

BIOSTRATIGRAPHIC AND STABLE ISOTOPE STUDY OF SELECTED  
FORAMINIFERA FROM THE TURONIAN LINDI FORMATION, SOUTHEASTERN  
TANZANIA (TANZANIA DRILLING PROJECT SITE 34 DRILL CORE)

by

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A Thesis  
Submitted to the  
Graduate Faculty  
of  
George Mason University  
in Partial Fulfillment of  
The Requirements for the Degree  
of  
Master of Science  
Environmental Science and Policy

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Date: November 9, 2016

Fall Semester 2016  
George Mason University  
Fairfax, VA

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Lindi Formation, Southeastern Tanzania (Tanzania Drilling Project Site 34 Drill Core)

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of  
Science at George Mason University

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## **DEDICATION**

This thesis is dedicated to all the pioneers in the scientific study of microfossils, especially foraminifera.

## **ACKNOWLEDGEMENTS**

The author thanks the staff of the Paleobiology department at the Smithsonian Institution for use of the Tanzanian Drilling Project materials, financial support, and use of their space and equipment. The author also thanks her thesis advisor, Dr. Uhen, and her thesis committee members, Drs. Verardo and Parsons, for their kind help.

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## ABSTRACT

### BIOSTRATIGRAPHIC AND STABLE ISOTOPIC STUDY OF SELECTED FORAMINIFERA FROM THE TURONIAN LINDI FORMATION, SOUTHEASTERN TANZANIA (TANZANIA DRILLING PROJECT SITE 34 DRILL CORE)

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George Mason University, 2016

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This thesis examines samples of foraminiferal specimens from selected depths within the site 34 drill core of the Tanzanian Drilling Project (TDP), including 3D imaging, for the purposes of biostratigraphy and geochemical analysis. The foraminifera from the Lindi Formation of the Kilwa Group are among the best preserved fossil foraminifera in the geological record. The site 34 drill core includes part of the Upper Cretaceous Kilwa Group, specifically strata from lower Turonian including the Lindi Formation. This study includes biostratigraphic analysis of two planktic foraminiferal species, *Helvetoglobotruncana helvetica* and *Helvetoglobotruncana praehelvetica*. In addition, this study includes biostratigraphic analysis of percent biserial to total planktic analysis and planktic/benthic ratio counts. The associated geochemical part of this study,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopic analyses, focuses on two selected planktic species (*Dicarinella hagni* and *Helvetoglobotruncana praehelvetica*) and four benthic taxa (*Berthelina berthelini*, *Epistomina* sp., *Lenticulina* sp., and *Lingulogavelinella convexa*). Analysis of

percent biserial forms shows that the percent ranges from zero to about 25 percent for the selected depths studied. The ratio of *Hv. helvetica* to *Hv. praehelvetica*, in samples from the site 34 drill core, indicates that the base of the *Hv. helvetica* Biozone occurs at 62.87 m depth, which is lower than previously known. The planktic/benthic ratio varies widely from sample to sample. The simplest explanation for the observed wide variations in compositional counts of biserials and planktic/benthic ratios is that there is a noteworthy contribution of shallow water foraminifera from gravity-emplaced sedimentary units in an overall deep-water setting. Isotopic analysis of the six selected species shows that all samples studied have similar  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  ratios, except the specimens from the sample at depth 66.18 m. At that depth, all specimens show noteworthy negative shifts in both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values. This depth coincides with a minor negative shift in bulk sample  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  as reported previously.

## CHAPTER ONE: INTRODUCTION

The present oceans provide the key to our understanding of past ocean environments. Studying well-preserved ancient marine sediments and their fossil content is a useful technique for helping to solve oceanographic and paleoceanographic problems. One of the best ways to determine past ocean conditions is by analyzing the skeletons of marine organisms preserved within these sediments. Organic materials like the tests of foraminifera are of interest to geologists and paleontologists because they help reconstruct complex ocean environments. Similarities between present-day marine organisms and those extant during Cretaceous include basic marine processes that affected their distributions and ecology. Foraminifera are excellent biostratigraphic and paleoclimatic indicator species that can help answer paleoceanographic questions like temperature and paleobathymetry because of their preservation, abundance, and global distribution. For these reasons, there is a lengthy history of study of foraminifera.

The present report is a biostratigraphic and isotopic ( $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ) study of extremely well preserved Turonian foraminifera from the Tanzania Drilling Project (TDP) core-hole site 34 (Figure 1). In particular, the emphasis of this study is on the biostratigraphic analysis of two planktic foraminiferal species, *Helvetoglobotruncana helvetica* and *Helvetoglobotruncana praehelvetica*. In addition, this study includes analysis of percent biserial to total planktic species analysis and planktic/benthic ratio

counts to help understand paleoenvironments. The stable isotopic study focuses on two selected planktic species (*Dicarinella hagni* and *Helvetoglobotruncana praehelvetica*) and four benthic taxa (*Berthelina berthelini*, *Epistomina* sp., *Lenticulina* sp., and *Lingulogavelinella convexa*). In particular, this study will show how these selected species have recorded paleo-isotopic trends and what these trends may mean.

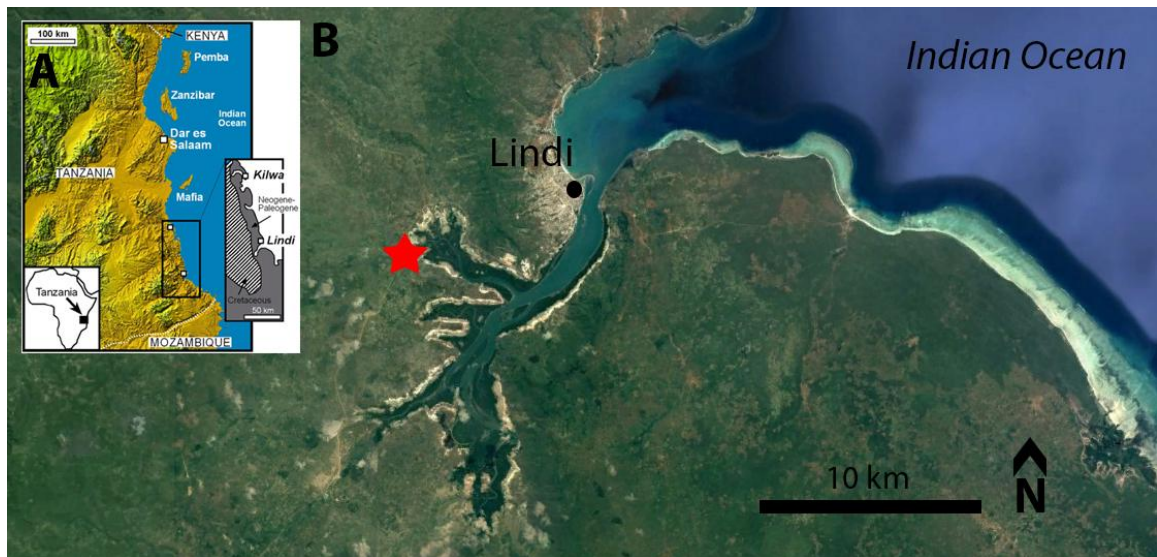


Figure 1: Site map of the study area. A) Upper – Map from Jiménez Berrocoso et al. (2012) showing location and surface geology. B) Lower – Satellite view of Lindi area, Tanzania, showing approximate location of TDP site 34 (red star).

Samples from the Kilwa Group, including the Lindi Formation of this study, contain a rich microfossil assemblage of some of the best preserved foraminiferal specimens in the geological record (Pearson et al., 2004; 2006; Bown, 2005; Lees, 2007; Bown et al., 2008; Huber and Petrizzo, 2014; MacLeod et al., 2013). Therefore, a study of the foraminiferal biostratigraphy can help with determination of paleoenvironment and

prevalent paleoclimate. In addition, a study of the stable isotopic record (i.e.,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ) of these well-preserved, and largely unaltered, specimens will help document paleoecological marine conditions of this region of the world during a key interval of geological time (i.e., Turonian; 93.9-89.8 +/- 0.3 Ma).

The pristine preservation among foraminifera of the Lindi Formation in the Kilwa Group, including early Turonian species of the present study, can be attributed to the high clay content of the Upper Cretaceous-Paleogene sediments (Bown et al., 2008). Clayey matrix in samples helps preserve foraminiferal tests by limiting diagenesis of the tests. No other location is known in the world that yields such pristine wall microstructures as those found in these Tanzanian microfossils (Pearson et al., 2004). Sediments of the Lindi Formation are generally deep-water deposits, which were deposited at low latitudes (Jiménez Berrocoso et al., 2010; 2012). The present project is an opportunity to understand both foraminiferal biostratigraphic characteristics and stable isotope trends in early Turonian deep-water environments.

## **Goals**

The goals of this investigation are to: (1) study the microfossil assemblage in selected depths of the TDP site 34 drill core, so as to provide local biostratigraphic analysis of a part of the Turonian section within the Lindi Formation; and (2) to assess the stable isotopic record (i.e.,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ) of two planktic species, and four benthic taxa, over that same stratigraphic interval. Secondary goals that are addressed include: (1) obtaining a biostratigraphic record through lower Turonian strata of selected single-species foraminiferal abundance counts; (2) obtain percent biserials and planktic/benthic

ratio counts; and (3) to re-assess existing interpretations of biostratigraphic and stable isotopic data from TDP site 34 drill core.

## **Previous Work**

### **Stratigraphy**

According to the review by Pearson et al. (2006), the stratigraphy of southern coastal Tanzania has not been well understood until recent years. This is still the case, even though the stratigraphic study of this area goes back over 100 years to Bornhardt (1900), who first noted that Cretaceous – and what was then regarded as Lower Tertiary (now called Paleogene) – strata were present in some local outcrops. All stratigraphic units were informal in the southern coastal area of Tanzania, until the building of roads produced many new road cuts, thus better exposing the local stratigraphy for description and nomenclature (Nicholas et al., 2006).

The Kilwa Group (Figure 2), which includes the newly named, Lindi Formation, was first described by Schlüter (1997), who based his proposed formal name (the “Kilwa Group”) on field observations by Geirlowski-Kordesch and Ernst (1987), Ernst and Schlüter (1989), and Ernst and Zander (1993). Schlüter (1997) noted that the Kilwa Group is a succession of clays, marls, and silty clays that contain typical deep-water flysch ichnofacies (i.e., dominated by the trace fossil *Nerites*). In an analysis by Nicholas et al. (2006), they note that the Kilwa Group is an unconformity-bounded, Santonian-Lower Oligocene succession that includes four formations, which are shown on Figure 2. Their work, from 2002 to 2005, was based on ~500 outcrop samples and the drill core

from the initial TDP core holes (numbers 1-20). They discussed a dozen stratigraphic cycles of sea-level change within the Kilwa. According to Nicholas et al. (2006), below the Kilwa Group there is an informal unit known as the Kingongo marls (first noted by Balduzzi et al., 1992), which is an informal Albian unit.

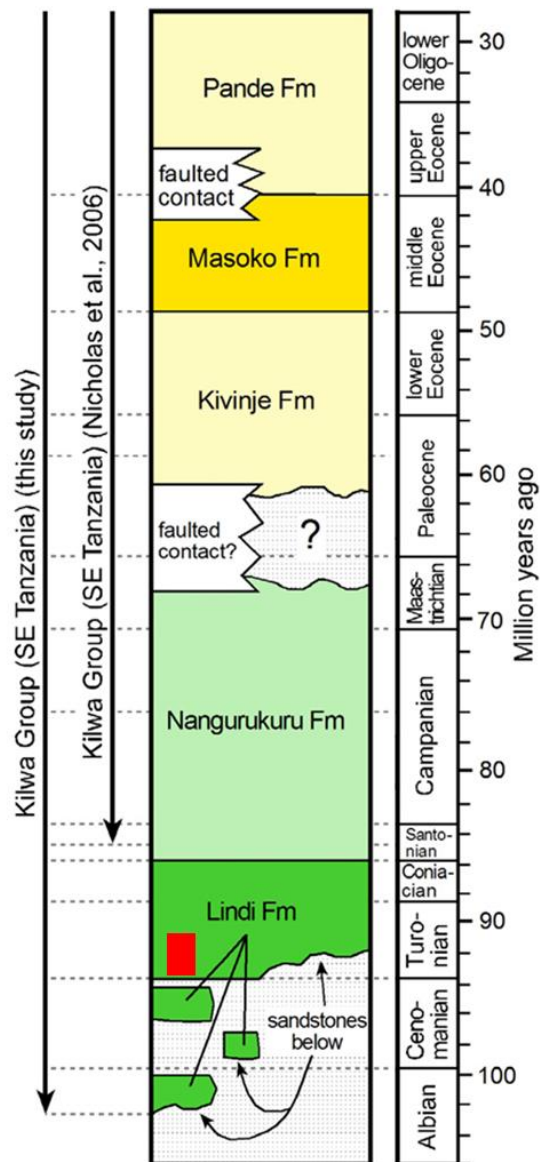


Figure 2: Stratigraphy of the Kilwa Group, southeastern Tanzania, with chronostratigraphic scale (modified from Jiménez Berrocoso et al. (2015). Arrows at left show the units included in the Kilwa Group by Nicholas et al. (2006) and expanded later by Jiménez Berrocoso et al. (2015). In this study, foraminifera from the Turonian part of the Lindi Formation were examined from site 34. The red box represents the range of site 34 drill core, dotted lines relate to chronostratigraphy. There are gaps in the chronostratigraphy in the Lindi Formation below the base of the core.

During the 2007 drilling season, TDP core holes 21-26 recovered previously only poorly known Turonian, Cenomanian, and upper Albian strata below what Nicholas et al. (2006) considered the base of the Kilwa Group (Jiménez Berrocoso et al., 2010) and above the Kingongo marls. Jiménez Berrocoso et al. (2010) noted that the disconformity at the base of the Kilwa Group likely encompassed only Coniacian strata, and that a previously unknown and/or unassigned stratigraphic unit lies between the Kilwa and the informal Kingongo marls. They also noted that TPD core hole 15 had sampled previously these previously unrecognized Turonian strata, which was also present in new core holes 21, 22, 24, 24B, and 26. Subsequently, Jiménez Berrocoso et al. (2012, p. 38) reported on TDP core holes 27-35 and noted that there is a “separate unit ... that will be defined elsewhere,” which underlies what was then thought to be the basal disconformity of the Kilwa Group. They noted that some lower Coniacian strata were found in the upper parts of TDP core holes 21 and 31, therefore diminishing the extent of the basal disconformity noted previously. Recently, Jiménez Berrocoso et al. (2015) named this upper Albian to Coniacian unit the Lindi Formation (Figure 3). The present report examines foraminifera from part of the Turonian section of the Lindi. The stratigraphic description of TDP site 34 drill core, including lithology, percent carbonate and total organic carbon (TOC), and whole (bulk) rock isotopic analyses is shown in Figure 3.

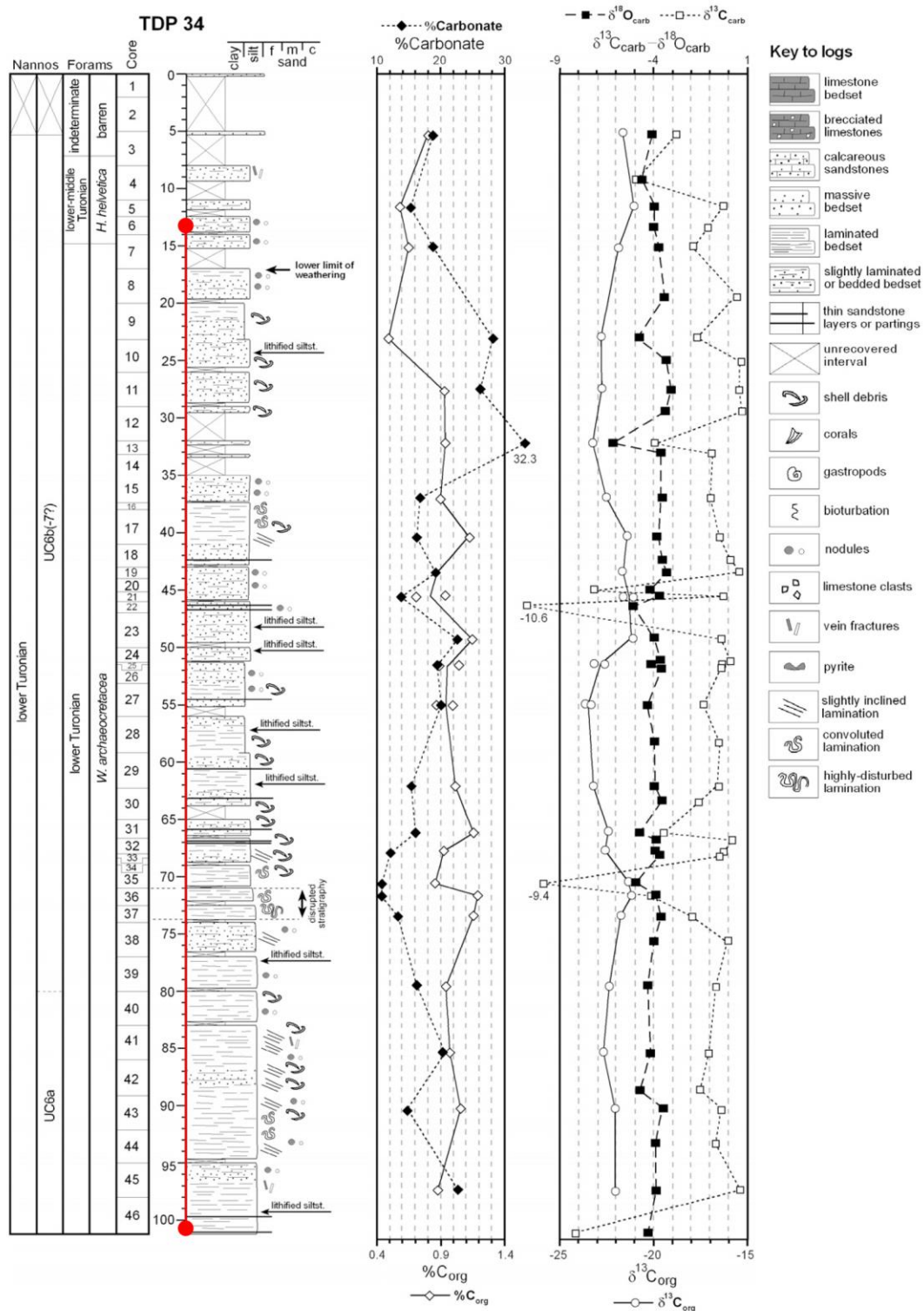


Figure 3: Stratigraphy (lithology, % carbonate, and whole (bulk) rock stable isotopic results for TDP site 34. Inset – key to logs. From Jiménez Berrocoso et al. (2012). Red line shows depths of samples for this report.

The Lindi Formation is a 355-m thick unit, which consists mainly of “dark gray claystone and siltstone interbeds, common finely laminated intervals, (and) minor cm-thick sandstones” (Jiménez Berrocoso et al., 2015, p. 282). They note that up to 2.6% organic carbon exists in the Turonian part of the formation. Previously, Jiménez Berrocoso et al. (2015) described the Lindi Formation as “olive brown, olive gray and greenish black claystones and silty claystones, with massive or slightly laminated fabrics.” In addition, they noted “interbedded, medium-to-dark gray, well-lithified siltstones” and “light gray, fine grained sandstone partings” in some places (Jiménez Berrocoso et al., 2012, p. 44). And, there are intervals that display soft-sediment deformation throughout. Shelly debris occurs in some beds and the debris is mainly of ammonite and inoceramid origin. The sedimentology of this new formation is similar to the overlying parts of the Kilwa Group, which strongly suggests a deep-water depositional environment (Figure 4). Jiménez Berrocoso et al. (2015) described this environment as “outer shelf to upper slope.” In this context, the coarser materials (sands and shell debris) are of gravity-driven origin, and are likely to have come originally from up-dip, shallower water settings (Figure 4). Jiménez Berrocoso et al. (2015) included those marls and some previously unknown fine-grained strata in a new formation that they named the Lindi Formation. They noted that the Lindi spans upper Albian through Coniacian strata in the area.

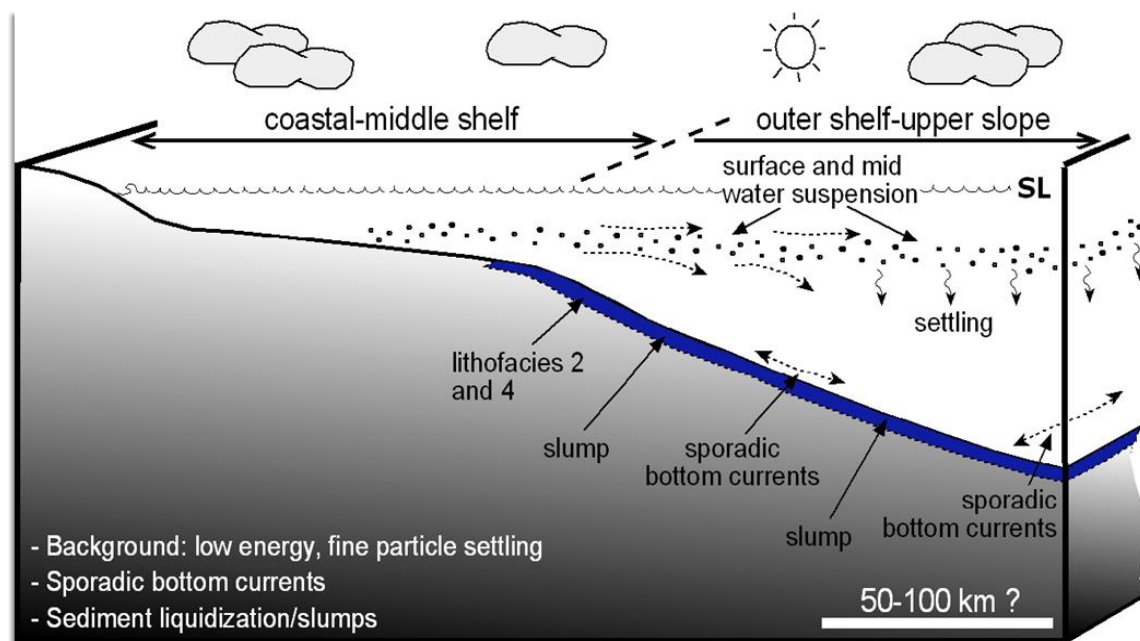


Figure 4: Block diagram showing the main depositional environments (outer shelf to upper slope) for the Turonian part of the Lindi Formation (as discussed by Jiménez Berrocoso et al., 2015). Lithofacies 2 and 4, depicted here, comprise approximately 90 percent of the Lindi Formation strata in TDP site 34; lithofacies 2 and 4 are finely laminated, organic-rich dark claystones and siltstones (Jiménez Berrocoso et al., 2015). Main depositional processes and approximate scale are indicated. Modified from a diagram provided to the author by Á. Jiménez Berrocoso.

At the Cenomanian-Turonian boundary, there was a global anoxic event, (known as “Ocean Anoxic Event 2” (OAE2)), but this event is absent in TDP cores. In describing TDP core sites 36-40, Jiménez Berrocoso et al. (2015) discussed the absence of this event in strata cored at TDP drill sites. They noted that there is a general lack of a well-preserved record of all Turonian carbon isotopic excursions (as compared to the excursions documented elsewhere by Jarvis et al., 2006) in TDP cores, including the one associated with OAE2. Jiménez Berrocoso et al. (2015) indicate that the Cenomanian-Turonian boundary is a short distance below the base of TDP drill core from site 34.

Therefore, the level of OAE2 must be missing as well, as indicated by their lithic descriptions and stable isotopic analysis.

### **Paleogeography**

The present day latitude and longitude of site 34 drill core are 10°1'46" S and 39°38'15" E, respectively, however, during early Turonian the study area was located farther south of the equator. In fact, the study area of southern coastal area of Tanzania was situated about 30 degrees south of the Turonian equator. The exact paleo-coordinates, as determined by the Paleobiology Database were latitude 29.1° S and longitude 29.2° E; at the center of the yellow circle in Figure 5. The present-day latitude and longitude for the geographic location of the study area was taken from Universal Transverse Mercator (UTM) coordinates the authors stated in the text of Jiménez Berrocoso et al., 2012. All UTM coordinates were converted to latitude and longitude using a free Montana State University online program (<http://www.rcn.montana.edu/resources/converter.aspx>). The paleo-coordinates (29.1° S, 29.2° E) of TDP Site 34 in Lindi, Tanzania were obtained from Tanzanian drilling collections data entered into the Paleobiology Database (<https://paleobiodb.org/#/>). In the Paleobiology Database, collections are entered along with present-day coordinates and geological ages and combined with paleogeographic rotation models to obtain reconstructed paleogeographic positions.

Collections are assigned present-day coordinates and geological ages and combined with paleogeographic rotation models to obtain reconstructed paleogeographic positions. The Turonian coastal plain was a low-lying area that received clastic input

from local streams and rivers (Jiménez Berrocoso et al., 2012). Further, the study area was a near a passive-margin shelfal area of the Tethys sea, which was dominated by clastics, and within an adjacent deeper area (slope and basinal area) that received sediment shed from distal deltaic system (Pearson et al., 2004; Nicholas et al., 2006). Jiménez Berrocoso et al. (2012) refer to this environment as “upper slope and outer shelf.” In their work with hundreds of specimens from nearby TDP drill site 31, Wendler et al. (2013) noted that benthic foraminiferal assemblages and ratios of planktic to benthic foraminifera suggest “a paleobathymetric position at the outer shelf to upper slope.” All foraminiferal specimens studied in the present report and in reports relating to TDP site 34 (i.e., Jimenez Berrocoso et al., 2010; 2012; and 2015) have been entered into the Paleobiology Database (paleobiodb.org). Paleobiology Database collection numbers are as follows: 179309; 179310; 179311; 179312; 179313; 179314; 179874; 179875; 179879; 179882; 179883; 179884; 179885.

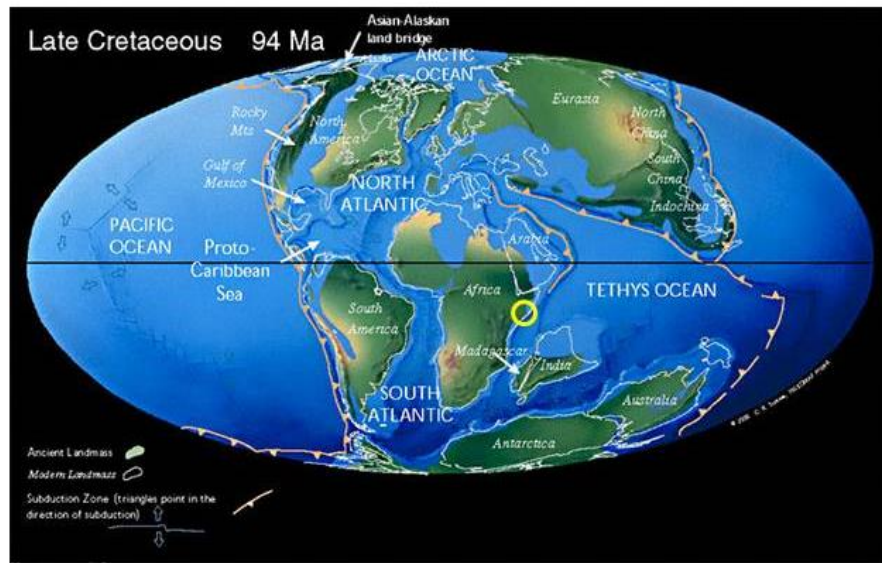


Figure 5: Paleogeography approximately 94 million years ago (Cenomanian-Turonian boundary age). Yellow circle shows Lindi, Tanzania, area. From [www.scotese.com](http://www.scotese.com).

## Biostratigraphy

According to the lithic, geochemical, and stable isotopic logs of site 34 drill core presented by Jiménez Berrocoso et al. (2012; Figure 3), the established foraminiferal biozones are defined by the ranges of *Hv. helvetica* and *W. archaeocretacea*. The boundary between these biozones is also the boundary between lower Turonian and “lower-middle Turonian” as defined by Jiménez Berrocoso et al. (2010; 2012).

The taxonomy and biostratigraphy of *Hv. helvetica* has been reviewed by Huber and Petrizzo (2013). Their review discusses the *Hv. helvetica* Biozone and the difficulties globally and in Tanzania of identifying the base of this biozone. They discuss an integrated correlation but leave open the question of where to consistently place the base of this biozone (or lowest occurrence datum).

In this study, all samples studied for biostratigraphic and stable isotopic analyses are from the part of the section in TDP drill core 34 that is below the established base of the *Hv. helvetica* Biozone according to Jimenez Berrocoso et al. (2012); however, this species is present below the established base of the biozone, and it occurs with a morphologically related species, *Hv. praehelvetica*.

### **Stable isotopic analysis**

Stable oxygen and carbon isotope systematics relating to differential fractionation between planktonic foraminifera (i.e., their shell walls and the surrounding sea water) have been reviewed in detail by Birch et al. (2013). Organisms like foraminifera that incorporate oxygen from sea water to build their shells do so with a different proportion of lighter to heavier oxygen ratio of the sea water in which they live. Regarding oxygen, at lower water temperatures, organisms like foraminifera take up  $^{18}\text{O}$  in a relatively larger proportion than at higher temperatures, because of the relatively slow motion of this heavier isotope. Thus, in colder water, for example during glacial times, the ratio of  $^{16}\text{O}$  to  $^{18}\text{O}$ , or  $\delta^{18}\text{O}$  is lower because of a relative density difference. However, during Turonian, there is isotopic and other evidence for an ice-free world (MacLeod et al., 2013). Regarding carbon, when the lighter isotope of carbon ( $^{12}\text{C}$ ) is rapidly buried and not returned to the atmosphere, there is a shift toward heavier isotopes of carbon, and this affects the  $^{12}\text{C}$ - $^{13}\text{C}$  ratio. A shift toward heavier carbon, results in a lower  $\delta^{13}\text{C}$  value (Birch et al., 2013). Studies by Birch et al. (2013) and others have shown that with proper selection of specimens for isotopic analysis, the stratigraphic, and thus temporal,

distribution of change in oxygen and carbon isotopes can be of great value in understanding changes in paleo-climate and the structure of the paleo-water column.

Stable oxygen and carbon isotope systematics in Turonian foraminifera from Tanzania has been previously studied by Wendler et al. (2013) and MacLeod et al. (2013). In their work with hundreds of specimens from nearby TDP drill site 31, Wendler et al. (2013) noted remarkably low variability within species (i.e., a consistently very low intraspecific standard deviation of less than 0.2). Among Turonian foraminifera they studied, there was not any strong evidence of major long-term environmental fluctuations, and their work suggested a well-stratified water column.

## **CHAPTER TWO: METHODS**

### **Imagery**

The first step in the study of foraminifera of the Turonian section in TPD core 34 was to collect a representative suite of planktic and benthic foraminifera from those cores. This was done in order to have a specimen collection to identify the species present and their preservation state. This representative collection was used to assess which species were best for biostratigraphic and stable isotopic studies, as described below.

As part of the imagery of this representative collection, both standard light microscopy and scanning electron microscopy (SEM) was used to identify and image the key foraminifera present. The best preserved foraminifera were selected for three-dimensional imaging to digitally render and further study the morphological detail of some foraminiferal species.

A new method combining SEM images using readily-available 3D visualization software and 3D printing technology to produce useful reproductions of foraminiferal tests was used in taxonomic analysis of selected species. A simple preparation method involved positioning an isolated foraminifer specimen within the SEM chamber in order to obtain a complete (360 degrees) external morphological reproduction of the foraminifera shell structure. The result was digital, high-resolution three-dimensional

(3D) models of selected species using SEM photomicrographs, attained through the use of photogrammetric algorithms.

The machine utilized was a Zeiss Evo MA15 and the scan speed was set at 8 so that the images were clear and noise-free. The specimen tilt was dictated by surface topography of the specimen. Ideally, three views of every point on the specimen were obtained. The tilt steps were 45, 65, and 90 degrees (the 65-degree step was needed for image stitching later on). After first imaging, the specimen was removed, flipped, and re-mounted. Then the specimen is imaged from the opposite side. The limitations of this sort of photogrammetry are: surface texture of the specimen; line of sight; and resolution of images versus quality of the 3D model. The final 3D computer model was a derivative of these images from one specimen. Two types of software were used for image processing. For more details, please see the subsequent chapter (Chapter 4) on Digital 3D imaging of foraminifera.

## **Biostratigraphic analysis**

Data for this thesis were obtained from samples taken from the drill core at TDP Site 34, which is a continuous drill core spanning the lower Turonian stratigraphic section. The planktic species selected for the biostratigraphic part of this study were *Helvetoglobotruncana helvetica* and *Helvetoglobotruncana praehelvetica*. The species selected for the stable isotopic part of this thesis project were chosen because they are present and abundant throughout the site 34 drill core. The selected species were: two planktic species (*Dicarinella hagni* and *Helvetoglobotruncana praehelvetica*); and four

benthic taxa (*Berthelina berthelini*, *Epistomina* sp., *Lenticulina* sp., and *Lingulogavelinella convexa*). These species compare to samples selected and analyzed in previous work on nearby sites.

Biostratigraphic samples from the drill core were already washed and sieved, and most had been split up to 2-4 times. Sample preparation for foraminifer identification involved the same techniques for both planktonic and benthic foraminifers. Core samples were soaked in distilled water and washed over a 63 µm mesh sieve. Lithified material was crushed, occasionally heated in a Calgon/hydrogen peroxide solution, and then sieved as above. All samples were dried on a <60°C hot plate. Dried samples were sieved over a 125-µm sieve, retaining the <125 µm size fraction for additional observation when necessary. Where lithified sediments were recovered, samples were disaggregated and then sieved first using a 500 µm mesh to facilitate foraminiferal picking and identification. The >125 µm size fraction specimens were examined under a binocular light microscope. An average of 353 individual planktic specimens and 215 benthic specimens were picked from each of 20 selected samples from drill-core intervals. This count was similar to counts used by Wendler et al. (2013) in their biostratigraphic analysis of TDP site 31 and these counts worked well in that instance. Each selected core interval represented about 20 cm of drill core sediment. The foraminiferal counts were divided into three categories: biserials and other planktics for each selected core interval; *Hv. helvetica*, *Hv. praeHelvetica*, and *Hv. helvetica*-*Hv. praeHelvetica* transitional forms; and other benthic forms.

Samples for biostratigraphic analysis in TDP core 34 were taken from 41.65 to 99.98 meters below the surface. Exact depth below the surface for each selected foraminiferal sample was determined by using a general look-up table that relates the core box number and interval (row) number to a depth below the surface for the core section's depth interval. For this study, samples were analyzed approximately every twenty meters depth.

### **Stable isotopic analysis**

Isotopic samples from the drill core were previously prepared for picking using standard techniques as noted above. The individual specimens were selected for analysis if they showed no apparent calcite overgrowth or infilling and were translucent. Samples of one species (1 to 30 specimens) were collected, submitted for analysis, and analyzed together in one analytical run. Foraminifera selected for isotopic analysis were analyzed carefully under a binocular light microscope for signs of diagenesis. Only the best specimens, with no signs of calcite overgrowth or test breakage, were selected and weighed before being delivered for isotopic analysis. Depending upon size of the individual specimens, up to 30 were run together, but usually the run consisted of a few specimens at one time. Counts were made of the number of individual specimens selected from each sample and the weight of those specimens was recorded in micrograms. Samples were analyzed by the Biogeochemistry Isotope Laboratory (BIL) at the University of Missouri (Columbia, Missouri). Isotopic values were measured at BIL using a Kiel III carbonate device and Thermo Finnigan™ DeltaPlus isotope ratio

mass spectrometer, and calibrated using an NBS-19 standard. Data were compiled and analyzed in a Microsoft Excel © spreadsheet.

Samples for isotopic analysis in TDP core 34 were taken from depths ranging from 25.41 to 97.80 m below the surface. Exact depth below the surface for each selected foraminiferal sample was determined in the same way as noted above (by the core box number and interval (row) number, which yields the depth below the surface for the core section's depth interval).

## CHAPTER THREE: RESULTS

### Imagery

Results from new photogrammetric methods in this study produced digital, high-resolution, 3D models of foraminifera from SEM photographs, using photogrammetric algorithms. These high-resolution images were used to produce accurately scaled, 3D models of foraminifera, including *Radotruncana calcarata*. The method used here allows for a more complete external morphological examination of foraminiferal shapes and surface textures. This modeling used relatively minor adaptations to the standard SEM mounting of the specimens, readily available software, and careful capture of images to produce a digital 3D representation of the specimen. These digital foraminifera renders are easily shareable as digital files and allow the generation of large numbers of scalable, printable 3D digital models that would be available for education, archiving and taxonomic research. The method used in this report is easier to accomplish and requires less time than the two older methods data collection of complex morphologies of small fossils, i.e., Computed Tomography (CT) and 3D laser scanning (described by Smith and Straight, 2008). More details on 3D imagery is presented in Chapter 4 on Digital 3D imaging of foraminifera.

## Biostratigraphic analysis

The two goals of biostratigraphic analysis previously noted were: (1) to obtain a biostratigraphic record through Turonian strata in this part of Tanzania of selected single species foraminiferal abundance counts; and (2) to obtain percent biserials and planktic/benthic ratio counts. As noted earlier, the selected single species were *Helvetoglobotruncana helvetica* and *Helvetoglobotruncana praehelvetica*.

Data were collected on planktic forms (counts of biserial, other planktics, and total planktics) and benthic forms (counts were divided into *Hv. helvetica*, *Hv. praehelvetica*, and other benthic forms). These were used to compute percentage of biserials to total planktic counts and to compute the ratio of *Hv. helvetica* to *Hv. praehelvetica* through the drill core section (Figure 6). The percentage of biserials is used by some workers to assess changing environmental conditions or changes in the water column. This ratio can be used to identify events in the history of depositional environments. The planktic/benthic (P/B) ratio is an indicator of water depth (van der Zwaan et al., 1990). To view the relationship between down-hole counts of the percent of biserials to total planktic species, a cross-plot was made showing the total biserial count as a percentage of total planktics versus depth in the site 34 drill core. All biostratigraphic data are presented in the Appendix.

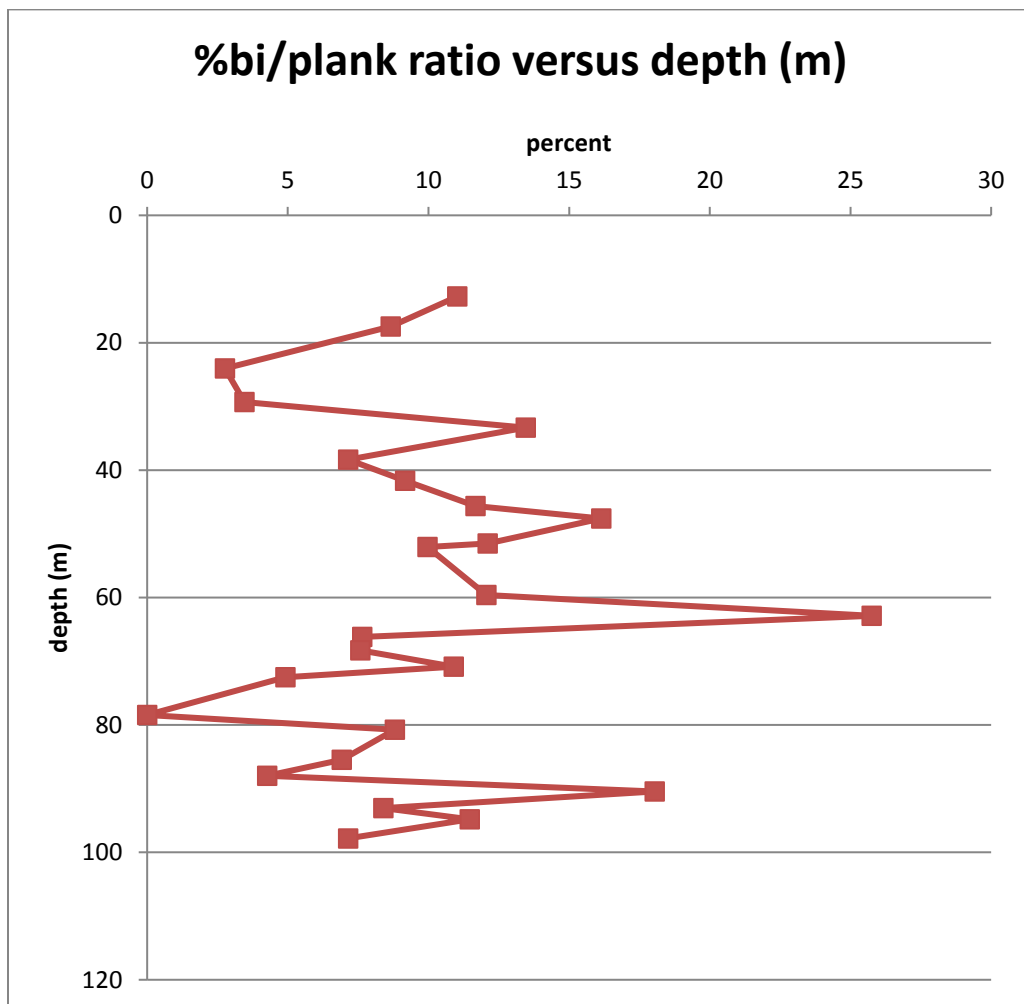


Figure 6: Depth in meters (vertical) versus the percentage of biserials to total planktic species. Note the single large value between 62 and 68 m. This high value likely relates to a change in sediment source.

To view the relationship between down-hole counts of the two selected single planktic species, a cross-plot was made showing the ratio of *Hv. helvetica* count to *Hv. praehelvetica* count versus depth in the drill core 34.

Figure 7 shows the cross-plot results. There is an abrupt shift toward a higher proportion of *Hv. helvetica* commencing between 62 and 68 meters (starts above 62.87

m) in the drill core. This shift in abundance is 47 to 53 meters below the established base of the *Hv. helvetica* Biozone's base (according to Jiménez Berrocoso et al., 2012) and therefore represents evidence for a new base of the *Hv. helvetica* Biozone.

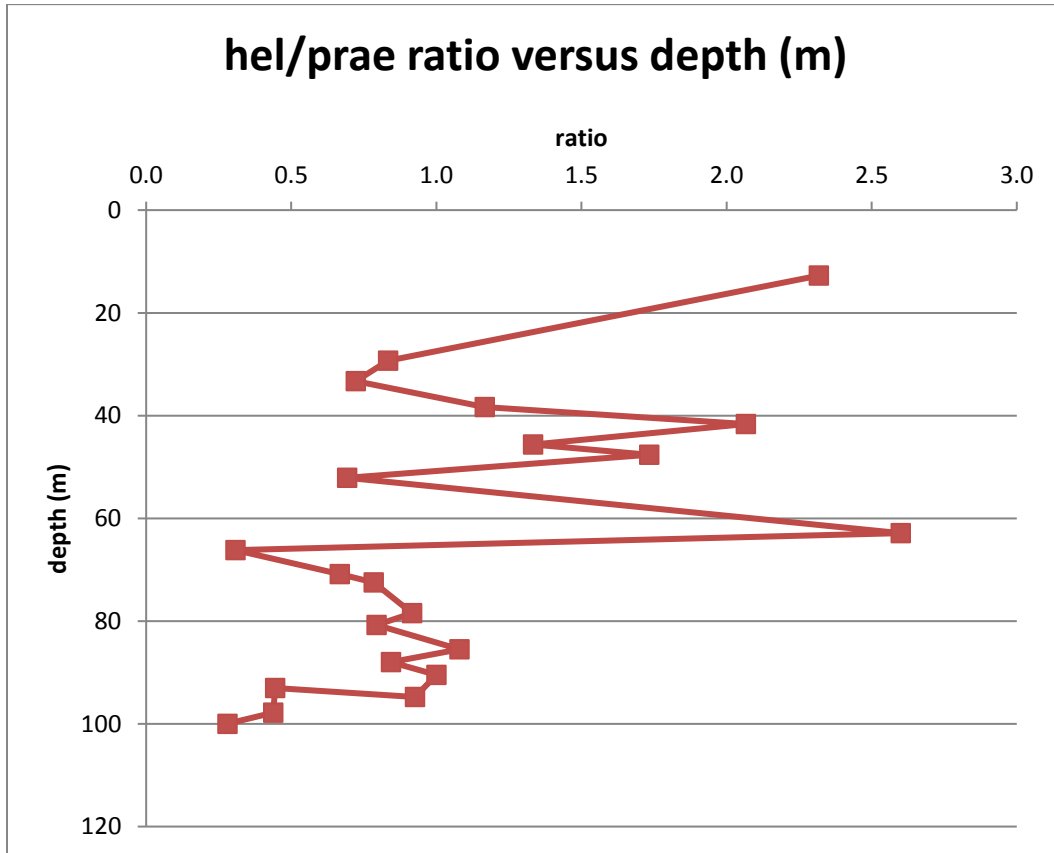


Figure 7: Depth in meters (vertical) versus the ratio of *Hv. helvetica* count to *Hv. praehelvetica* counts.

Both Figure 6 and 7 show a similar pattern of abrupt shift in the different data sets between the same depth (62.87 m). The pattern is also similar in that the indicators in each instance do not remain high, but instead above the abrupt shift, they return in some samples to levels more typical of the section below 68 meters.

According to Jiménez Berrocoso et al. (2012), who presented the lithologic log for TDP drill core 34, the interval between 62 and 68 meters is mainly a silty clay and clayey silt that is slightly bedded. In the lower part, there are inclined laminations and much of this 6-m interval contains shell debris. This is not a remarkable interval within drill core 34 in terms of lithology or other characteristics logged by Jiménez Berrocoso et al. (2012), including carbonate content. Therefore, it appears that the excursions in the two data sets noted above (% biserials and the ratio of counts of two key planktic species (*Hv. helvetica* count to *Hv. praehelvetica*) are notable biostratigraphic anomalies (Figure 8).

**To view the relationship between down-hole total counts of planktic and benthic foraminifera, a planktic/benthic ratio was computed and plotted versus depth in the site 34 drill core.**

Figure 9 shows the graphic results. There are many abrupt shifts back and forth in this ratio throughout the drill core section studied. This finding contrasts sharply with the results given for TDP drill core 31 in the same general area. Wendler et al. (2013) noted that their counts of percent benthics and planktic/benthic (P/B) ratios consistently showed the same deep water paleoenvironment. Taken literally, the abrupt shifts in these P/B data from drill core 34 suggest substantial changes consistent with greatly varying water depth, on a scale of a few meters of section. A more likely interpretation is that the deep-water environment was receiving shallow water sediment via episodic sediment flows that contained a different P/B ratio.

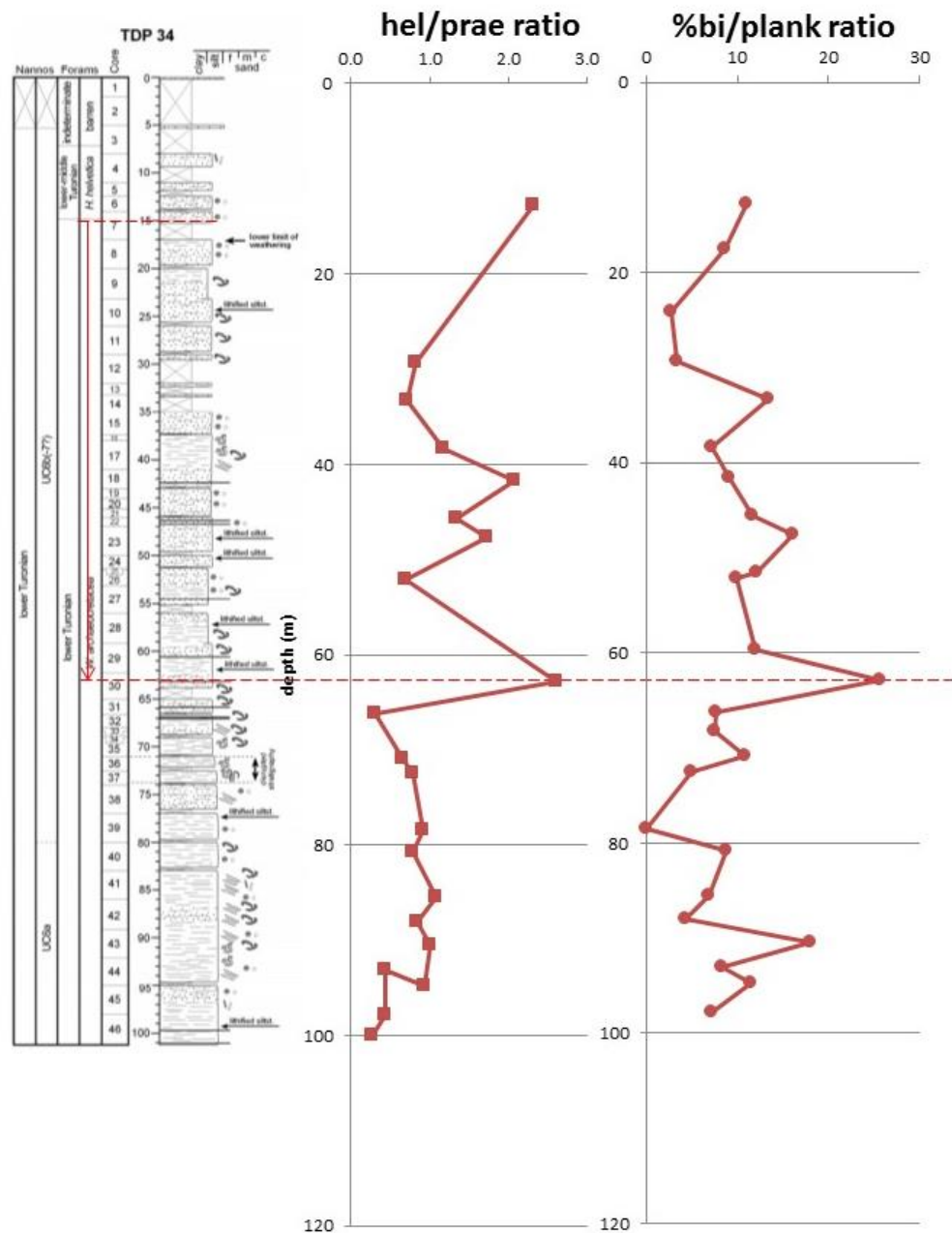


Figure 8: Shown on left are the stratigraphy results for TDP site 34 from Jiménez Berrocoso et al. (2012). Red line shows new lower base of *Hv. helvetica* Biozone at 62.87 m for this report. Also shown on the right are the data set of both the ratio of counts of two key planktic species (*Hv. helvetica* count to *Hv. praehelvetica*) and the percentage of biserials. Both show a similar pattern of abrupt shift between the same depth (62.87 m) and are notable biostratigraphic anomalies.

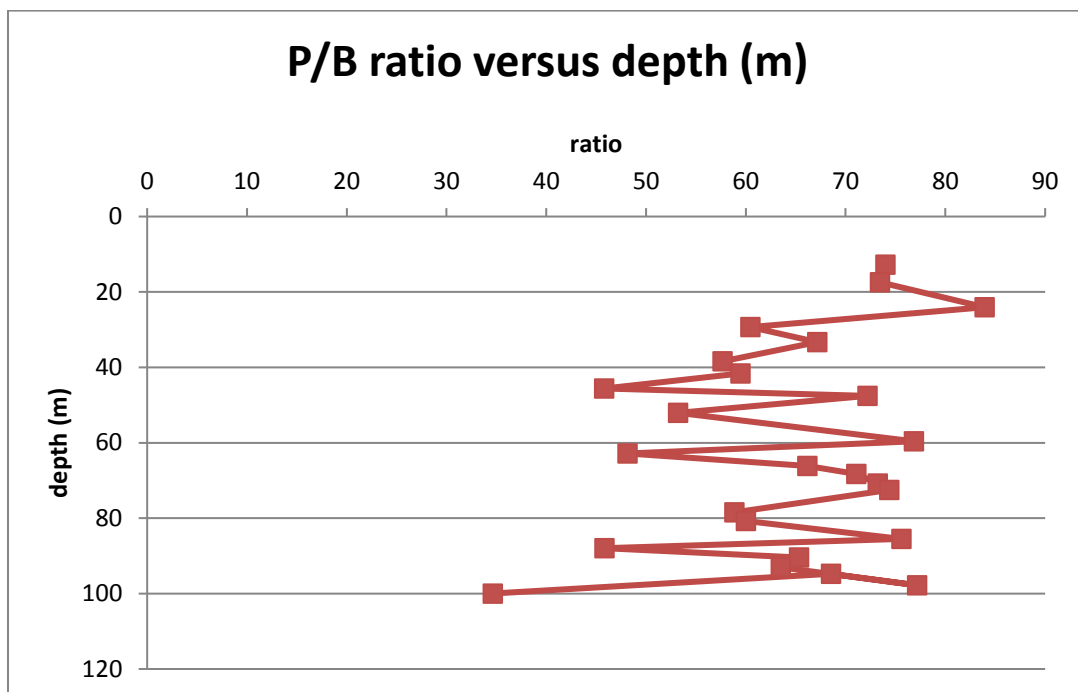


Figure 9: Depth in meters (vertical) versus the planktic/benthic (P/B) ratio.

## Stable isotopic analysis

Of the species selected for stable isotopic analysis (*B. berthelini*, *D. hagni*, *Epistomina* sp., *H. praehelvetica*, *Lenticulina* sp., and *L. convexa*; Figure 10), *Lenticulina* sp. was the most abundant among the best preserved specimens in each sample studied. *Epistomina* sp. was the largest and, therefore, has the most mass ( $\mu\text{g}$ ) of the specimens. Data were organized so that the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data could be studied in relation to species, depth, and mass. All isotopic data are presented in the Appendix.



Figure 10: Foraminifera used for isotopic analysis. A) *Berthelina berthelini*; B) *Epistomina* sp.; C) *Lingulogavelinella convexa*; D) *Lenticulina* sp; E) *Dicarinella. hagni*; and F) *Helvetoglobotruncana praehelvetica*.

The isotopic data set of the present study shows that the variation in values for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  among all samples (i.e., all species) studied in TDP site 34 drill core is relatively large, except for the planktic species *D. hagni* and the benthic species *L. convexa*. Wendler et al. (2013), who studied the foraminiferal stable isotopes of same-age strata of Tanzania in TDP site 31 drill core, reported that their  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data were remarkably low in intra-species variability ( $< 0.2$  standard deviation). However, the data set produced in this study, has by comparison with Wendler et al. (2013) examples of substantial variation. Standard deviations of all  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data for all six species studied here were much higher than the 0.2 value reported as a *maximum* value by

Wendler et al. (2013). Except for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data for *D. hagni* and *L. convexa* and  $\delta^{18}\text{O}$  data for *Lenticulina* sp., all other data sets were substantially higher in standard deviation than 0.25.

Figure 11, which plots  $\delta^{18}\text{O}$  versus depth for all six species (using different symbols), shows that the planktic species, *D. hagni* and *H. praehelvetica*, are consistently higher than the four benthic species. This is a finding consistent with similar isotopic analyses of the TDP site 31 drill core by Wendler et al. (2013).

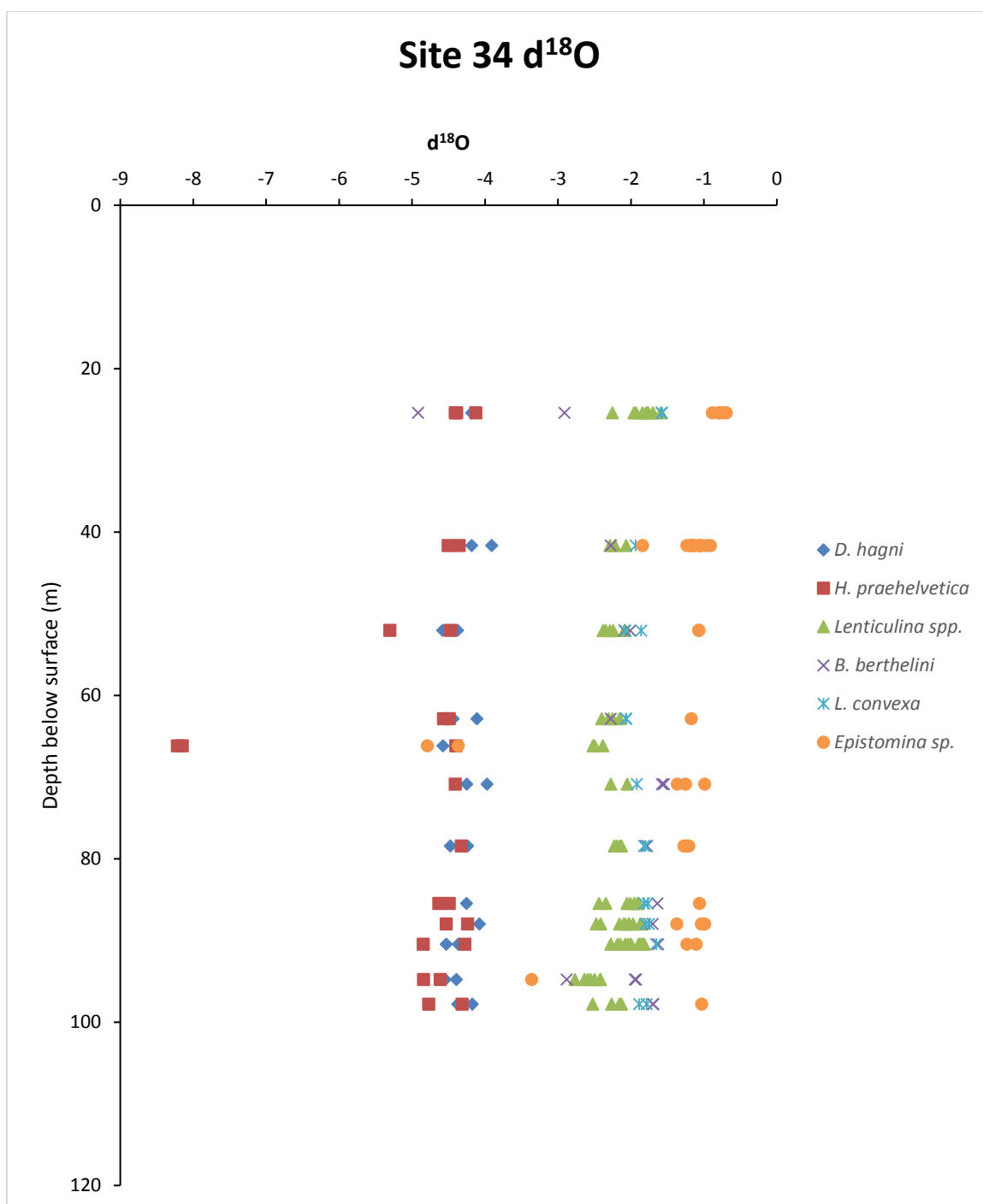


Figure 11: Plot of  $\delta^{18}\text{O}$  versus depth for all six species (using different symbols as indicated).

Figure 12, which plots  $\delta^{13}\text{C}$  versus depth for all six species (using the same symbols as in Figure 12), shows that  $\delta^{13}\text{C}$  ranges from about 1 to 4‰. This, too, is a finding consistent with previous work by Wendler et al. (2013). Regarding

Figure 11 and 12, it is noteworthy that there is a consistent, high-value anomaly at 66.18 m depth. In

Figure 11, this involves *Hv. praehelvetica* and  $\delta^{18}\text{O}$  and in, this involves *Hv. praehelvetica* and a benthic species, *Epistomina* sp. It is worth noting that the depth of this anomaly (66.18 m) is in the midst of the 62-68 meter interval wherein the percentage of biserials, and ratio of the *Hv. helvetica* count to the *Hv. praehelvetica* count, shift (as noted above, see Figure 6 and 7).

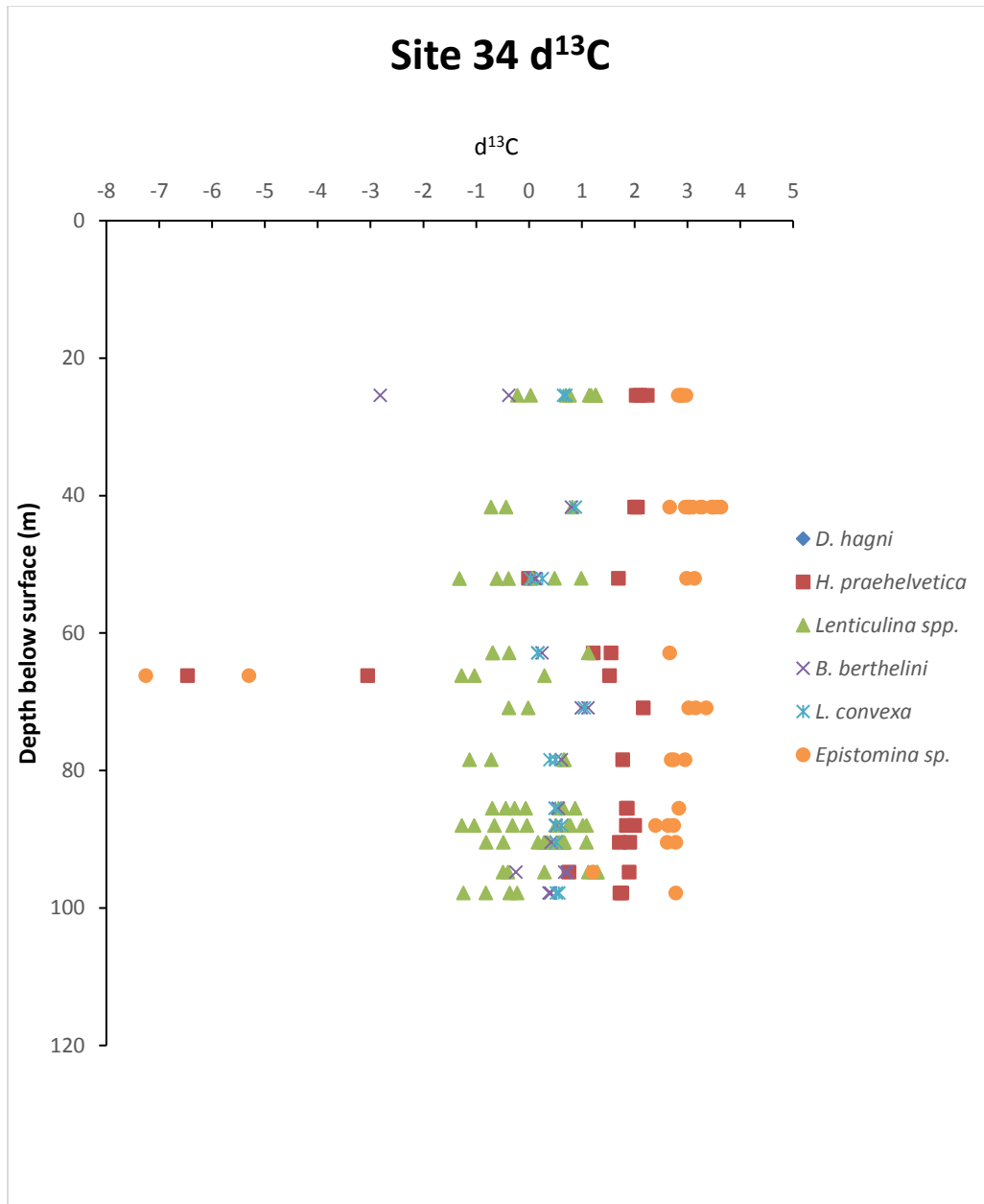
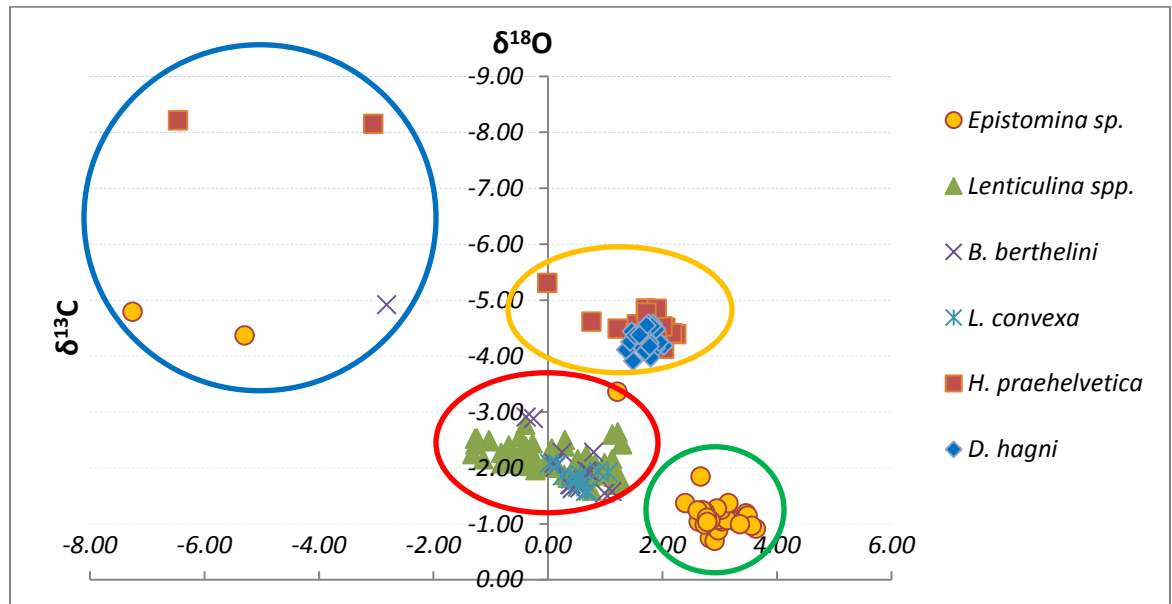


Figure 12: Plot of  $\delta^{13}\text{C}$  versus depth for all six species (using different symbols as indicated).

Figure 13, a cross-plot of  $\delta^{13}\text{C}$  versus  $\delta^{18}\text{O}$  where  $\delta^{18}\text{O}$  ranges from -9 at the top to 0 at the bottom, shows a general separation of groups according to environmental and biological factors. Each point is an analyzed sample that is species-specific. The group

of points on the upper right circled in yellow are planktics, the group of points forming a wider band in the central area circled in red are epifaunal benthics, and the group of points on the lower right circled in green are benthics. There are five anomalous points on the left side of the vertical axis circled in blue that do not agree with any grouping. This three-fold grouping is generally consistent with the scheme presented by Wendler et al. (2013) who synthesized the results of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopic analyses of numerous species (nearly 1000 individual analyses) and discussed the results in light of what is presently known about influences on isotopic analyses of foraminifera, similar to those used in this study.



**Figure 13:** Cross-plot of  $\delta^{13}\text{C}$  versus  $\delta^{18}\text{O}$  where  $\delta^{18}\text{O}$  ranges from -9 at the top to 0 at the bottom and shows a general separation of groups according to environmental and biological factors: red circle contains epifaunal benthic points (*Lenticulina* spp., *L. convexa*, *B. berthelini*), green circle contains benthic points (*Epistomina* sp.), yellow circle contains planktic points (*H. praehelvetica* and *D. hagni*), and blue circle contains outlier points.

Figure 14 and 15 show the relationship between calculated mass and both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values for two data groups: all specimens analyzed; and the *Lenticulina* sp. data set alone. Figure 14 shows that mass does not seem to have much of an effect on  $\delta^{13}\text{C}$  values, but  $\delta^{18}\text{O}$  values seem to separate into two groups of points for masses in the range of about 25 to 75  $\mu\text{m}$ . Regarding *Lenticulina* sp. only (Figure 15), the plots show that  $\delta^{13}\text{C}$  versus mass yields a spread of points, whereas  $\delta^{18}\text{O}$  versus mass yields a narrow range of points suggesting little effect of mass on  $\delta^{18}\text{O}$  values.

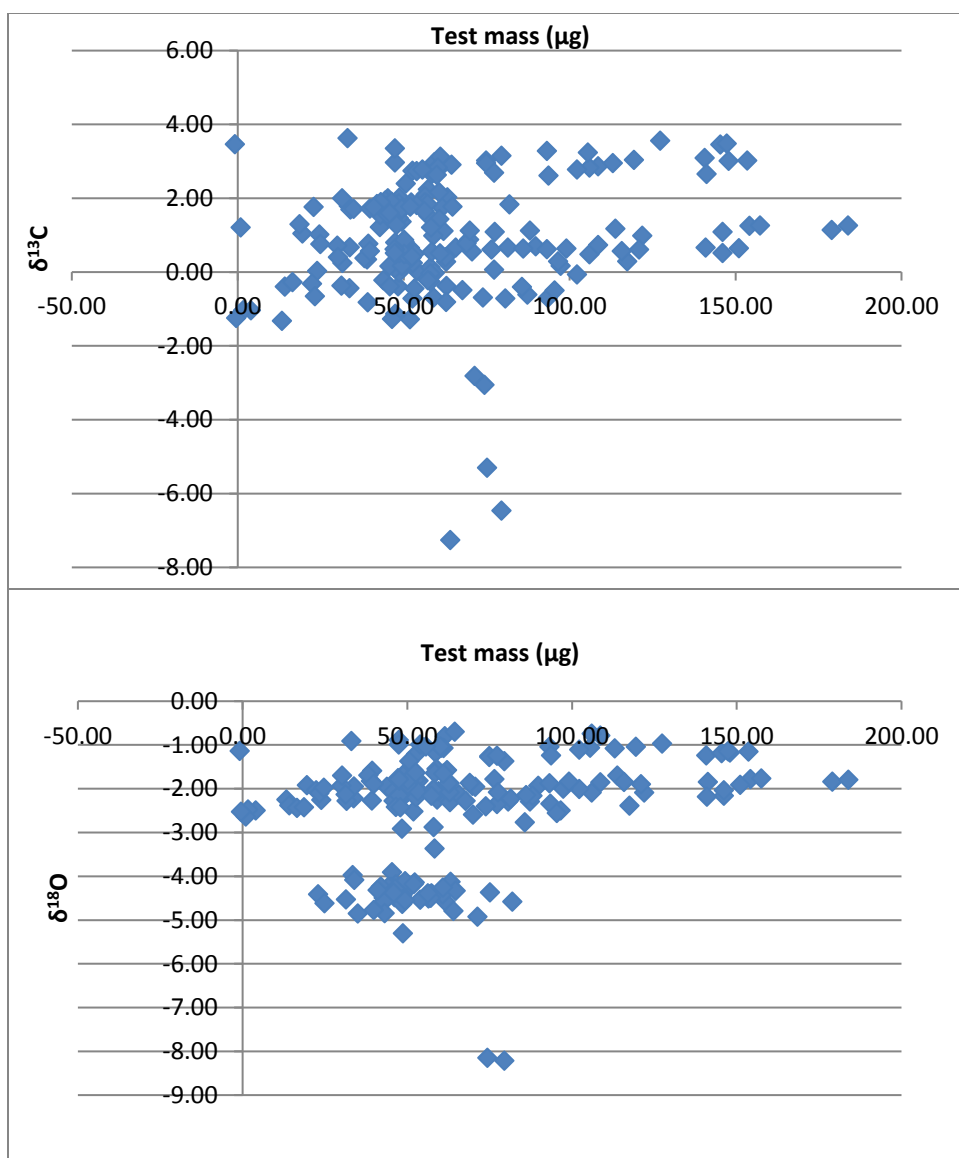


Figure 14: Upper plot shows  $\delta^{13}\text{C}$  versus test mass for all species analyzed; lower plot shows  $\delta^{18}\text{O}$  versus test mass. Test mass (μg) is on the horizontal axis in both plots.

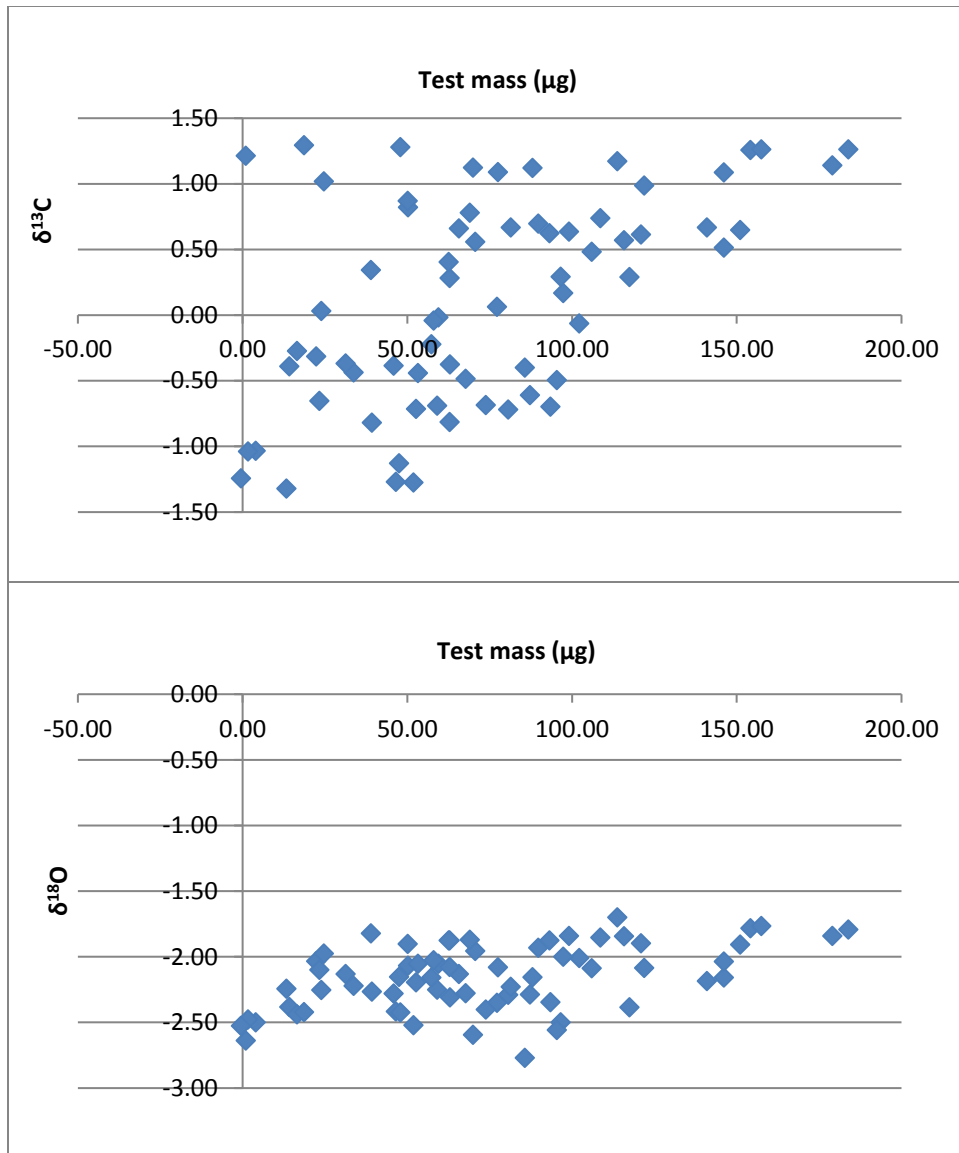


Figure 15: Upper plot shows  $\delta^{13}\text{C}$  versus test mass for all *Lenticulina* sp. tests analyzed; lower plot shows  $\delta^{18}\text{O}$  versus *Lenticulina* sp. test mass. Test mass ( $\mu\text{g}$ ) is on the horizontal axis in both plots.

Figure 16 shows a possible relationship between five weighted *Epistomina* sp. specimens and  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ . As expected, there may be a general positive relationship between mass and  $\delta^{13}\text{C}$  and there may be a general negative relationship between mass and  $\delta^{18}\text{O}$  regarding this species.

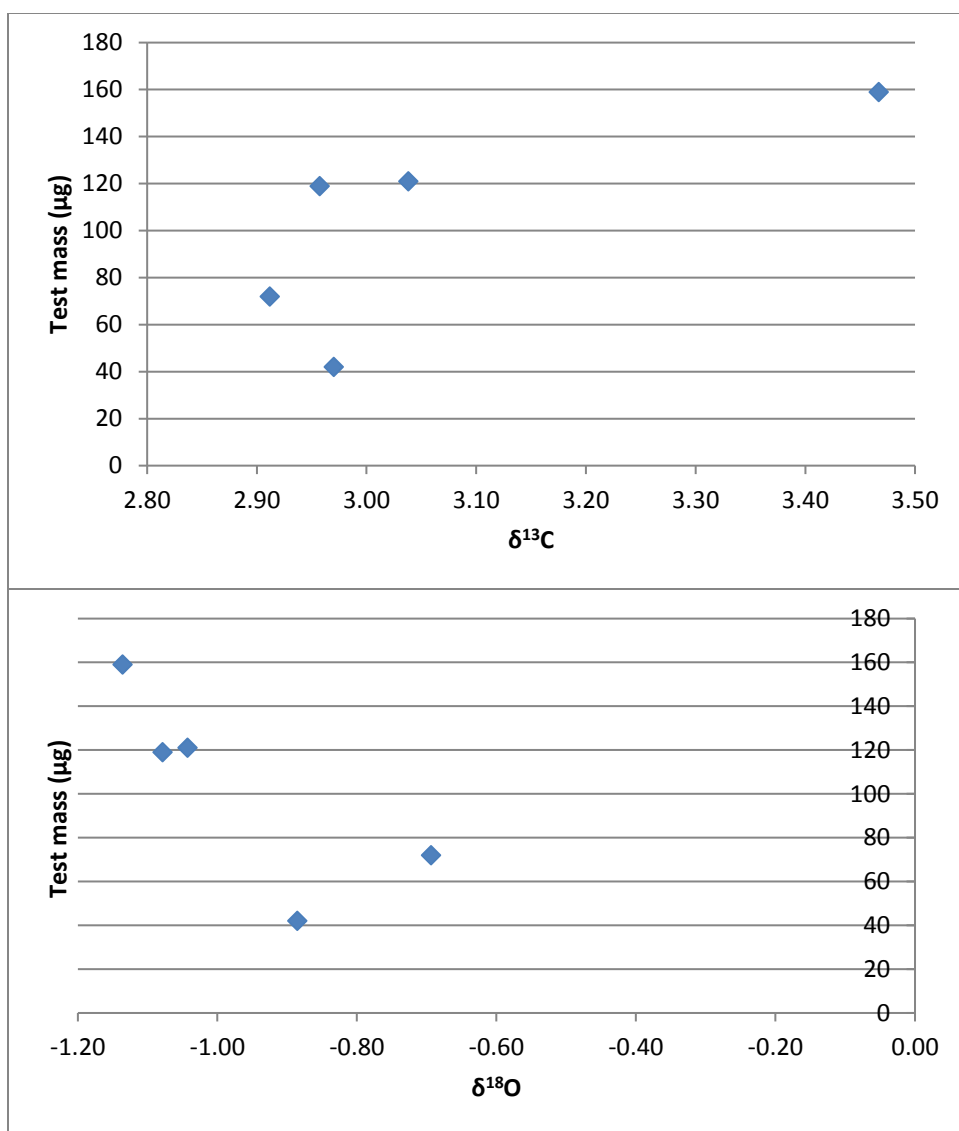
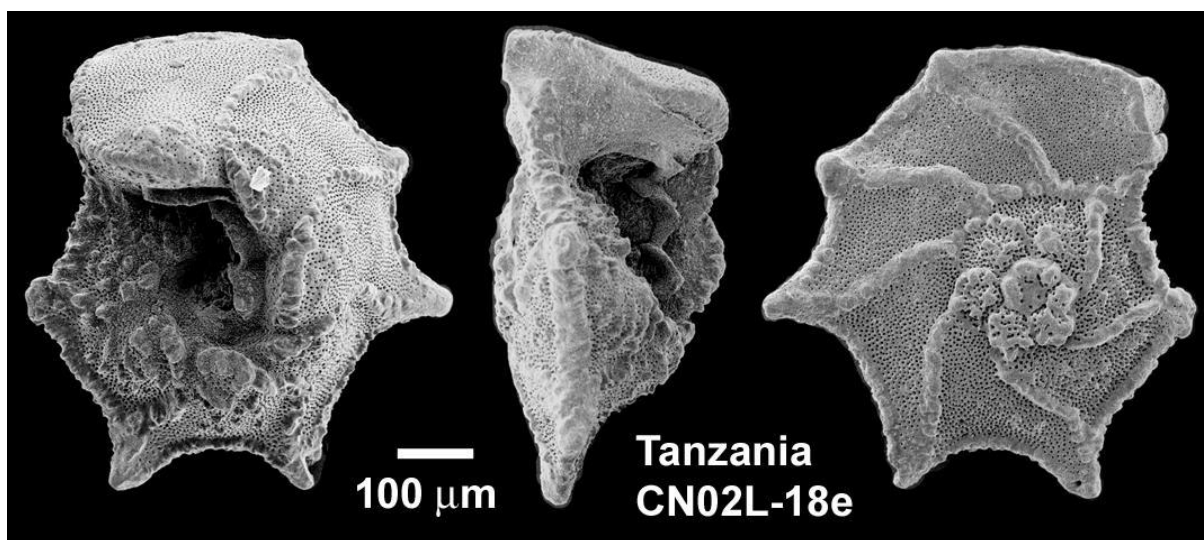


Figure 16: Upper plot shows  $\delta^{13}\text{C}$  versus test mass for all *Epistomina* sp. tests analyzed and individually weighed; lower plot shows  $\delta^{18}\text{O}$  versus *Epistomina* sp. test mass. Test mass ( $\mu\text{g}$ ) is on the vertical axis in both plots.

## CHAPTER FOUR: DIGITAL 3D IMAGING OF FORAMINIFERA

### Overview

Conventional SEM imaging of foraminifera involves taking three images with different views of the same specimen (Smith and Straight, 2008; Falkingham, 2012; Görög et al., 2012). Figure 17 shows this conventional approach of SEM imaging involving a single specimen. Some of the drawbacks of this conventional approach to imaging include the need for three separate work sessions for each specimen, lack of detail about possible important specimen characteristics, and the relatively large amount of time spent imaging one specimen (estimated to be up to 10 hours).



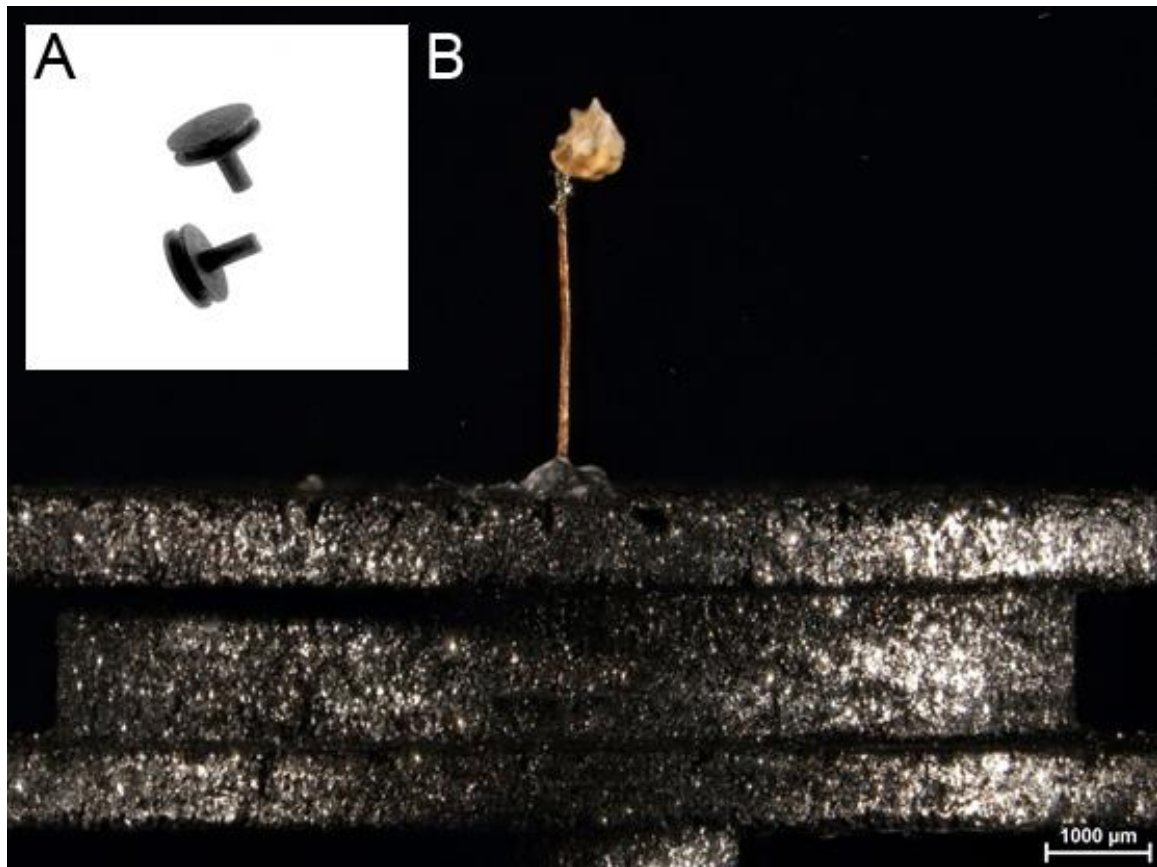
**Figure 17: A conventional SEM image of foraminifera involves taking three images with different views of the same specimen (images from Brian T. Huber).**

Microcomputer tomography (micro-CT) technology is employed in the 3D imaging of foraminifera (or any other microfossil or very small object). In 3D imaging, both external and internal shell morphologies can be obtained at the same time. The data collected is then processed using photogrammetry software. The result is a 3D image that can be examined by viewing on a computer screen, or printed using a 3D printer.

Descriptions in this chapter were compiled by notes and observations from Holly Little, Scott Whittaker, and the present author. Petruny et al. (2015) presented some preliminary results.

## **Methods**

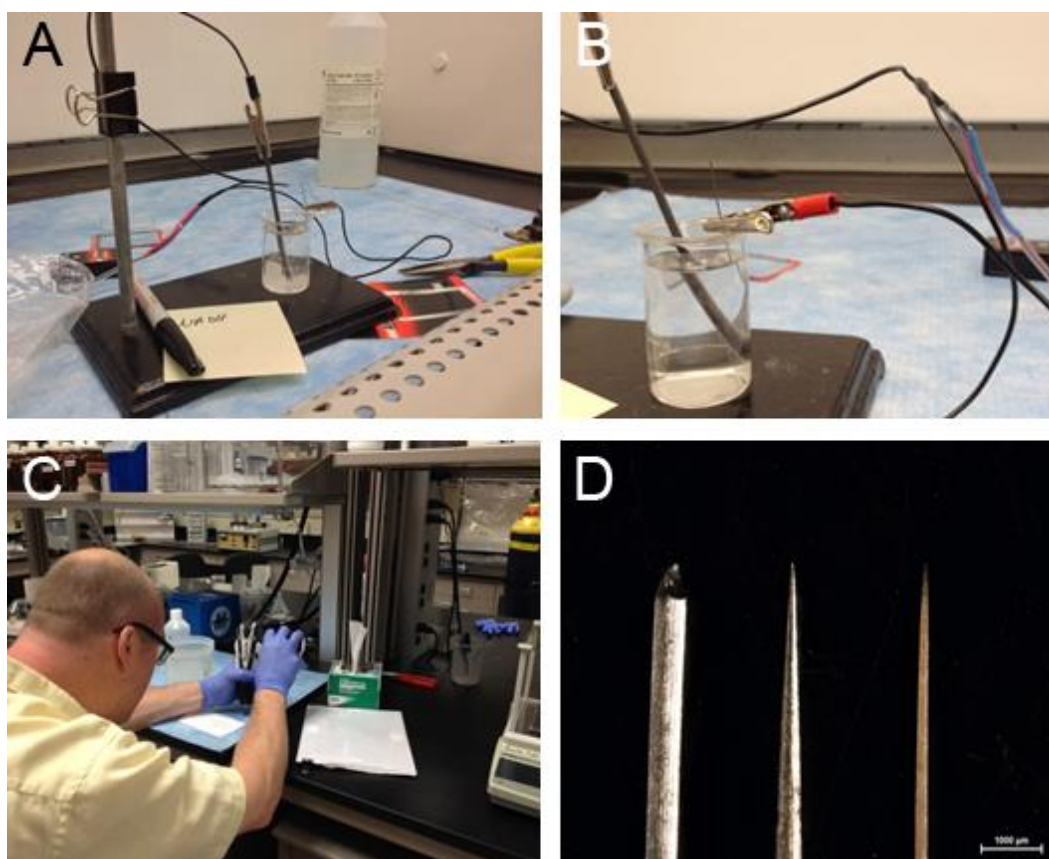
This section presents the methods in much greater detail than previously in the present report. The first step in obtaining a 3D image is specimen mounting. In micro-CT work, a 12-5 mm carbon specimen stub is used for mounting (Figure 18A). The standard carbon stub must be drilled with a small hole in the exact center of the stub's circular top. Tungsten wires, fabricated by Scott Whittaker at the Smithsonian Institution's SEM imaging lab fabricated these drilling wires and fabricated the wire tips needed for drilling the small hole. A cactus needle with the specimen to be subjected to 3D imaging mounted on the tip was inserted through the drilled hole and held out above the surface of the carbon stub (see Figure 18B).



**Figure 18: A) Carbon stubs for specimen mounting (from <http://www.agarscientific.com/carbon-stubs.html>). B) Foraminiferal specimen mounted on the tip of a cactus needle that has been inserted through the carbon SEM stub (lower dark material).**

The tungsten wires had to be modified for the drilling process. The wires were modified by an electrochemical process of erosion of the wire tip. This process involves anodic dissolution of the metal in an aqueous-based solution at a standard redox potential of -2.49 V. The reduction of water forms H<sub>2</sub> bubbles and hydroxide anions (standard oxidation potential of +1.05 V). Etching of the tungsten wire occurred at the air/electrolyte interface when a positive voltage was applied to the wire. The surface of tension produced a meniscus around the wire. The rate of etching at the top of the

meniscus is slower than at the bottom because of a concentration gradient produced by the diffusion of  $\text{OH}^-$  anions to the anode. The part of the tip under the meniscus is normally etched away, but a flow of the denser tungsten oxide, falling down into the solution, protects the end of the tip. Therefore, the rate of the reaction in the lower part of the wire is smaller than the reaction in the meniscus. The etching process conducted by Scott Whittaker consisted of constantly dipping the tungsten wire ( $\sim 0.25$  mm in diameter) in a NaOH (10 ml) electrolytic solution. The counter electrode was a 9V battery. Figure 19 shows key steps in this process.



**Figure 19: Tungsten drilling tip fabrication.** Clockwise: Fabrication set up; sharpening of the tungsten wire through the electrochemical process; carbon SEM stub being drilled with tungsten wire; and tungsten wire, sharpened tungsten wire, and a cactus needle.

Cactus needles used to mount specimens and insert them through the drilled hole in the carbon stub must be as straight as possible so that they hold the specimen at a 90-degree angle to the plane of the top of the carbon stub. This angle is necessary to reduce wobble during rotation. The needles' ends were dipped in a small amount of water-soluble Elmer's Glue-All © and the glued needle tips were steamed for a few seconds. Steamed needles were then used to pick up a single foraminiferal specimen and then the glue was finally allowed to dry. The specimens are not coated or otherwise prepared. This process took about 10 minutes per specimen.

Once the specimen is mounted on the cactus needle above the carbon stub and at a 90-degree angle to the stub (Figure 18B), the next step is to load the mounted specimen into the SEM chamber and start capturing images. The photogrammetric details include: resolution of 3072 x 2304; dwell time of 1.5 minutes; tilt of 45 to 90 degrees; and rotation (ideally 10 degrees, but can be up to a maximum of 25 degrees). Resolution and dwell time were picked to maximize resolution. Tilt and rotation were determined by experimentation. The best results occurred at the tilts and rotations noted previously. The tilt and rotation are dependent upon the surface relief on the specimen. The lower the relief, the smaller the required amount of rotation and fewer ranges of tilt are needed.

The machine used was a Zeiss Evo MA 15 at the Smithsonian Institution's SEM Imaging Laboratory. The machine scan speed was set at 8, which was best for noise-free images. Ideally, we would obtain three views of every point on the specimen, which typically required tilt steps at 45, 65, and 90 degrees. The 65-degree step was necessary also for the image stitching process, discussed below. After the first imaging session for each specimen, the specimen was removed, flipped, and re-mounted. Then, the specimen was imaged from the opposite side. The final 3D image was a derivative of all these images from one specimen as obtained from photogrammetric software (Figure 20).

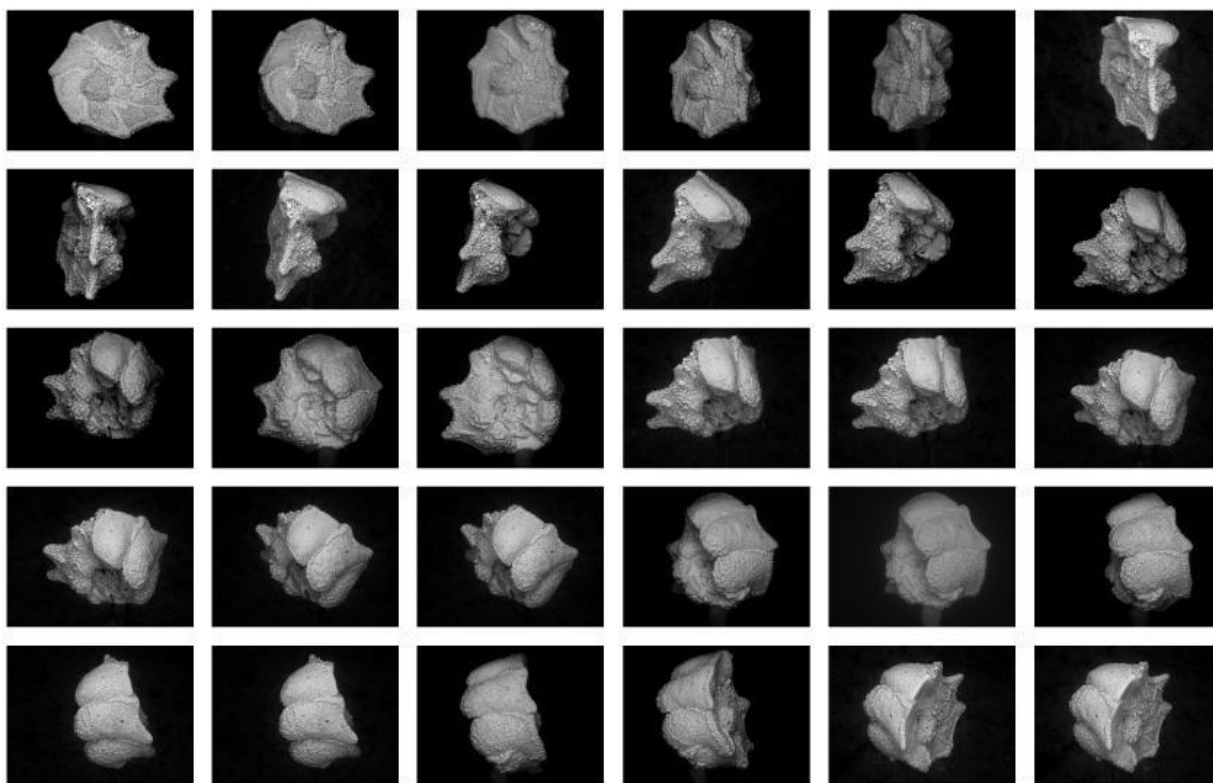


Figure 20: SEM images obtained during one hour of imaging time. The final 3D computer model will be a derivative of these images from one specimen. Foraminifer imaged – *Radotruncana calcarata*.

Two photogrammetric processing programs were used in this work. Autodesk Recap 360 is a cloud-based program and Agisoft is desktop software (Figure 21). In Autodesk Recap 360, having 20 images results in the best end product. Agisoft analyses and compares the input images in order to triangulate each pixel and form them into a point cloud. In Figure 21B, each blue rectangle represents the camera position for each image.

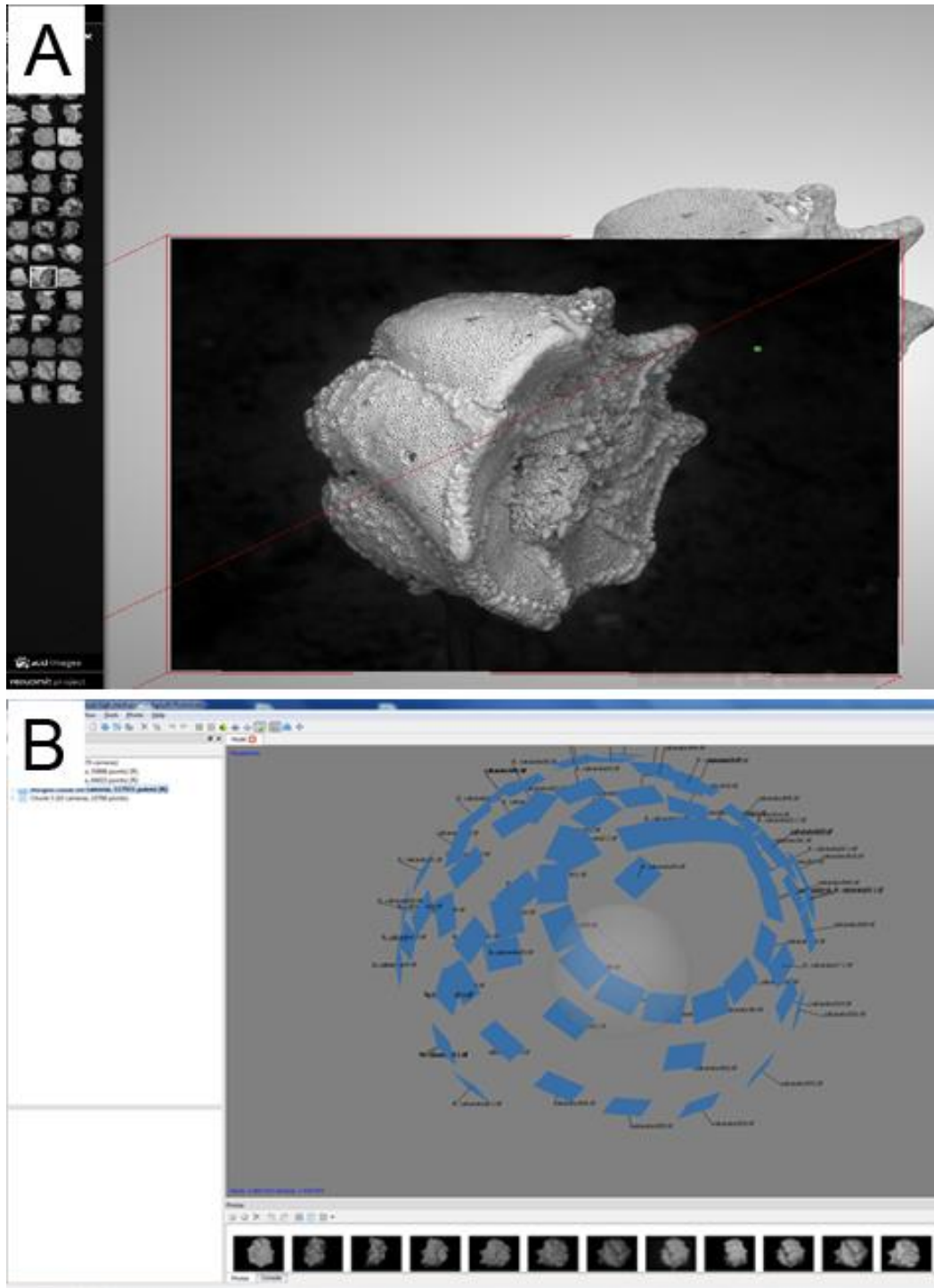
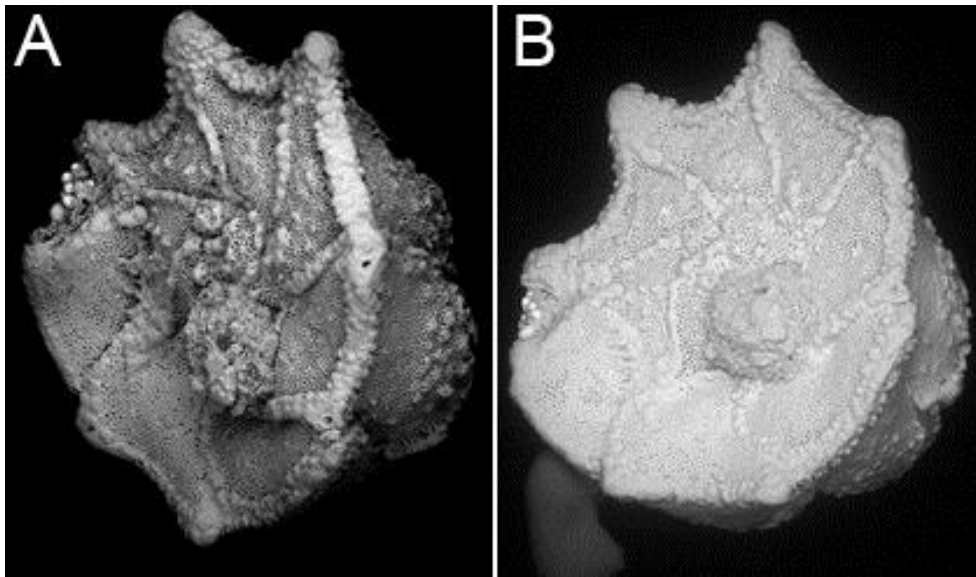


Figure 21: A) Compiled 3D image from Autodesk Recap 360. B) Agisoft 3D rendering; each blue rectangle represents the camera position for each image. Specimen is *Radotruncana calcarata*.

Contrast and brightness are variables that need to be set in each instance to get the best results (Figure 22). During the imaging process, it is important to continually assess how the camera and the SEM are collecting the data for the image, and then re-assess the contrast and brightness settings.



**Figure 22: Examples of the effects of contrast (left) versus brightness (right) for the same 3D specimen (*Radotruncana calcarata*).**

When the specimen is flipped (to image the other side or to acquire missing data from a previous session) scale issues can arise. In some instances, the surface models of the specimen do not emerge from the software at the same scale. In order to work around this problem, surface models at different scales were imported into Geomagic ®, a program that can reduce the scale differences to nearly zero. This work requires

choosing a minimum of three similar points, which is usually not a problem with the specimens because of the high level of surface detail in the images.

## **Applications**

The 3D imaging done for the present study shows that there is substantial value in research, publishing, and maintenance of collections of foraminiferal specimens in general. Files created using this method of 3D imaging can be stored, compared, published, and 3D printed. The materials used in 3D printers that yield good results for such specimens are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Being able to hold a greatly enlarged specimen of 3D printed foraminifera is a great breakthrough for research, teaching, and outreach.

## **CHAPTER FIVE: DISCUSSION**

### **Imagery**

As suggested by the present study, the potential uses for 3D imagery in micropaleontology in general - and foraminiferal paleontology in particular - seem almost limitless. For example, 3D rendering has the potential to transform digital archiving for many aspects of teaching and research for all foraminifera of all geological ages. Once a digital file is rendered, it can be stored, downloaded, printed, and permanently archived. For example, with digital type specimens, a digital file can be shared and the researcher does not have to travel to the museum holding the actual type specimens. Also, any foram can be printed at much larger size for teaching and research purposes. Recent examples of such 3D work include Smith and Straight (2008), Falkingham (2012), and Görög et al. (2012).

### **Biostratigraphic analysis**

Examination of the sedimentology of site 34 drill core presented in Jiménez Berrocoso et al. (2012) shows that the site 34 drill core, between ~ 40 and 100 m depth (the depth span of the comparative counts of taxa in this study), shows no significant change in sedimentary character that would indicate anything other than overall deep-water sedimentation. One expected component of this deep-water sedimentary record is

the episodic input of shelf-derived clastic material, which contains shallow water foraminiferal species. This observation suggests that the influence of shallow-water sourcing of some foraminiferal grains is far more likely than a brief sea-level change (i.e., shallowing) when it comes to explaining the foraminiferal components of the sedimentary record in this drill core. Even so, comparative counts show two identifiable vertical trends in the percentage of biserials and in the count ratio of *Hv. helvetica* to *Hv. praehelvetica*.

One of the main comparative counts of taxa used in this project, namely percent biserials among total planktic species show a substantial peak shift (to slightly over 25%) within the interval 62 to 68 meters depth interval (specifically within the sample from that interval, which was taken at 62.87 m below top of core; see Figure 6**Error! Reference source not found.** in the Results chapter). This depth is near the only negative shift in both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values from among the specimens analyzed for the present study (see Geochemistry section below). As with intermediate counts at several depths in the present study, there is no corresponding isotopic shift and no change in other comparative counts. The high value at 62.87 m could relate to sediment provenance (i.e., sediment transported from more shallow water settings). This seems more likely than actual sea level change within the basin or globally.

In another comparative count, the ratio of *Hv. helvetica* to *Hv. praehelvetica* is generally low in the lower part of the section in the present study, but rises sharply at a depth of 62.87 m (see

Figure 7 in the Results chapter). The values are generally much higher in samples examined above 62.87 m. Jiménez Berrocoso et al. (2012) suggests that the base of the

*Hv. helvetica* Biozone (as noted by Jiménez Berrocoso et al., 2012; their Figure 13) is much lower. They suggest a base of this biozone at between 14 and 15 m in the site 34 core, but the rise in counts suggests this base is much lower, actually somewhere slightly below the sample depth of 62.87 m.

Planktic-benthic (P/B) ratios fluctuate from significantly high-to-low over spans of about 5 to 15 meters between ~40 and 100 m depth in the drill core (see Figure 9 in the Results chapter). This fluctuation is not consistent with previous findings from adjacent Tanzanian drill cores, which showed more or less constant P/B ratios, which were interpreted to mean consistent deep water environments in this part of the Tanzanian section (Wendler et al., 2013). The P/B ratio determined here is below 50 in four depth levels (Figure 9), and one of those is the 62-68 m interval (sample depth 62.87 m) discussed above. The fluctuation of P/B ratios over relatively short vertical distances in a sedimentary section, noteworthy for its lack of sedimentologic diversity and consistent deep-water character, suggests that foraminiferal provenance is the changing variable and that shallow water foraminifera are episodically coming into the deep-water sedimentary environment. Given Jiménez Berrocoso et al.'s (2012) description of the drill core, episodic sea-level fluctuations are not feasible in this instance. Alternatively, others have suggested that the influence of benthic foraminifera influence can strongly affect the P/B ratio in otherwise seemingly monotonous deep-water facies (van der Zwaan et al., 1990).

## **Stable isotopic analysis**

Reporting the bulk-rock geochemistry of site 34 and others, Jiménez Berrocoso et al. (2012) showed that there are several, relatively major negative excursions in  $\delta^{13}\text{C}_{\text{carb}}$  (ranging from -4 to -10.6), over the span between 25 and 100 m depth, in the site 34 drill core examined here. These excursions occur at depths of 32.3, 44.75, 46.25, 66.18, and 70.85 m. Jiménez Berrocoso et al. (2012) dismiss these excursions as being related to carbonate diagenesis, mainly cementation. However, as shown in their data, only the  $\delta^{13}\text{C}_{\text{carb}}$  excursion at 32.3 coincides with a high percentage of carbonate in the drill core (see their Figure 13).

In the present study, at 66.18 m, both foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  have noteworthy negative values from individual species that stand out from the others within the depth span of  $\sim 8$  to 100 in the site 34 drill core (see Figure 11 and 12 in the Results chapter). These negative values at 66.18 m affect all or nearly all species studied and are independent for the most part from variations in test mass. This isotopic shift coincides with the suggested new base of the *Hv. helvetica* Biozone (see above).

The coincidence of the  $\delta^{13}\text{C}_{\text{carb}}$  peak at 66.18 m, with the observed negative shift in  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  among species studied here, suggests that the data are related to the same excursion event, based on bulk sediment analysis done by Jiménez Berrocoso et al. (2012). No other samples studied in the present study have depths that exactly match the other excursion levels of Jiménez Berrocoso et al. (2012), so it is not known if these excursions would have been replicated in this work, as is noted at 66.18 m. One way to test this hypothesis in the future would be to obtain samples from the site 34 drill core that exactly match the depths of the bulk sediment-based excursions, and conduct  $\delta^{13}\text{C}$

and  $\delta^{18}\text{O}$  analyses upon them, to see if they have similar  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopic characteristics to the sample from 66.18 m.

Regarding the  $\delta^{13}\text{C}$  versus  $\delta^{18}\text{O}$  cross plots (Figure 13), the group of points on the upper right are planktics, the group of points forming a wider band in the central area are epifaunal benthics, and the group of points on the lower right are benthics (cf. Wendler et al., 2013). There are five anomalous points on the left side of the vertical axis that do not agree with any grouping, and it is unclear what if anything these points mean. A three-fold grouping, as seen here, is generally consistent with the paleobiotic scheme presented by Wendler et al. (2013), who synthesized the results of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopic analyses of numerous species, and nearly 1000 individual specimens.

Results of comparisons between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  and test mass for all specimens, test mass for *Lenticulina* sp., and test mass for *Epistomina* sp., are given in Figure 15 and Figure 16. There is a general horizontal scatter of points within a relatively narrow range of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values for all tests of a wide range of masses. There is some noteworthy vertical scatter among tests with masses of about 75  $\mu\text{g}$ , which may be related to one or two species with common test masses in that range. Regarding *Lenticulina* sp., there is less scatter among points for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ . Regarding *Epistomina* sp., there is a negative correlation between test mass and  $\delta^{18}\text{O}$  and a positive correlation between test mass and  $\delta^{13}\text{C}$ . These findings are generally consistent with previous work by Wendler et al. (2013), and references therein, who examined this issue in more detail, and came to the conclusion that test mass is likely not a strong influence upon  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data.

That said, there are some species-specific trends that may be of note, e.g., with regard to *Lenticulina* sp. and *Epistomina* sp., which may deserve further study.

## CHAPTER SIX: CONCLUSIONS

The section of Tanzanian site 34 drill core that was studied with imagery, biostratigraphic analysis techniques, and geochemistry (isotopic ratios  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ) spans a  $\sim 60$  m interval (approximately -40 to -100 m depth), which is mainly a monotonous deep water clastic deposit. The stratigraphic section contains many beds composed of sediment that was transported from a neighboring shallow shelf. This section of the drill core is entirely within the lower Turonian section. The foraminifers of the studied interval are exquisitely preserved and their imagery, particularly 3D imagery, shows amazing details of preservation. The 3D imagery of these specimens serves as an outstanding example of what can be done with digital archiving of foraminiferal morphologies.

Previous work suggests that there is little variation in this part of the Tanzanian Turonian stratigraphic section with regard to its interpreted deep-water sedimentology, foraminiferal biostratigraphy and related foraminiferal counts, and geochemistry of foraminiferal tests (i.e.,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ). However, this study suggests that there are some noteworthy features that depart from that monotony. For example, at depths of 66.18 and 80.75 m, there are important variations in foraminiferal counts of biserials among total planktic species that range from about 25% to zero, respectively. Other counts of % biserials range between those values and may fluctuate due to input of sediment from the

shallow shelf (not sea-level change). Regarding counts relating to the ratio of *Hv. helvetica* to *Hv. praehelvetica*), a rise in the *Hv. helvetica* count at 62.87 m suggests that the base of that biozone is near or at that level rather than higher as suggested in previous work. Further, over the 60 m interval~ studied, there are noteworthy wide shifts in P/B ratios. These findings suggest that shallow water-derived materials may have moved into deeper water, thus affecting the foraminiferal abundance counts. This is viewed as a simpler explanation rather than rapidly shifting sea-level events during Turonian.

Foraminifera-based  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  measures on selected foraminifer species show that in one instance (depth 66.18 m) there is a shift in values coincident with previously observed bulk-rock  $\delta^{18}\text{O}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{carb}}$  values. The bulk rock values are not related to carbonate diagenesis, therefore the observed foraminiferal excursion at 66.18 m is not interpreted in that way. This excursion appears to be related to a short-lived change in sedimentation, which may be related to influx of shallow water foraminifers being transported into deeper water. The depth of 66.18 m coincides with the observed maximum in biserial counts and is near the newly suggested base of the *Hv. helvetica* Biozone (Figure 23).

The present work suggests that further study of the relationship between shelf-derived sediment input and on-going deep-water sedimentation, and its effects on compositional counts and geochemical analyses, is needed.

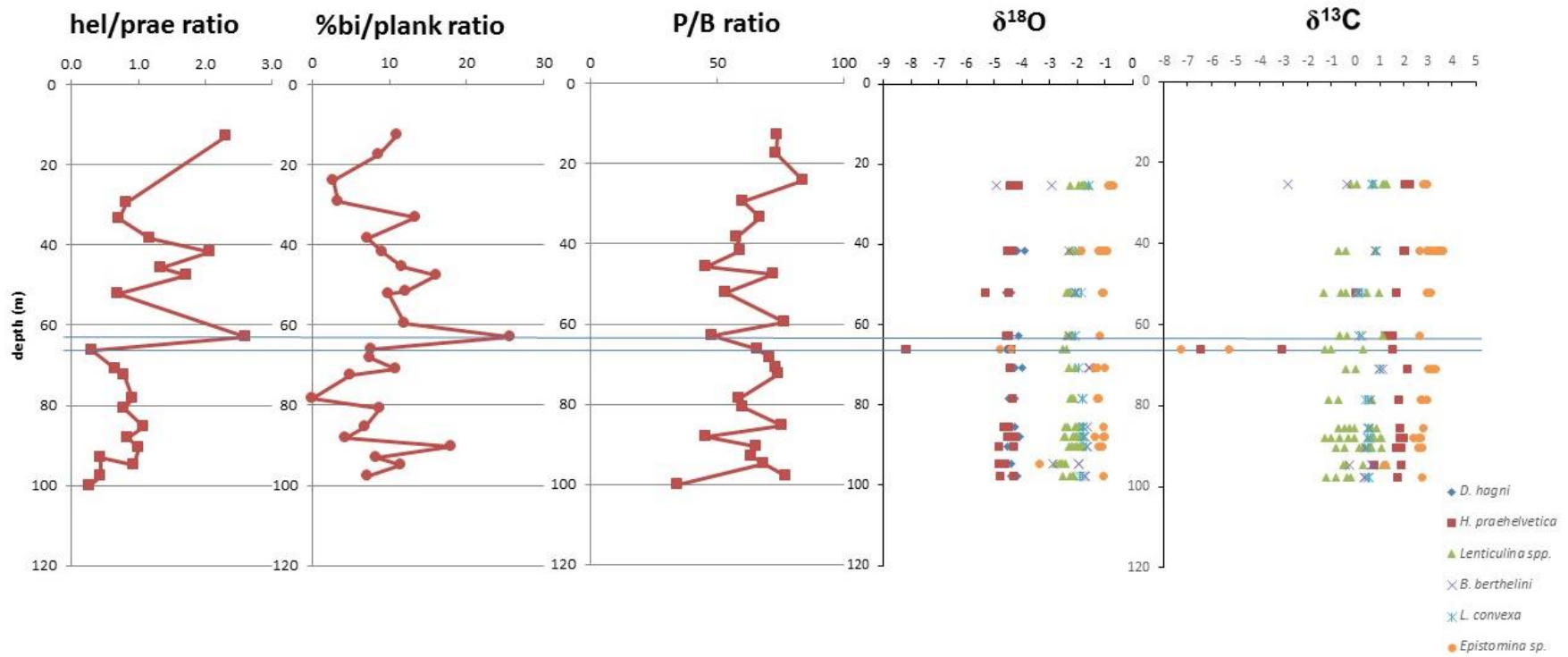


Figure 23: Shown together: cross plots from this study of foraminiferal biostratigraphy and related foraminiferal counts; and geochemistry of foraminiferal tests (i.e.,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ). There are noteworthy wide shifts (note blue horizontal lines, depth 66.18 m) in all ratios plotted. This excursion appears to be related to a short-lived change in sedimentation, which may be related to influx of shallow water foraminifers being transported into deeper water.

## APPENDIX

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**Table 1: Count data for biostratigraphic analysis.**

| TDP site 34 foraminiferal counts |        |          |          |                |          |       |                 |           |            |       |       |                          |              |               |       |        |       |       |        |
|----------------------------------|--------|----------|----------|----------------|----------|-------|-----------------|-----------|------------|-------|-------|--------------------------|--------------|---------------|-------|--------|-------|-------|--------|
| CORE                             | DEPTHS | box/slot | interval | PLANTIC COUNTS |          |       | PLANKTIC COUNTS |           |            | TOTAL | SPLIT | PLANKTICS - GRID NUMBERS |              |               | RATIO | RATIO  | RATIO | RATIO |        |
|                                  |        |          |          | TOTAL          | BISERIAL | OTHER | helvetica       | praehelev | transition |       |       | BENTHIC                  | helvetica    | praehelevetca |       |        |       |       | transi |
| 12.75                            | 6/1    | 7-35cm   |          | 617            | 68       | 549   | 51              | 22        | 0          | 217   | 0     | 25-26                    | 28-29        | na            | 73.98 | 11.021 | 2.318 | 2.318 |        |
| 17.47                            | 8/1    | 27-47 cm |          | 843            | 73       | 775   |                 |           |            | 305   | 1     |                          |              |               | 73.43 | 8.660  |       |       |        |
| 24.04                            | 10/1   | 61-89 cm |          | 1521           | 42       | 1479  |                 |           |            | 291   | 1     |                          |              |               | 83.94 | 2.761  |       |       |        |
| 29.29                            | 12/1   | 6-29 cm  |          | 318            | 11       | 307   | 5               | 6         | 0          | 208   | 4     | 25                       | 27           | na            | 60.46 | 3.459  | 0.833 | 0.833 |        |
| 33.32                            | 14/1   | 0-22cm   |          | 483            | 65       | 418   | 13              | 18        | 0          | 236   | 3     | 29                       | 32-33        | na            | 67.18 | 13.458 | 0.722 | 0.722 |        |
| 38.36                            | 17/1   | 10-36cm  |          | 350            | 25       | 375   | 35              | 30        | 0          | 257   | 4     | 25-27                    | 28-29,31-32  | na            | 57.66 | 7.143  | 1.167 | 1.167 |        |
| 41.65                            | 18/1   | 40-65cm  |          | 349            | 32       | 317   | 31              | 15        | 0          | 238   | 4     | 25-26                    | 27-30        | na            | 59.45 | 9.169  | 2.067 | 2.067 |        |
| 45.61                            | 21/1   | 23-46cm  |          | 60             | 7        | 53    | 4               | 3         | 0          | 71    | 0     | 25                       | 29           | na            | 45.80 | 11.667 | 1.333 | 1.333 |        |
| 47.6                             | 23/1   | 43-69cm  |          | 756            | 122      | 634   | 78              | 45        | 0          | 291   | 2     | 25-29                    | 30-34        | na            | 72.21 | 16.138 | 1.733 | 1.733 |        |
| 51.5                             | 25/1   | 0-20 cm  |          |                |          |       |                 |           |            | 283   | 1     |                          |              |               |       |        |       |       |        |
| 52.08                            | 26/1   | 25-53cm  |          | 190            | 23       | 167   | 9               | 13        | 0          | 167   | 6     | 25                       | 26-27        | na            | 53.22 | 12.105 | 0.692 | 0.692 |        |
| 59.6                             | 29/1   | 18-40cm  |          | 973            | 97       | 876   |                 |           |            | 293   | 0     |                          |              |               | 76.86 | 9.969  |       |       |        |
| 62.87                            | 30/1   | 42-69cm  |          | 257            | 31       | 226   | 26              | 10        | 0          | 277   | 4     | 25-26                    | 29           | na            | 48.13 | 12.062 | 2.600 | 2.600 |        |
| 66.18                            | 31/2   | 0-18cm   |          | 264            | 68       | 196   | 4               | 13        | 0          | 135   | 4     | 25                       | 26-27        | na            | 66.17 | 25.758 | 0.308 | 0.308 |        |
| 68.29                            | 33/1   | 3-22 cm  |          | 484            | 37       | 484   |                 |           |            | 197   | 1     |                          |              |               | 71.07 | 7.645  |       |       |        |
| 70.86                            | 35/2   | 70-91cm  |          | 317            | 24       | 293   | 10              | 15        | 0          | 116   | 4     | 25-26                    | 29-30        | na            | 73.21 | 7.571  | 0.667 | 0.667 |        |
| 72.5                             | 37/1   | 72-95cm  |          | 853            | 93       | 760   | 40              | 51        | 0          | 294   | 1     | 18-19                    | 20-21        | na            | 74.37 | 10.903 | 0.784 | 0.784 |        |
| 78.44                            | 39/2   | 22-44cm  |          | 183            | 9        | 174   | 22              | 24        | 0          | 122   | 4     | 25                       | 27, 29       | na            | 60.00 | 4.918  | 0.917 | 0.917 |        |
| 80.75                            | 40/1   | 55-75cm  |          | 292            | 0        | 292   | 27              | 34        | 0          | 204   | 0     | 26-27                    | 28-31        | na            | 58.87 | 0.000  | 0.794 | 0.794 |        |
| 85.47                            | 41/3   | 26-47cm  |          | 375            | 33       | 342   | 27              | 25        | 0          | 121   | 4     | 25-26                    | 27-28, 30-32 | na            | 75.60 | 8.800  | 1.080 | 1.080 |        |
| 88                               | 42/2   | 79-100cm |          | 347            | 24       | 323   | 54              | 64        | 0          | 410   | 3     | 26-28                    | 30-33        | na            | 45.84 | 6.916  | 0.844 | 0.844 |        |
| 90.45                            | 43/2   | 19-40cm  |          | 375            | 16       | 359   | 29              | 29        | 0          | 199   | 3     | 27                       | 29-32        | na            | 65.33 | 4.267  | 1.000 | 1.000 |        |
| 93.05                            | 44/1   | 80-100cm |          | 726            | 131      | 595   | 38              | 41        | 0          | 417   | 1     | 31-33                    | 26-30        | na            | 63.52 | 18.044 | 0.927 | 0.927 |        |
| 94.79                            | 44/3   | 54-74cm  |          | 274            | 23       | 251   | 4               | 9         | 0          | 81    | 5     | 29                       | 30-32        | na            | 77.18 | 8.394  | 0.444 | 0.444 |        |
| 97.8                             | 45/3   | 58-80cm  |          | 218            | 25       | 193   | 7               | 16        | 0          | 100   | 4     | 28-29                    | 25-27        | na            | 68.55 | 11.468 | 0.438 | 0.438 |        |
| 99.98                            | 46/2   | 76-98cm  |          | 168            | 12       | 156   | 7               | 25        | 1          | 317   | 3     | 28                       | 25           | 25            | 34.64 | 7.143  | 0.280 | 1.280 |        |

Table 256: Stable isotopic data for geochemical analysis. Color coded for each taxon.

| Depth<br>Below<br>surface | <i>Lenticulina sp.</i> |                   | <i>B. berthelini</i> |                   | <i>D. hagni</i>   |                   | <i>H. praevelvetica</i> |                   | <i>L. convexa</i> |                   | <i>Epistomina sp.</i> |                   | LMP sample ID                      | $\delta^{13}\text{C}$ | $\delta^{18}\text{O}$ | Depth<br>Below<br>surface |
|---------------------------|------------------------|-------------------|----------------------|-------------------|-------------------|-------------------|-------------------------|-------------------|-------------------|-------------------|-----------------------|-------------------|------------------------------------|-----------------------|-----------------------|---------------------------|
| 25.41                     | 6 <sup>13</sup> C      | 6 <sup>18</sup> O | 6 <sup>13</sup> C    | 6 <sup>18</sup> O | 6 <sup>13</sup> C | 6 <sup>18</sup> O | 6 <sup>13</sup> C       | 6 <sup>18</sup> O | 6 <sup>13</sup> C | 6 <sup>18</sup> O | 6 <sup>13</sup> C     | 6 <sup>18</sup> O | TDP 34:10-3, 2 cm/Epis (1)         | 2.86                  | -0.78                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/Epis (2)         | 2.87                  | -0.80                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/Epis (2)         | 2.83                  | -0.74                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   | 1.76              | -4.41             |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/hagni (1)        | 1.76                  | -4.41                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   | 2.02              | -4.18             |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/hagni (3)        | 2.02                  | -4.18                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   | 1.88              | -4.14             |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/hagni (3)        | 1.88                  | -4.14                 | 25.41                     |
| 25.41                     | 0.77                   | -1.59             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent (1)         | 0.77                  | -1.59                 | 25.41                     |
| 25.41                     | 0.70                   | -1.93             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent (1)         | 0.70                  | -1.93                 | 25.41                     |
| 25.41                     | 0.03                   | -2.25             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent (1)         | 0.03                  | -2.25                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   | 2.10                    | -4.41             |                   |                   |                       |                   | TDP 34:10-3, 2 cm/praelhel (3)     | 2.10                  | -4.41                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   | 2.24                    | -4.39             |                   |                   |                       |                   | TDP 34:10-3, 2 cm/praelhel (3)     | 2.24                  | -4.39                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   | 2.03                    | -4.13             |                   |                   |                       |                   | TDP 34:10-3, 2 cm/praelhel (4)     | 2.03                  | -4.13                 | 25.41                     |
| 25.41                     |                        |                   | 2.82                 | -4.92             |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/berth (4)        | 2.82                  | -4.92                 | 25.41                     |
| 25.41                     |                        |                   | 0.34                 | 2.91              |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/berth (4)        | 0.34                  | 2.91                  | 25.41                     |
| 25.41                     | 0.22                   | -1.96             |                      |                   |                   |                   |                         |                   | 0.65              | -1.57             |                       |                   | TDP 34:10-3, 2 cm/lent (1)         | 0.22                  | -1.96                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   |                         |                   | 0.70              | -1.58             |                       |                   | TDP 34:10-3, 2 cm/convexa (15)     | 0.70                  | -1.58                 | 25.41                     |
| 25.41                     | 1.14                   | -1.84             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent A frags     | 1.14                  | -1.84                 | 25.41                     |
| 25.41                     | 1.17                   | -1.70             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent A frags     | 1.17                  | -1.70                 | 25.41                     |
| 25.41                     | 1.26                   | -1.78             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent A frags     | 1.26                  | -1.78                 | 25.41                     |
| 25.41                     | 1.26                   | -1.76             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent A frags     | 1.26                  | -1.76                 | 25.41                     |
| 25.41                     | 1.26                   | -1.79             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:10-3, 2 cm/lent A frags     | 1.26                  | -1.79                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 2.91                  | -0.69             | TDP 34:10-3, 2 cm/Epis (2) 72 ug   | 2.91                  | -0.69                 | 25.41                     |
| 25.41                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 2.97                  | -0.89             | TDP 34:10-3, 2 cm/Epis (2) 42 ug   | 2.97                  | -0.89                 | 25.41                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.63                  | -0.91             | TDP 34:18-1, 40-65 cm/Epis (1)     | 3.63                  | -0.91                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.02                  | -1.18             | TDP 34:18-1, 40-65 cm/Epis (1)     | 3.02                  | -1.18                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.10                  | -1.23             | TDP 34:18-1, 40-65 cm/Epis (1)     | 3.10                  | -1.23                 | 41.65                     |
| 41.65                     | 0.72                   | -2.29             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:18-1, 40-65 cm/lent (6)     | 0.72                  | -2.29                 | 41.65                     |
| 41.65                     | 0.44                   | -2.22             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:18-1, 40 cm/lent (4)        | 0.44                  | -2.22                 | 41.65                     |
| 41.65                     |                        |                   | 0.80                 | 2.28              |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:18-1, 40 cm/berth (7)       | 0.80                  | 2.28                  | 41.65                     |
| 41.65                     | 0.82                   | -2.07             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:18-1, 40 cm/lent (1)        | 0.82                  | -2.07                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   | 0.88              | -1.93             |                       |                   | TDP 34:18-1, 40 cm/convex (30)     | 0.88                  | -1.93                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   | 1.48              | -3.91             |                         |                   |                   |                   |                       |                   | TDP 34:18-1, 40 cm/hagni (2)       | 1.48                  | -3.91                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   | 1.63              | -4.18             |                         |                   |                   |                   |                       |                   | TDP 34:18-1, 40 cm/hagni (2)       | 1.63                  | -4.18                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   | 2.00                    | -4.36             |                   |                   |                       |                   | TDP 34:18-1, 40 cm/praelhel (4)    | 2.00                  | -4.36                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   | 2.05                    | -4.50             |                   |                   |                       |                   | TDP 34:18-1, 40 cm/praelhel (4)    | 2.05                  | -4.50                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 2.66                  | -1.84             | TDP 34:18-1, 40 cm/Epis A frags    | 2.66                  | -1.84                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 2.96                  | -1.08             | TDP 34:18-1, 40 cm/Epis (1) 119 ug | 2.96                  | -1.08                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.02                  | -1.15             | TDP 34:18-1, 40 cm/Epis (1)        | 3.02                  | -1.15                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.04                  | -1.04             | TDP 34:18-1, 40 cm/Epis (1) 121 ug | 3.04                  | -1.04                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.24                  | -1.06             | TDP 34:18-1, 40 cm/Epis B frags    | 3.24                  | -1.06                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.28                  | -1.04             | TDP 34:18-1, 40 cm/Epis B orig     | 3.28                  | -1.04                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.46                  | -1.19             | TDP 34:18-1, 40 cm/Epis A frags    | 3.46                  | -1.19                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.47                  | -1.14             | TDP 34:18-1, 40 cm/Epis (1) 159 ug | 3.47                  | -1.14                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.49                  | -1.15             | TDP 34:18-1, 40 cm/Epis A frags    | 3.49                  | -1.15                 | 41.65                     |
| 41.65                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.56                  | -0.96             | TDP 34:18-1, 40 cm/Epis A frags    | 3.56                  | -0.96                 | 41.65                     |
| 52.03                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 2.98                  | -1.07             | TDP 34:26-1, 25 cm/Epis (6)        | 2.98                  | -1.07                 | 52.03                     |
| 52.03                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.13                  | -1.07             | TDP 34:26-1, 25 cm/Epis (7)        | 3.13                  | -1.07                 | 52.03                     |
| 52.03                     |                        |                   |                      |                   | 1.64              | -4.38             |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/hagni (2)       | 1.64                  | -4.38                 | 52.03                     |
| 52.03                     |                        |                   |                      |                   | 1.75              | -4.58             |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/hagni (3)       | 1.75                  | -4.58                 | 52.03                     |
| 52.03                     | 0.99                   | -2.09             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/lent (1)        | 0.99                  | -2.09                 | 52.03                     |
| 52.03                     | 0.48                   | -2.09             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/lent (1)        | 0.48                  | -2.09                 | 52.03                     |
| 52.03                     | 0.86                   | -2.35             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/lent (1)        | 0.86                  | -2.35                 | 52.03                     |
| 52.03                     |                        |                   |                      |                   |                   |                   | 0.01                    | -5.30             |                   |                   |                       |                   | TDP 34:26-1, 25 cm/praelhel (2)    | 0.01                  | -5.30                 | 52.03                     |
| 52.03                     |                        |                   |                      |                   |                   |                   | 1.69                    | -4.48             |                   |                   |                       |                   | TDP 34:26-1, 25 cm/praelhel (3)    | 1.69                  | -4.48                 | 52.03                     |
| 52.08                     | 1.32                   | -2.24             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/lent (3) 18 ug  | 1.32                  | -2.24                 | 52.08                     |
| 52.08                     | 0.61                   | -2.39             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/lent A frags    | 0.61                  | -2.39                 | 52.08                     |
| 52.08                     | 0.39                   | -2.38             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/lent (1) 28 ug  | 0.39                  | -2.38                 | 52.08                     |
| 52.08                     |                        |                   |                      |                   |                   |                   |                         |                   | 0.03              | -2.08             |                       |                   | TDP 34:26-1, 25 cm/convex (15)     | 0.03                  | -2.08                 | 52.08                     |
| 52.08                     |                        |                   | 0.19                 | -2.09             |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/berth (10)      | 0.19                  | -2.09                 | 52.08                     |
| 52.08                     |                        |                   | 0.13                 | -2.01             |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:26-1, 25 cm/berth (10)      | 0.13                  | -2.01                 | 52.08                     |
| 52.08                     |                        |                   |                      |                   |                   |                   |                         |                   | 0.25              | -1.86             |                       |                   | TDP 34:26-1, 25 cm/convex (15)     | 0.25                  | -1.86                 | 52.08                     |
| 62.87                     | -0.69                  | -2.25             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:30-1, 42 cm/lent (4)        | -0.69                 | -2.25                 | 62.87                     |
| 62.87                     | -0.69                  | -2.40             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:30-1, 42 cm/lent (1)        | -0.69                 | -2.40                 | 62.87                     |
| 62.87                     | -0.38                  | -2.31             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:30-1, 42 cm/lent (3)        | -0.38                 | -2.31                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   |                   |                   |                         |                   | 0.17              | -2.06             |                       |                   | TDP 34:30-1, 42 cm/convex (17)     | 0.17                  | -2.06                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   |                   |                   |                         |                   | 0.17              | -2.07             |                       |                   | TDP 34:30-1, 42 cm/convex (18)     | 0.17                  | -2.07                 | 62.87                     |
| 62.87                     | 1.12                   | -2.16             |                      |                   | 0.24              | -2.28             |                         |                   |                   |                   |                       |                   | TDP 34:30-1, 42 cm/berth (10)      | 0.24                  | -2.28                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   |                   |                   | 1.12                    | -2.16             |                   |                   |                       |                   | TDP 34:30-1, 42 cm/lent (1)        | 1.12                  | -2.16                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:30-1, 42 cm/praelhel (1)    | 1.12                  | -2.16                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   | 1.36              | -4.11             |                         |                   |                   |                   |                       |                   | TDP 34:30-1, 42 cm/hagni (3)       | 1.36                  | -4.11                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   | 1.46              | -4.44             |                         |                   |                   |                   |                       |                   | TDP 34:30-1, 42 cm/hagni (3)       | 1.46                  | -4.44                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   |                   |                   | 1.55                    | -4.57             |                   |                   |                       |                   | TDP 34:30-1, 42 cm/praelhel (3)    | 1.55                  | -4.57                 | 62.87                     |
| 62.87                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 2.66                  | -1.17             | TDP 34:30-1, 42 cm/Epis (10)       | 2.66                  | -1.17                 | 62.87                     |
| 66.18                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 7.25                  | -4.79             | TDP 34:31-2, 0 cm/Epis (2)         | 7.25                  | -4.79                 | 66.18                     |
| 66.18                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 5.30                  | -4.37             | TDP 34:31-2, 0 cm/Epis (3)         | 5.30                  | -4.37                 | 66.18                     |
| 66.18                     |                        |                   |                      |                   | 1.83              | -4.58             |                         |                   |                   |                   |                       |                   | TDP 34:31-2, 0 cm/hagni (6)        | 1.83                  | -4.58                 | 66.18                     |
| 66.18                     | 0.29                   | -2.39             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:31-2, 0 cm/lent (1)         | 0.29                  | -2.39                 | 66.18                     |
| 66.18                     | -1.27                  | -2.52             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:31-2, 0 cm/lent (5)         | -1.27                 | -2.52                 | 66.18                     |
| 66.18                     | -1.03                  | -2.50             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:31-2, 0 cm/lent (5) sz      | -1.03                 | -2.50                 | 66.18                     |
| 66.18                     |                        |                   |                      |                   |                   |                   | 4.46                    | -8.23             |                   |                   |                       |                   | TDP 34:31-2, 0 cm/praelhel (2)     | 4.46                  | -8.23                 | 66.18                     |
| 66.18                     |                        |                   |                      |                   |                   |                   | 3.05                    | -8.15             |                   |                   |                       |                   | TDP 34:31-2, 0 cm/praelhel (3)     | 3.05                  | -8.15                 | 66.18                     |
| 66.18                     |                        |                   |                      |                   |                   |                   | 1.52                    | -4.40             |                   |                   |                       |                   | TDP 34:31-2, 0 cm/praelhel (3)     | 1.52                  | -4.40                 | 66.18                     |
| 70.86                     |                        |                   | 1.12                 | -1.58             |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:35-2, 70 cm/berth (7)       | 1.12                  | -1.58                 | 70.86                     |
| 70.86                     |                        |                   | 0.99                 | -1.55             |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:35-2, 70 cm/berth (8)       | 0.99                  | -1.55                 | 70.86                     |
| 70.86                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.02                  | -1.25             | TDP 34:35-2, 70 cm/Epis (4)        | 3.02                  | -1.25                 | 70.86                     |
| 70.86                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.35                  | -0.99             | TDP 34:35-2, 70 cm/Epis (5)        | 3.35                  | -0.99                 | 70.86                     |
| 70.86                     |                        |                   |                      |                   |                   |                   |                         |                   |                   |                   | 3.15                  | -1.37             | TDP 34:35-2, 70 cm/Epis (6)        | 3.15                  | -1.37                 | 70.86                     |
| 70.86                     | -0.02                  | -2.05             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:35-2, 70 cm/lent (10)       | -0.02                 | -2.05                 | 70.86                     |
| 70.86                     | -0.38                  | -2.28             |                      |                   |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:35-2, 70 cm/lent (10)       | -0.38                 | -2.28                 | 70.86                     |
| 70.86                     |                        |                   |                      |                   |                   |                   |                         |                   | 1.05              | -1.92             |                       |                   | TDP 34:35-2, 70 cm/convex (5)      | 1.05                  | -1.92                 | 70.86                     |
| 70.86                     |                        |                   |                      |                   | 1.79              | -3.97             |                         |                   |                   |                   |                       |                   | TDP 34:35-2, 70 cm/hagni (2)       | 1.79                  | -3.97                 | 70.86                     |
| 70.86                     |                        |                   |                      |                   | 1.94              | -4.25             |                         |                   |                   |                   |                       |                   | TDP 34:35-2, 70 cm/hagni (3)       | 1.94                  | -4.25                 | 70.86                     |
| 70.86                     |                        |                   |                      |                   |                   |                   | 2.16                    | -4.41             |                   |                   |                       |                   | TDP 34:35-2, 70 cm/praelhel (5)    | 2.16                  | -4.41                 | 70.86                     |
| 78.44                     |                        |                   | 0.61                 | -1.78             |                   |                   |                         |                   |                   |                   |                       |                   | TDP 34:39-2, 22 cm/berth (15)      | 0.61                  | -1.78                 | 78.44                     |
| 78.44                     |                        |                   |                      |                   |                   |                   |                         |                   | 0.50              | -1.82             |                       |                   | TDP 34:39-2, 22 cm/convex (17)     | 0.50                  | -1.82                 | 78.44                     |

Table 2 (cont'd)

| Depth<br>Below<br>surface | <i>Lenticulina sp.</i> |                       | <i>B. berthelini</i>  |                       | <i>D. hagni</i>       |                       | <i>H. praeaelvetica</i> |                       | <i>L. convexa</i>     |                       | <i>Epistomina sp.</i> |                       | LMP sample ID                       | $\delta^{13}\text{C}$ | $\delta^{18}\text{O}$ | Depth<br>Below<br>surface |  |
|---------------------------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-------------------------------------|-----------------------|-----------------------|---------------------------|--|
| sort1/sort2               | $\delta^{13}\text{C}$  | $\delta^{18}\text{O}$ | $\delta^{13}\text{C}$ | $\delta^{18}\text{O}$ | $\delta^{13}\text{C}$ | $\delta^{18}\text{O}$ | $\delta^{13}\text{C}$   | $\delta^{18}\text{O}$ | $\delta^{13}\text{C}$ | $\delta^{18}\text{O}$ | $\delta^{13}\text{C}$ | $\delta^{18}\text{O}$ |                                     | $\delta^{13}\text{C}$ | $\delta^{18}\text{O}$ | sort1/sort2               |  |
| 85.47                     |                        |                       | 0.55                  | -1.64                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/berth (12)       | 0.55                  | -1.64                 | 85.47                     |  |
| 85.47                     |                        |                       |                       |                       |                       |                       |                         |                       | 0.50                  | -1.77                 |                       |                       | TDP 34-41-3, 26 cm/convex (15)      | 0.50                  | -1.77                 | 85.47                     |  |
| 85.47                     |                        |                       |                       |                       |                       |                       |                         |                       | 0.49                  | -1.82                 |                       |                       | TDP 34-41-3, 26 cm/convex (15)      | 0.49                  | -1.82                 | 85.47                     |  |
| 85.47                     | 0.65                   | -1.91                 |                       |                       | 1.44                  | -4.25                 |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/hagni (5)        | 1.44                  | -4.25                 | 85.47                     |  |
| 85.47                     | 0.56                   | -1.96                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/leat (1)         | 0.65                  | -1.91                 | 85.47                     |  |
| 85.47                     | 0.70                   | -2.34                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/leat (1)         | 0.56                  | -1.96                 | 85.47                     |  |
| 85.47                     | 0.44                   | -2.05                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/leat (1) 49 ug   | -0.70                 | -2.34                 | 85.47                     |  |
| 85.47                     | 0.27                   | -2.44                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/leat (1) 21 ug   | -0.27                 | -2.44                 | 85.47                     |  |
| 85.47                     | 0.06                   | -2.01                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/leat (1) 116 ug  | -0.06                 | -2.01                 | 85.47                     |  |
| 85.47                     | 0.87                   | -1.90                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-41-3, 26 cm/leat (1) 46 ug   | 0.87                  | -1.90                 | 85.47                     |  |
| 85.47                     |                        |                       |                       |                       |                       |                       | 1.85                    | -4.49                 |                       |                       |                       |                       | TDP 34-41-3, 26 cm/praelhel (5)     | 1.85                  | -4.49                 | 85.47                     |  |
| 85.47                     |                        |                       |                       |                       |                       |                       | 1.86                    | -4.63                 |                       |                       |                       |                       | TDP 34-41-3, 26 cm/praelhel (5)     | 1.86                  | -4.63                 | 85.47                     |  |
| 85.47                     |                        |                       |                       |                       |                       |                       |                         |                       |                       |                       | 2.84                  | -1.06                 | TDP 34-41-3, 26 cm/Epis (15)        | 2.84                  | -1.06                 | 85.47                     |  |
| 88                        |                        |                       | 0.52                  | -1.70                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/berth (10)       | 0.52                  | -1.70                 | 88                        |  |
| 88                        |                        |                       |                       |                       |                       |                       |                         |                       | 0.49                  | -1.81                 |                       |                       | TDP 34-42-2, 79 cm/convex (15)      | 0.49                  | -1.81                 | 88                        |  |
| 88                        |                        |                       |                       |                       |                       |                       |                         |                       | 0.62                  | -1.76                 |                       |                       | TDP 34-42-2, 79 cm/convex (15)      | 0.62                  | -1.76                 | 88                        |  |
| 88                        |                        |                       |                       |                       | 1.70                  | -4.08                 |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/hagni (2)        | 1.70                  | -4.08                 | 88                        |  |
| 88                        |                        |                       |                       |                       | 1.77                  | -4.24                 |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/hagni (3)        | 1.77                  | -4.24                 | 88                        |  |
| 88                        | 0.78                   | -1.87                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (1)         | 0.78                  | -1.87                 | 88                        |  |
| 88                        | 1.09                   | -2.08                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (1)         | 1.09                  | -2.08                 | 88                        |  |
| 88                        | 0.52                   | -2.16                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (1)         | 0.52                  | -2.16                 | 88                        |  |
| 88                        | 0.31                   | -2.03                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (2) sz      | -0.31                 | -2.03                 | 88                        |  |
| 88                        | -1.04                  | -2.48                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (3) sz      | -1.04                 | -2.48                 | 88                        |  |
| 88                        | -0.65                  | -2.10                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (4) sz      | -0.65                 | -2.10                 | 88                        |  |
| 88                        | -1.27                  | -2.42                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (1)         | -1.27                 | -2.42                 | 88                        |  |
| 88                        | -0.04                  | -2.03                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (B)fr tran  | -0.04                 | -2.03                 | 88                        |  |
| 88                        | 0.74                   | -1.85                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (B)fr orig  | 0.74                  | -1.85                 | 88                        |  |
| 88                        | 1.02                   | -1.97                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-42-2, 79 cm/leat (A1) MP     | 1.02                  | -1.97                 | 88                        |  |
| 88.00                     |                        |                       |                       |                       |                       |                       | 1.84                    | -4.24                 |                       |                       |                       |                       | TDP 34-42-2, 79 cm/praelhel (4)     | 1.84                  | -4.24                 | 88.00                     |  |
| 88                        |                        |                       |                       |                       |                       |                       | 2.00                    | -4.53                 |                       |                       |                       |                       | TDP 34-42-2, 79 cm/praelhel (3)     | 2.00                  | -4.53                 | 88                        |  |
| 88.00                     |                        |                       |                       |                       |                       |                       |                         |                       |                       |                       | 2.40                  | -1.37                 | TDP 34-42-2, 79 cm/Epis (7)         | 2.40                  | -1.37                 | 88.00                     |  |
| 88                        |                        |                       |                       |                       |                       |                       |                         |                       | 2.63                  | -1.04                 |                       |                       | TDP 34-42-2, 79 cm/Epis (3)         | 2.63                  | -1.04                 | 88                        |  |
| 88                        |                        |                       |                       |                       |                       |                       |                         |                       | 2.74                  | -0.99                 |                       |                       | TDP 34-42-2, 79 cm/Epis (5)         | 2.74                  | -0.99                 | 88                        |  |
| 90.45                     |                        |                       |                       |                       |                       |                       |                         |                       | 2.61                  | -1.24                 |                       |                       | TDP 34-43-2, 19 cm/Epis (7)         | 2.61                  | -1.24                 | 90.45                     |  |
| 90.45                     |                        |                       |                       |                       |                       |                       |                         |                       | 2.78                  | -1.11                 |                       |                       | TDP 34-43-2, 19 cm/Epis (8)         | 2.78                  | -1.11                 | 90.45                     |  |
| 90.45                     |                        |                       |                       |                       | 1.52                  | -4.37                 |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/hagni (2)        | 1.52                  | -4.37                 | 90.45                     |  |
| 90.45                     | 1.09                   | -2.04                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat (1)         | 1.09                  | -2.04                 | 90.45                     |  |
| 90.45                     | 0.67                   | -2.18                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat (1)         | 0.67                  | -2.18                 | 90.45                     |  |
| 90.45                     |                        |                       |                       |                       |                       |                       | 1.71                    | -4.85                 |                       |                       |                       |                       | TDP 34-43-2, 19 cm/praelhel (2)     | 1.71                  | -4.85                 | 90.45                     |  |
| 90.45                     |                        |                       |                       |                       |                       |                       | 1.90                    | -4.28                 |                       |                       |                       |                       | TDP 34-43-2, 19 cm/praelhel (3)     | 1.90                  | -4.28                 | 90.45                     |  |
| 90.45                     | 0.64                   | -2.15                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat (1)         | 0.64                  | -2.15                 | 90.45                     |  |
| 90.45                     | 0.81                   | -2.08                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat (2) sz      | -0.81                 | -2.08                 | 90.45                     |  |
| 90.45                     | 0.48                   | -2.28                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat (3) sz      | -0.48                 | -2.28                 | 90.45                     |  |
| 90.45                     | 0.17                   | -2.00                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat A orig      | 0.17                  | -2.00                 | 90.45                     |  |
| 90.45                     | 0.28                   | -1.87                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat A frags     | 0.28                  | -1.87                 | 90.45                     |  |
| 90.45                     | 0.35                   | -1.82                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat A frags     | 0.35                  | -1.82                 | 90.45                     |  |
| 90.45                     | 0.40                   | -1.87                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat A frags     | 0.40                  | -1.87                 | 90.45                     |  |
| 90.45                     |                        |                       | 0.42                  | -1.63                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/berth (11)       | 0.42                  | -1.63                 | 90.45                     |  |
| 90.45                     |                        |                       |                       |                       |                       |                       |                         |                       | 0.51                  | -1.66                 |                       |                       | TDP 34-43-2, 19 cm/convex (20)      | 0.51                  | -1.66                 | 90.45                     |  |
| 90.45                     | 0.57                   | -1.84                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat B orig      | 0.57                  | -1.84                 | 90.45                     |  |
| 90.45                     | 0.62                   | -1.90                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat B Frag boss | 0.62                  | -1.90                 | 90.45                     |  |
| 90.45                     | 0.62                   | -1.87                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat B frags     | 0.62                  | -1.87                 | 90.45                     |  |
| 90.45                     | 0.64                   | -1.84                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/leat B frags     | 0.64                  | -1.84                 | 90.45                     |  |
| 90.45                     |                        |                       |                       |                       | 1.81                  | -4.53                 |                         |                       |                       |                       |                       |                       | TDP 34-43-2, 19 cm/hagni (3)        | 1.81                  | -4.53                 | 90.45                     |  |
| 94.79                     |                        |                       | 0.25                  | -1.88                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/berth (8)        | 0.25                  | -1.88                 | 94.79                     |  |
| 94.79                     | 0.29                   | -2.50                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/leat (1)         | 0.29                  | -2.50                 | 94.79                     |  |
| 94.79                     | 0.40                   | -2.77                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/leat (1)         | -0.40                 | -2.77                 | 94.79                     |  |
| 94.79                     | 1.12                   | -2.59                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/leat (1)         | 1.12                  | -2.59                 | 94.79                     |  |
| 94.79                     | 0.49                   | -2.56                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/leat (2)         | -0.49                 | -2.56                 | 94.79                     |  |
| 94.79                     |                        |                       | 0.68                  | -1.95                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/berth (4)        | 0.68                  | -1.95                 | 94.79                     |  |
| 94.79                     |                        |                       | 0.72                  | -1.93                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/berth (3)        | 0.72                  | -1.93                 | 94.79                     |  |
| 94.79                     |                        |                       |                       |                       |                       |                       | 0.76                    | -4.61                 |                       |                       |                       |                       | TDP 34-44-3, 54 cm/praelhel (2)     | 0.76                  | -4.61                 | 94.79                     |  |
| 94.79                     |                        |                       |                       |                       |                       |                       |                         |                       |                       |                       | 1.21                  | -3.36                 | TDP 34-44-3, 54 cm/Epis (7)         | 1.21                  | -3.36                 | 94.79                     |  |
| 94.79                     | 1.21                   | -2.64                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/leat (A) rod     | 1.21                  | -2.64                 | 94.79                     |  |
| 94.79                     | 1.28                   | -2.42                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/leat (A) orig    | 1.28                  | -2.42                 | 94.79                     |  |
| 94.79                     | 1.29                   | -2.42                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/leat (A) trans   | 1.29                  | -2.42                 | 94.79                     |  |
| 94.79                     |                        |                       |                       |                       | 1.65                  | -4.39                 |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/hagni (3)        | 1.65                  | -4.39                 | 94.79                     |  |
| 94.79                     |                        |                       |                       |                       | 1.72                  | -4.55                 |                         |                       |                       |                       |                       |                       | TDP 34-44-3, 54 cm/hagni (2)        | 1.72                  | -4.55                 | 94.79                     |  |
| 94.79                     |                        |                       |                       |                       |                       |                       | 1.90                    | -4.84                 |                       |                       |                       |                       | TDP 34-44-3, 54 cm/praelhel (3)     | 1.90                  | -4.84                 | 94.79                     |  |
| 97.8                      | -1.24                  | -2.53                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/leat (4)         | -1.24                 | -2.53                 | 97.8                      |  |
| 97.8                      | 0.82                   | -2.27                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/leat (1)         | -0.82                 | -2.27                 | 97.8                      |  |
| 97.80                     | -0.37                  | -2.13                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/leat (1)         | -0.37                 | -2.13                 | 97.80                     |  |
| 97.80                     | -0.22                  | -2.16                 |                       |                       |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/leat (1)         | -0.22                 | -2.16                 | 97.80                     |  |
| 97.8                      |                        |                       | 0.38                  | -1.69                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/berth (7)        | 0.38                  | -1.69                 | 97.8                      |  |
| 97.8                      |                        |                       | 0.41                  | -1.70                 |                       |                       |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/berth (7)        | 0.41                  | -1.70                 | 97.8                      |  |
| 97.8                      |                        |                       |                       |                       |                       |                       |                         |                       | 0.52                  | -1.79                 |                       |                       | TDP 34-45-3, 58 cm/convex (15)      | 0.52                  | -1.79                 | 97.8                      |  |
| 97.80                     |                        |                       |                       |                       |                       |                       |                         |                       | 0.57                  | -1.89                 |                       |                       | TDP 34-45-3, 58 cm/convex (14)      | 0.57                  | -1.89                 | 97.80                     |  |
| 97.8                      |                        |                       |                       |                       | 1.60                  | -4.37                 |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/hagni (3)        | 1.60                  | -4.37                 | 97.8                      |  |
| 97.8                      |                        |                       |                       |                       |                       |                       | 1.72                    | -4.77                 |                       |                       |                       |                       | TDP 34-45-3, 58 cm/praelhel (2)     | 1.72                  | -4.77                 | 97.8                      |  |
| 97.80                     |                        |                       |                       |                       |                       |                       | 1.76                    | -4.31                 |                       |                       |                       |                       | TDP 34-45-3, 58 cm/praelhel (3)     | 1.76                  | -4.31                 | 97.80                     |  |
| 97.8                      |                        |                       |                       |                       | 1.78                  | -4.17                 |                         |                       |                       |                       |                       |                       | TDP 34-45-3, 58 cm/hagni (3)        | 1.78                  | -4.17                 | 97.8                      |  |
| 97.80                     |                        |                       |                       |                       |                       |                       |                         |                       |                       |                       | 2.78                  | -1.03                 | TDP 34-45-3, 58 cm/Epis (13)        | 2.78                  | -1.03                 | 97.80                     |  |
| Std Dev                   | 0.78                   | 0.25                  | 0.88                  | 0.83                  | 0.17                  | 0.19                  | 1.95                    | 1.06                  | 0.26                  | 0.15                  | 2.17                  | 0.89                  |                                     |                       | 1.57                  | 1.34                      |  |
| Avg                       | 0.15                   | -2.11                 | 0.28                  | -1.98                 | 1.63                  | -4.11                 | 1.20                    | -4.59                 | 0.49                  | -1.72                 | 2.44                  | -1.29                 |                                     |                       | 0.95                  | -2.54                     |  |

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