: Extraterrestrial and terrestrial
causes: Geological Society of America, Special Paper, 424, pp. 1–23.

WoRMS Editorial Board (2014). World Register of Marine Species. Available from
http://www.marinespecies.org at VLIZ. Accessed 2014-01-19.

Zunk, B, Johnson, K., Judge, S. A. (2006). *Pleistocene grain-size analysis and*
micropaleontology of west Tasmania slope sediments (ODP Leg 189, Site 1168).
North Central Geological Sociaty of America Abstracts with Program, 38, 27.

Appendix A : Foraminiferal Taxonomy

SUBORDER LITUOULINA
SUPERFAMILY LITOULOIDEA
LITOULIDEA
Ammobaculites agglutinans (d'Orbigny), 1846; Holbourn, et al, 2013, pg. 26.

SUBORDER TEXTULARIINA
SUPERFAMILY TEXTULARIOIDEA
TEXTULARIIDAE
Siphotextularia concava (Karrer), 1868; Holbourn, et al, 2013, pg. 516.

SUPERFAMILY EGGERELLOIDEA
VULVULINIDAE
Cribrogoesella robusta (Brady), 1881; Barker, 1960, Plate 45, Figures 9-16, pg. 93.

EGGERELIDAE
Eggerella bradyi (Cushman), 1911; Holbourn, et al, 2013, pg. 232.
Martinottiella communis (d'Orbigny), 1826; Holbourn, et al, 2013, pg. 350.

SUBORDER MILIOLINA
SUPERFAMILY MILOILOIDEA
HAUERINIDAE
Pyrgo clypeata (d'Orbigny), 1846; Hayward, et al, 2010, Plate 7, Figures 7-10, pg. 291.

Pyrgo comata (Brady), 1881; Holbourn, et al, 2013, pg. 452.
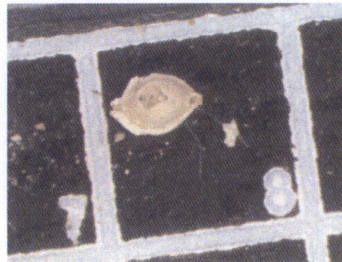
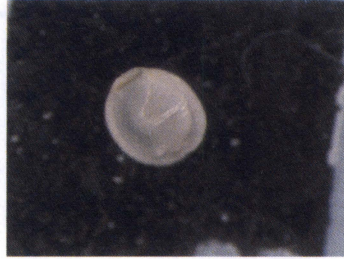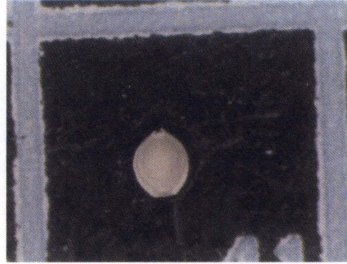*Pyrgo depressa* (d'Orbigny), 1826; Hayward, et al, 2010, Plate 7, Figures 13-14, pg. 291.

Pyrgo inornata (d'Orbigny), 1846; Hayward, et al, 2010, Plate 7, Figures 15-19, pg. 291.
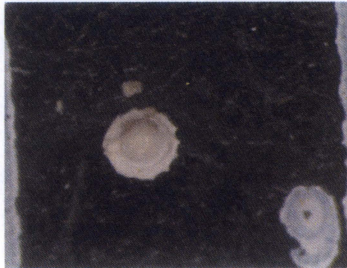

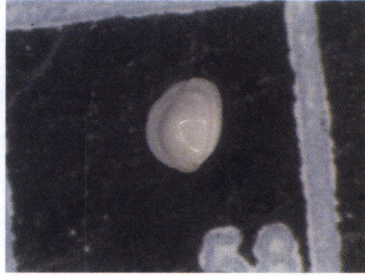*Pyrgo lucernula* (Schwager), 1866; Holbourn, et al, 2013, pg. 456.

Pyrgo murrhina (Schwager), 1866; Holbourn, et al, 2013, pg. 458.

Pyrgo serrata (Bailey), 1861; Holbourn, et al, 2013, pg. 460.

Pyrgo tasmanensis (Vella), 1957; Hayward, et al, 2010, Plate 8, Figures 7-8, pg. 293.

Triloculina trigonula (Lamarck), 1804; Holbourn, et al, 2013, pg. 566.

SUPERFAMILY NODOSARIODEA
NODOSARIIDAE

Laevidentalina communis (d'Orbigny), 1826; Barker, 1960, Dentalina communis, Plate 62, Figures 21-22, pg. 131.

Laevidentalina filiformis (d'Orbigny), 1826; Hayward, et al, 1999, Plate 6, Figures 18-19, pg. 227.

Pseudonodosaria brevis (d'Orbigny), 1846; Hayward, et al, 2010, Plate 12, Figures 62-63, pg. 301.

PLECTOFRONDICULARIIDAE

Mucronina compressa (Costa), 1855; Hayward, et al, 2012, Plate 9, Figures 30-32, pg. 333.

VAGINULINIDAE

Lenticulina convergens (Bornemann), 1855; Holbourn, et al, 2013, pg. 332.

Lenticulina culturata (Montfort), 1808; Hayward, et al, 2010, Plate 14, Figures 11-2, pg. 305.

Marginulina obesa (Cushman), 1923; Holbourn, et al, 2013, pg. 346.

LAGENIDAE

Lagena apiculata (Reuss), 1851; Hayward, Bruce, 7/29/2013, www.marinespecies.org

Lagena sp. ; Barker, 1960, Plate 57, Figures 14-20, pg. 117.

Lagena sulcata (Walker & Jacob), 1798; Holbourn, et al, 2013, pg. 324.

Reussoolina laevis (Mantagu), 1803; Hayward, Bruce, 08/20/2010, www.marinespecies.org

SUPERFAMILY POLYMORPHINOIDEA
POLYMORPHINIDAE

Globulina minuta (Roemer), 1838; Barker, 1960, Plate 71, Figures 15-16, pg. 149.

Guttulina austriaca (d'Orbigny), 1846; Barker, 1960, Plate 73, Figure 4, pg. 153.

Guttulina communis (d'Orbigny), 1826; Hayward, Bruce, 07/02/2012, www.marinespecies.org

Pseudopolymorphina sp. (Cushman & Ozawa), 1928; Barker, 1960, Plate 72, pg. 151.

Sigmoidella elegantissima (Parker & Jones), 1865; Hayward, et al, 2010, Plate 13, Figures 10-13, pg. 303.

ELLIPSOLAGENIDAE

Fissurina annectens (Burrows & Holland), 1895; Hayward, Bruce, 03/25/2010, www.marinespecies.org

Fissurina longispina (Brady), 1881; Barker, 1960, Oolina longispina, Plate 56, Figure 36, pg. 115.

Fissurina submarginata (Goomgaart), 1949; Hayward, Bruce, 03/26/2010, www.marinespecies.org

GLANDULINIDAE

Glandulina ovula (d'Orbigny), 1846; Hayward, et al, 2010, Plate 12, Figures 1-2, pg. 301.

SUPERFAMILY CERATOBULIMINOIDAE

EPISTOMINIDAE

Epistomina elegans (d'Orbigny), 1826; Hayward, et al, 2010, Hoeglundina elegans, Plate 16, Figures 16-21, pg. 309.

SUPERFAMILY BOLIVINOIDEA

BOLIVINIDAE

Bolivina incrassata (Reuss), 1851; Cushman, 1980, Plate 27, Figure 28, pg. 533.

SUPERFAMILY CASSIDULINOIDEA
CASSIDULINIDAE

Globocassidulina subglobosa (Brady), 1881; Hayward, et al, 2010, Plate 20, Figures 4-6, pg. 317.

Comment: many of these specimens appeared to more ornate tests (swirling) than is shown in reference books, some of these specimens may actually be *Evolvocassidulina orientalis* (Cushman), 1922; Hayward, et al, 1999, Plate 8, Figure 28, pg. 231.
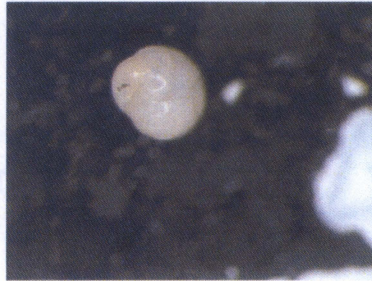
Ehrenbergina pacifica (Cushman), 1927; Hayward 2010, Plate 18, Figures 6-8, pg. 313.
SUPERFAMILY DISCORBOIDEA

DISCORBIDAE

Gavelinopsis praegeri (Heron-Allen & Earland), 1913; Hayward, et al, 2010, Plate 31, Figures 18-21, pg. 339.

SPHAEROIDINIDAE

Sphaeroidina bulloides (d'Orbigny), 1826; Holbourn, et al, 2013, pg. 520.

SUPERFAMILY GLABRATELLOIDEA
HERONALLENIIDAE

Heronallenia lingulata (Burrows & Holland), 1895; Hayward, et al, 1999, Plate 13, Figures 4-6, pg. 241.

SUPERFAMILY DISCORBINELLOIDEA

PARRELLOIDIDAE

Cibicidoides dispars (d'Orbigny), 1839; Hayward, et al, 2010, Plate 22, Figures 4-9, pg. 321.
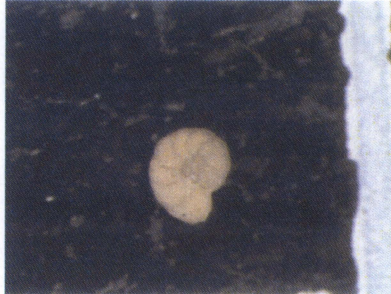
Cibicidoides globulosus (Chapman & Parr), 1937; Gross, Onno, 12/21/2004, www.marinespecies.org

Cibicidoides mundulus (Brady, Parker, & Jones), 1888; Holbourn, et al, 2013, pg. 196.
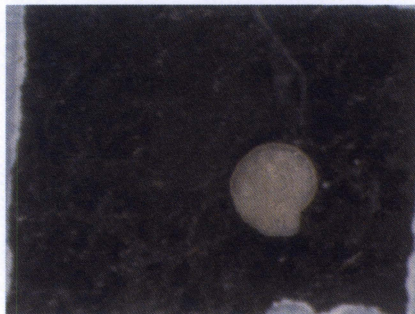
Cibicidoides robertsonianus (Brady), 1881; Hayward, et al, 2010, Plate 23, Figures 1-3, pg. 323.
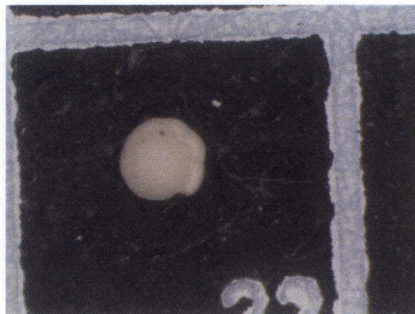
Cibicidoides subhaidingerii (Parr), 1950; Holbourn, et al, 2013, pg. 204.

PSEUDOPARRELLINAE
Epistominella exigua (Brady), 1884; Holbourn, et al, 2013, pg. 240.

SUPERFAMILY PLANORBULINOIDEA
CIBICIDIDEA
Cibicides refulgens (de Montfort), 1808; Holhourn, 2013, pg. 154.

Cibicides wuellerstorfi (Schwager), 1866; Hayward, et al, 2010, Plate 23, Figures 20-22, pg. 323.

Lobatula lobatula (Walker & Jacob), 1798; Holbourn, et al, 2013, Cibicides lobatulus, pg. 152.

SUPERFAMILY BULIMINOIDEA
BULIMINIDAE
Bulimina aculeate (d'Orbigny), 1826; Holhourn, 2013, pg. 88.
Globobulimina pacifica (Cushman), 1927; Holbourn, et al, 2013, pg. 260.

UVIGERINIDAE
Siphouvigerina hispida (Schwager), 1866; Holbourn, et al, 2013, pg. 592.
Siphouvigerina proboscidae (Schwager), 1866; Hayward, Bruce, 09/14/2009, www.marinespecies.org
Uvigerina hornibrook (Boersma), 1984; Hayward, et al, 2010, Plate 21, Figures 21-23, pg. 319.
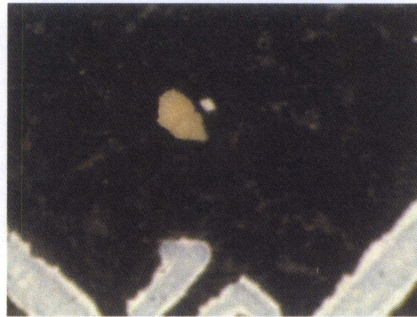
Uvigerina peregrina (Cushman), 1923; Hayward, et al, 2010, Plate 21, Figures 27-28, pg. 319.

SUPERFAMILY PLEUROSTOMELLOIDEA
PLEUROSTOMELLIDAE
Pleurostomella incrassata (Hantken), 1883; Hayward, et al, 2012, Plate 37, Figures 16-21, pg. 398.

ELLIPSOIDINIDAE
Ellipsoglandulina labiata (Schwager), 1866; Hayward, et al, 2012, Plate 25, Figures 14-19, pg. 365.
Ellipsoidina ellipsoides (Sequenza), 1859; Hayward, et al, 2012, Plate 28, Figures 11-16, pg. 371.

SUPERFAMILY STILOSTOMELLOIDEA

STILOSTOMELLIDEA

Siphonodosaria bradyi (Cushman), 1927; Hayward, et al, 2012, Plate 16, Figures 24-27, pg. 347.

Siphonodosaria campana (Hayward & Kawagata), 2012; Hayward, et al, 2012, Plate 16, Figures 29-32, pg. 347.

Siphonodosaria consobrina (d'Orbigny), 1846; Hayward, et al, 2012, Plate 16, Figures 33-38, pg. 347.
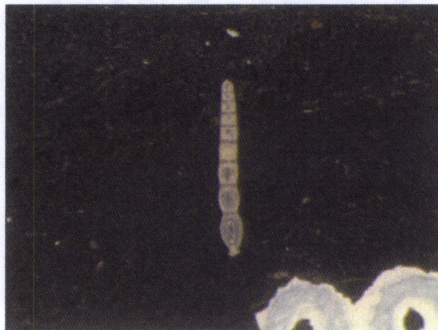
Siphonodosaria lepidula (Schwager), 1866; Hayward, et al, 2012, Plate 18, Figures 6-20, pg. 351.

Stilostomella fistuca (Schwager), 1866; Hayward, et al, 2010, Plate 20, Figures 1-14, pg. 355.

SUPERFAMILY ASTERIGERINOIDEA
EPISTOMARIIDAE
Nuttallides umbonifera (Cushman), 1933; Hayward, et al, 2010, Plate 25, Figures 16-19, pg. 327.

SUPERFAMILY CHILOSTOMELLOIDEA
CHILOSTOMELLIDAE
Chilostomella ovoidea (Reuss), 1850; Barker, 1960, Plate 55, Figures 19-20, pg. 113.

ALABAMINIDE
Osangularia culter (Parker & Jones), 1896; Holbourn, et al, 2013, pg. 386.

ORIDORSALIDAE
Oridorsalis umbonatus (Reuss), 1851; Holbourn, et al, 2013, pg. 384.

HETEROLEPIDAE
Heterolepa bradyi (Trauth), 1918; Holbourn, et al, 2013, Cibicidoides bradyi, pg. 162.

GAVELINELLIDEA
Anomalinoides globosus (Chapman & Parr), 1937; Holbourn, et al, 2013, pg. 52
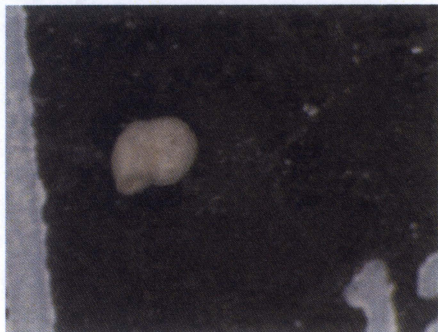
Discanomolina coronata (Parker & Jones), 1865; Barker, 1960, Plate 97, Figures 1-2, pg. 201.

Comment: most of these specimens were very green from oxidation.

Discanomolina semipunctata (Bailey), 1851; Barker, 1960, Anomalina semipunctata, Plate 97, Figures 3-6, pg. 200.

Comment: most of these specimens were very green from oxidation.

Hansenisca soldanii (d'Orbigny), 1826; Hayward, et al, 2010, Gyroidina soldanii, Plate 27, Figures 7-12, pg. 331.

SUPERFAMILY ROTALOIDEA
ELPHIDIIDAE

Elphidium crispum (Linnaeus), 1759; Holbourn, et al, 2013, pg. 236.

Notoralia clathrata (Brady), 1884; Hayward, et al, 1999, Figure 152, pg. 171.

Parrellina imperatrix (Brady), 1881; Barker, 1960, Plate 110, Figures 13-15, pg. 227.

SUPERFAMILY NONIONOIDEA

NONIONIDAE

Melonis barleeanus (Williamson), 1858; Holbourn, et al, 2013, Melonis barleeanum, pg. 354.

Appendix B: Complete List of Correlation Coefficients

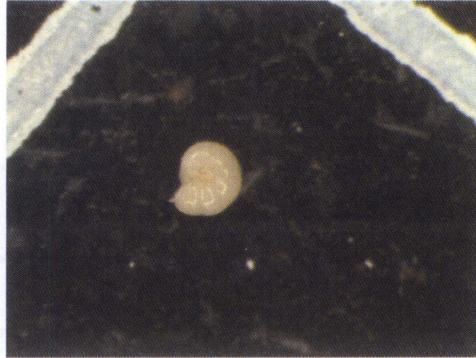|	Depth	Abundance	Density	Mag. Sus.	Lightness	CO_3	TOC	Silici-clastics	Coarse Fraction	Chlorin	Al	Ba	Fe	Ti
Depth														
Abudance	0.111													
Density	0.523	-0.376												
Mag. Sus.	-0.264	0.275	-0.858											
Lightness	0.567	-0.446	0.787	-0.519										
CO_3	0.0162	-0.545	0.465	-0.272	0.820									
TOC	-0.814	0.230	-0.476	0.119	-0.725	-0.420								
Siliciclastics	-0.0225	0.593	-0.500	0.322	-0.847	-0.996	0.413							
Coarse Fraction	-0.233	0.511	-0.596	0.405	-0.582	-0.648	0.576	0.612						
Chlorin	-0.883	0.00592	-0.211	-0.0631	-0.496	-0.0490	0.832	0.0704	0.0390					
Al	0.333	0.491	-0.195	0.205	-0.525	-0.850	-0.0796	0.861	0.286	-0.308				
Ba	0.925	0.141	-0.128	0.211	0.0227	-0.340	-0.563	0.336	0.0320	-0.765	0.577			
Fe	0.161	0.626	-0.388	0.349	-0.720	-0.897	0.117	0.923	0.328	-0.087	0.961	0.456		
Ti	0.170	0.620	-0.353	0.326	-0.686	-0.904	0.0950	0.924	0.368	-0.139	0.976	0.458	0.994	
Pyrgo spp.	-0.323	0.618	-0.234	-0.0175	-0.701	-0.600	0.732	0.617	0.366	0.676	0.376	-0.504	0.522	0.518
E. elegans	-0.254	0.682	-0.379	0.0825	-0.510	-0.588	0.808	0.568	0.908	0.405	0.166	-0.343	0.281	0.308
G. subglobosa	0.406	0.455	0.168	-0.464	0.0473	-0.342	0.135	0.309	0.133	-0.039	0.175	0.532	0.163	0.129
Cibicidoides spp.	0.596	0.714	0.0786	-0.0135	0.188	-0.243	0.0258	0.291	0.396	-0.165	0.225	0.2382	0.340	0.329
Cibicides spp.	-0.209	0.772	-0.407	0.349	-0.481	-0.606	0.181	0.642	0.452	-0.007	0.642	-0.0031	0.712	0.736
Uvigerina spp.	0.211	0.841	-0.361	0.379	-0.388	-0.179	-0.0793	0.231	0.294	-0.225	0.217	0.292	0.320	0.305
Siphondosaria spp.	0.317	0.857	-0.198	0.316	-0.231	-0.410	-0.311	0.451	0.232	-0.470	0.652	0.416	0.643	0.667
A. globosus	0.0797	0.733	0.0769	-0.189	-0.335	-0.540	-0.0857	0.551	0.147	-0.165	0.751	0.0495	0.690	0.737
H. soldanii	-0.545	0.0412	-0.581	0.571	-0.497	-0.0528	0.791	0.0712	0.484	0.704	-0.357	-0.680	-0.138	-0.157
N. clathrata	0.387	0.893	-0.102	0.0914	-0.0495	-0.136	-0.340	0.192	0.0926	-0.411	0.336	0.430	0.385	0.376
M. barleeanus	0.297	0.572	-0.429	0.604	-0.180	0.00901	-0.356	0.0597	-0.184	-0.272	0.194	0.461	0.281	0.233
Ostracods	0.689	0.447	0.348	-0.183	0.240	0.599	-0.651	-0.588	-0.175	-0.617	-0.359	0.208	-0.44	-0.42

	Pyrgo spp.	E. elegans	G. subglobosa	Cibicidoides spp.	Cibicides spp.	Uvigerina spp.	Siphondosaria spp.	A. globosus	H. soldanii	N. clathrata	M. barleeanus
Depth											
Abudance											
Density											
Mag. Sus.											
Lightness											
CO₃											
TOC											
Siliciclastics											
Coarse Fraction											
Chlorin											
Al											
Ba											
Fe											
Ti											
Pyrgo spp.											
E. elegans	0.619										
G. subglobosa	0.175	0.391									
Cibicidoides spp.	0.0711	0.429	0.596								
Cibicides spp.	0.491	0.632	0.0907	0.430							
Uvigerina spp.	0.569	0.383	0.243	0.514	0.428						
Siphondosaria spp.	0.397	0.360	0.212	0.634	0.773	0.771					
A. globosus	0.798	0.482	0.347	0.344	0.623	0.638	0.735				
H. soldanii	0.287	0.335	-0.523	-0.195	0.0588	0.146	-0.187	-0.227			
N. clathrata	0.307	0.419	0.588	0.848	0.597	0.759	0.838	0.623	-0.286		
M. barleeanus	0.0155	-0.116	0.0910	0.469	0.315	0.697	0.647	0.164	-0.0354	0.661	
Ostracods	0.272	0.0961	0.318	0.590	-0.0625	0.680	0.466	0.467	-0.100	0.547	0.331

Appendix C: Complete list of foraminifera absolute abundances by depth

Species	Depth(mbsf)	0.28	1.78	4.78	6.28	7.58	9.08	10.58	12.08
					Absolute Abundance				
Ammobaculites agglutinans		0	0	0	0	0	0	2	0
Siphotextularia concava		0	0	0	0	0	0	0	0
Cribrogoesella robusta		0	0	0	0	0	0	0	1
Eggerella bradyi		7	0	1	0	1	0	0	0
Martinottiella communis		0	0	2	0	0	1	3	4
Pyrgo clypeata		0	0	0	0	0	1	0	0
Pyrgo comata		0	0	0	0	0	0	3	0
Pyrgo depressa		3	0	1	0	0	0	1	1
Pyrgo inornata		0	0	1	0	0	0	0	0
Pyrgo lucernula		1	0	2	0	0	1	1	0
Pyrgo murrhina		6	4	9	2	6	3	16	2
Pyrgo serrata		2	0	1	0	0	0	0	0
Pyrgo tasmanensis		1	8	0	0	0	0	0	0
Triloculina trigonula		0	0	0	0	0	0	1	0
Laevidentalina communis		0	0	0	0	0	0	0	1
Laevidentalina filiformis		0	0	0	0	0	0	1	0
Pseudonodosaria brevis		0	0	1	0	0	0	0	0
Mucronina compressa		0	0	0	0	2	0	0	0
Lenticulina convergens		0	0	0	0	1	0	0	1
Lenticulina culturata		0	0	0	0	0	0	1	0
Marginulina obesa		1	0	0	0	0	0	0	0
Lagena apiculata		0	0	0	0	0	3	0	0
Lagena sp.		0	0	0	0	1	0	0	0
Lagena sulcata		0	0	0	0	0	0	1	0
Reussoolina laevis		0	0	0	0	0	0	1	0
Globulina minuta		0	0	0	0	1	0	0	0
Guttulina austriaca		0	0	0	0	0	0	0	1
Guttulina communis		0	0	0	0	4	0	1	3
Pseudopolymorphina sp.		0	0	0	0	1	0	0	0
Sigmoidella elegantissima		0	0	0	0	0	0	1	0
Fissurina annectens		0	0	0	0	0	0	1	0
Fissurina longispina		0	0	1	0	0	0	0	0
Fissurina submarginata		0	0	0	0	0	0	2	0
Glandulina ovula		0	0	1	0	0	0	0	0
Epistomina elegans		9	0	5	0	2	0	7	5
Bolivina incrassata		0	0	0	0	0	0	0	4
Globocassidulina subglobosa		1	0	0	0	0	3	4	4
Ehrenbergina pacifica		0	0	0	0	0	0	1	0
Gavelinopsis praegeri		0	0	1	0	0	0	0	0
Sphaeroidina bulloides		0	3	1	0	0	0	0	0
Heronallenia lingulata		0	0	1	0	0	0	0	0
Cibicidoides dispars		0	0	1	0	2	0	7	6

Cibicidoides globulosus	0	0	0	0	1	0	0	0
Cibicidoides mundulus	2	0	0	0	1	0	0	0
Cibicidoides robertsonianus	0	0	0	0	1	0	0	2
Cibicidoides subhaidingerii	0	0	0	0	0	0	0	1
Epistominella exigua	0	0	0	0	1	0	1	0
Cibicides refulgens	3	0	3	0	0	0	0	0
Cibicides wuellerstorfi	0	2	3	0	5	0	4	4
Lobatula lobatula	1	0	1	0	0	0	0	0
Bulimina aculeata	0	0	0	0	9	2	0	0
Globobulimina pacifica	0	0	0	0	2	0	0	0
Siphouvigerina hispida	0	0	0	0	1	0	0	0
Siphouvigerina proboscidae	0	0	0	0	1	0	0	0
Uvigerina hornibrook	0	0	0	0	3	0	7	0
Uvigerina peregrina	2	0	1	0	4	0	3	0
Pleurostomella incrassata	0	0	0	0	1	0	0	0
Ellipsoglandulina labiata	0	0	0	0	0	0	1	0
Ellipsoidina ellipsoides	0	0	0	0	0	0	1	0
Siphonodosaria bradyi	0	0	0	0	3	0	3	1
Siphonodosaria campana	0	0	0	0	1	0	0	1
Siphonodosaria consobrina	0	0	0	0	0	0	1	0
Siphonodosaria lepidula	0	0	3	0	0	0	0	0
Stilostomella fistuca	0	0	0	0	0	0	1	0
Nuttallides umbonifera	0	0	0	0	0	0	1	1
Chilostomella ovoidea	0	0	0	0	0	0	1	0
Osangularia culter	1	1	0	0	0	0	0	0
Oridorsalis umbonatus	1	0	0	0	0	0	0	0
Heterolepa bradyi	0	0	0	0	1	0	0	0
Anomalinoides globosus	0	1	4	0	1	0	6	1
Discanomolina coronata	0	0	0	0	0	0	1	3
Discanomolina semipunctata	0	0	0	1	2	0	0	0
Hansenisca soldanii	4	2	1	1	2	0	1	0
Elphidium crispum	0	0	0	0	0	0	0	1
Notoralia clathrata	0	0	1	0	5	0	7	5
Parrellina imperatrix	0	0	0	0	1	0	0	0
Melonis barleeanus	0	1	0	0	4	1	2	1
Bryozoans	0	0	1	0	4	1	7	1
Echinoderm spines	1	0	2	2	2	2	5	1
Ostracods	0	0	0	1	1	0	4	1
Teeth	0	0	0	0	1	0	0	0