NORTHERN ILLINOIS UNIVERSITY

The El Nino Southern Oscillation Climate System

University Honors Program

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Department of

Geology

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HONORS THESIS ABSTRACT

The El Nino Southern Oscillation climate system, ENSO, is the largest coherent climate system on Earth. The variability of ENSO effects climate and environmental conditions across the globe, impacting the daily lives of hundreds of millions of people. There has been intensive study on the behavior of this system. While the mechanisms that control ENSO are now largely understood, the variability of these mechanisms is unknown. It is also unknown how ENSO will respond to global warming. Currently there is a void of data on the history of ENSO over the past several thousand years. A comprehensive record of ENSO will provide a deeper understanding of the system and allow scientists to predict how ENSO may change as a result of global warming. My aim is to help fill the gap in history by working with two NIU senior faculty advisors on an integrated project involving archeology and paleoclimate science. I will be developing records of ENSO variability from 2,500 to 3,500 years before present using material from archeological sites on coastal Peru and geochemical analytical methods to reconstruct one of the key elements of ENSO, sea surface temperatures in the eastern equatorial Pacific. This work will benefit climate change research and help develop a body of data suitable for testing theories on ENSO response to global climate change.

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University Honors Program

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Introduction

The El Nino Southern Oscillation, ENSO, is a major climate system on Earth that alters temperatures and rainfall over large parts of the globe affecting hundreds of millions of people worldwide. (Philander, 1990).Understanding its behavior is crucial to adapting to this system. Currently there is a lack of information on the history of ENSO with little known about the activity of this system over the past several thousand years. Without this information it is difficult to predict its variability. It is also unknown how ENSO will react to climate change. The aim of this project is to establish a record of past sea surface temperatures in the eastern equatorial Pacific Ocean for examining ENSO events in order to enhance our understanding of the current ENSO system and also provide insight into the impact of global warming on this climate system. I specifically work on reconstructing past sea surface temperatures in the eastern equatorial Pacific for a time period of 2,500–3,500 years before present. I worked with two faculty advisors from Northern Illinois University: Dr. Paul Loubere of the Department of Geology and Environmental Geosciences, and Dr. Winifred Creamer of the Department of Anthropology on this project.

Background

In the early 19^{th} century scientists found an oddity in pressure fluctuations across the Pacific Ocean. In general a low pressure system persisted in the west and was accompanied by a high pressure system in the east. And that every two to ten years this system flip-flopped such that a high pressure system developed in the western equatorial Pacific and a low pressure system developed in the eastern equatorial Pacific Ocean. Furthermore the changes in pressure contributed to major changes in atmospheric and oceanic conditions that altered temperature and precipitation both in the Pacific and also globally. The pressure system in the equatorial Pacific Ocean was termed the Southern Oscillation (ENSO) by Sir Gilbert Walker, and it has been studied extensively since its discovery.

The Southern Oscillation has two distinct end member states (figure 1, top). The development of a low pressure system over the eastern equatorial Pacific is the El Nino state of ENSO. An El Nino is indicative to a multitude of changes in the equatorial Pacific climate. There is also the La Nina state. A La Nina is the intensification of the normal conditions; there is a stronger stratification of the pressure and climate states across the equatorial Pacific Ocean (figure 1, bottom). This state also incurs climatic changes, however we are mostly interested in measuring El Nino so that my discussion here is centered on El Nino. As a climatic system, ENSO exists in a variety of climatic conditions. Each El Nino and La Nina is different but particularly with El Nino there is an underlying set of characteristics that appear again and again. Currently ENSO oscillates between normal conditions to El Nino like conditions on a variable timescale. It appears that this system may have undergone changes in the past and perhaps even operated on a different timescale (Philander, 1990).

In order to understand what brings about an El Nino state, a discussion of atmospheric circulation in the equatorial Pacific under normal conditions is needed. As mentioned previously a low pressure system operates in the western equatorial Pacific Ocean while a high pressure system exists in the eastern equatorial Pacific Ocean. In the oceans, air converges over warm, low pressure regions. The converging air picks up moisture and is forced upward where it cools and condenses, producing high precipitation. It then travels to areas of high pressure where it sinks depleted of moisture. In the equatorial Pacific there are two major circulation patterns: the Hadley Cell (figure 2) which moves air to higher latitudes and the Walker Circulation which moves air east to west at surface elevations, and west to east at altitude (figure 3). Within the Hadley Cell there is the Intertropical Convergence zone (ITCZ). This portion of the Hadley Cell only comprises the converging and rising air. The convergence centers shift around, strengthen, and weaken throughout the year in response to changes in solar radiation (insolation) associated with changing seasons.

The ITCZ tracks north and south laterally across the equator. During the northern hemisphere summer, when this part of the world receives the most insolation and thus has the warmest water in the Pacific, the ITCZ trends northward. During the northern hemisphere winter the ITCZ trends southward to be position over the warmest water again. Movements of the ITCZ correspond to changes in precipitation patterns for regions in the equatorial Pacific. Central and eastern equatorial Pacific experience maximum rainfall between March and April when the ITCZ is in its southern most position, for most of the rest of the year when the ITCZ is more northward this region is arid (Philander, 1990). The precipitation associated with the ITCZ is kept in a small band that runs from east to west across the Pacific. This band of high precipitation is such that slight changes in the position of the ITCZ produce dramatic changes in precipitation patterns (Philander, 1990).

Another key component of the eastern equatorial atmospheric pattern is the trade winds. The trade winds are a pattern that moves from the east to the west side of the Pacific Ocean. Wind moves from high pressure regions to low pressure regions. This has major implications for the Southern Oscillation since an El Nino state is a change in the distribution of high and low pressure systems across the equatorial Pacific. An El Nino event is associated with major changes in trade wind patterns.

This leads us to a discussion specifically on how an El Nino event is initiated. The development of El Nino is closely tied to sea surface temperatures particularly in the eastern equatorial Pacific Ocean (figure 1). Variations in sea surface temperature are controlled by a number of factors. To list those factors here briefly: variation in trade wind strength which drives a process called upwelling, thermocline depth, and insolation changes. There are multiple feedbacks involved in this system so that a change in one variable results in multiple changes in the system as a whole. Increased sea surface temperatures in the normally cold eastern equatorial Pacific Ocean are indicative of El Nino. It seems reasonable therefore that El Nino is most likely to develop during the Austral summer when the water just south of the equator in the eastern Pacific Ocean is at its warmest. A positive feedback, often referred to as a snowballing effect, can develop. It works such that a change in variable A induces a change in variable B which in turn induces more change in variable A. It is a loop that maximizes the effects of change. More direct sunlight during the summer disperses clouds. Less cloud cover allows more sunlight to reach the surface of the ocean, heating the water which in turn breaks up lower level clouds (Loubere, Creamer, 2009). Thus the heating builds. During the early calendar months the system is in a balancing position where it is apt to go either into an El Nino or fall into a normal weather pattern. The tipping point comes in thermocline depth which is a product of the trade winds and the interaction of waves within the ocean.

The thermocline is a thin layer in the ocean that separates cold bottom water from warm surface water. In the Pacific Ocean this layer is not horizontal. Rather it is tilted such that it tends to be deeper in the western Pacific Ocean and shallower in the eastern Pacific. This is what generates the temperature gradient in sea surface temperatures across the Pacific. The shallower thermocline in the east means that cold bottom water is often brought to the surface but the thermocline is too deep to produce cold water in the west (figure 3). As the trade winds move across the ocean basin from the east to the west, they drag the surface ocean along with. A shallower theromocline in the east means that as the warm surface water is dragged westward with the trades the water is replaced by cold bottom water through a process known as upwelling (figure 5). In the west there is a surplus of warm surface water piling up which drives the thermocline deep. While in general the thermocline is shallower in the east than west, its depth can vary significantly. Furthermore the thermocline is not a one uniform temperature. The upper portion of the thermocline is warmer while the bottom is colder water. If the thermocline is driven deeper in the eastern equatorial Pacific Ocean then the trade winds drag less cold water to the surface via upwelling. This will increase the temperature of the eastern equatorial Pacific. Winds move in response to temperature gradients: the stronger the temperature difference between two areas, the stronger the winds will move. Increasing the temperature in the east means a decrease in the temperature gradient across the Pacific Ocean. In other words the surface temperature of the Pacific Ocean levels off throughout the equatorial portion of the basin. This weakens the trade wind strength. Weaker trade winds thus induce less upwelling furthering the progress of a uniform Pacific Ocean surface temperature, and again another positive feedback system can develop. The system is such that only a momentary increase in the theromocline depth can result in the development of a full scale El Nino event.

Let me summarize some of the climatic conditions associated with El Nino and La Nina states.

		Sea Surface temperature	**Precipitation**	**Trade Wind Strength**	**Upwelling**	**Thermocline depth**
El Nino	East	Warmer	Wet	Weak	Minimized	Deep
	West	Cooler-Normal	Dry	Weak	N/A	Deep
La Nina	East	Colder	Dry	Strong	Maximized	Shallow
	West	Warmer-Normal	Wet	Strong	N/A	Deep

This chart highlights some of the important changes from El Nino to La Nina observed in the equatorial Pacific Ocean. The green highlighted column is simply emphasizing some of the most important aspects of an El Nino. The majority of the action of ENSO occurs in the eastern equatorial Pacific. It is in the eastern equatorial Pacific that an El Nino event is triggered. The changes in the western Pacific are induced by changes in the eastern Pacific.

An El Nino event alters temperature and precipitation patterns in many regions of the world, even regions that are far from the equatorial Pacific. This process is called teleconnections. One quarter of the globe is significantly affected by El Nino events, with tropical and mid-latitudes most affected while higher latitudes less so (noaa, 2007). During an El Nino the eastern equatorial Pacific Ocean warms up thus the convergence centers in the Pacific Ocean form in the east. The ITCZ remains shifted into its southern most position. Also the Walker Circulation spreads out across the basin (figure 3). With a southerly shifted ITCZ and expanded Walker Circulation, rainfall for the eastern equatorial Pacific increases so that the usually arid regions are drenched (Philander, 1990). Essentially the low pressure system that is otherwise confined to the western portion of the equatorial Pacific spreads out across the ocean. El Nino is responsible for heavy rains along west coast of South America in countries such as Peru and Ecuador. From figure 6 it is apparent that an El Nino culminates with year long dry conditions over northern Australia, Indonesia and the Philippines. For part of the year southeastern Africa and northern Brazil also experience dry spells. Indian monsoons may fail to develop during the northern hemisphere summer of an El Nino year impacting agriculture (noaa, 2007; Philander, 1990)

Objectives

In order to understand and predict present ENSO we want to learn more about its past. El Nino is most markedly seen in the eastern equatorial Pacific where sea surface temperatures increase significantly (figure 7). We need a method to track past sea surface temperatures in the eastern equatorial Pacific so that a record of the frequency of El Nino events in the past can be established. We can build that record through the study of a surf clam called *Mesodesma donacium* (figure 8).

I am working with specimen of *Mesdesma donacium* from a time period referred to as the Initial Period which occurred 2,500–3,500 years ago (figure 9). It is thought that El Nino is recorded in lake records as flood deposits in Ecuador, a region inundated by rain during an event. Lake records support a moderate level of El Nino events for the Initial time period (figure 9). I am building a record of sea surface temperatures in order to establish what the El Nino frequency was during the Initial Period. We are also interested in if our results support the data from the lake records. Figure 7 shows in black the normal annual sea surface temperature, and in red the annual sea surface temperature in El Nino. It is clear that the seasonal cycle of sea surface temperature during an El Nino year is significantly affected. It is this departure from normal conditions we are looking for in the shells. We use a variety of analytical and geochemical methods to build our record.

Anthropologic Connection

This project has both geologic and anthropologic aspects. If ENSO has changed, how has that played a role in shaping civilizations living on the coast of Peru? Ancient coastal Peruvians collected shells such as *Mesodesma donacium* for a food source. They also farmed seasonally in the lowlands near streams. This area is arid except for the Austral spring, February to April, when the rainy season occurs. The rainfall that does occur in the spring is dependent on the sea surface temperature off the coast. When the eastern equatorial Pacific is cool there is less evaporation and the atmospheric airflow is strongly away from the continent. Thus a lower sea surface temperature results in less rainfall for the South American coast. If the ocean is warmer there is more evaporation plus the atmospheric circulation tends to move air toward the coast. The air then encounters the Andes and is forced to rise, cool and condense producing rain for the foothills of the Andes.

We have focused in on two time periods: the Archaic Period which occurred 3,500–4,500 years ago, and the Initial Period which occurred 3,500–2,500 years ago. From Ecuadorian lake records ENSO appears to have been muted during the Archaic Period and much more robust during the Initial Period. Excavation sites dating to the Archaic Period display small scale societies with more limited human construction. Peruvians at this time were not producing pottery or loom-woven cloths. The protein source was entirely sea based. Irrigated farming was focused on growing cotton, perhaps to make nets for fishing. This lifestyle persisted for 2 millennia only to end abruptly 5,800–3,500 years before present. This was followed by a gradual move to an economy that emphasized plant and animal domestication along with the production of pottery and woven goods (Sandweiss, 2008). The change in Peruvian society corresponds with the time in which ENSO is thought to have strengthened, making El Nino events more frequent. Perhaps the change in the ENSO system spurred the change in Peruvian civilization.

A complete record of El Nino frequency in the past, coupled with evidence from archeological excavation sites may help uncover why there was such an abrupt change in lifestyle on the Peruvian Coast.

Oxygen Isotopes Ratios

One way to establish past ocean temperature is through comparison of oxygen isotopes in preserved fossil carbonate shells. Most any element in the periodic table has isotopes. Oxygen normally exists with a weight of 16, ^{16}O. In nature however oxygen can have different amounts of neutrons which increase oxygen's weight most commonly to 18, ^{18}O. These two weights of oxygen can be detected.

Most all shelled organisms, including the common Peruvian surf clam *Mesodesma donacium*, build their shells from calcium carbonate which has a chemical formula $CaCO_3$. There is both ^{16}O and ^{18}O in the $CaCO_3$. The abundance ratio of the heavy to the light isotope depends on the temperature at which the clam secreted its shell.

When clams grow in seawater, they intake calcium, Ca, and bicarbonate, HCO_3^-. Bicarbonate exists in the oceans in two forms: a lighter form containing ^{16}O and more rare heavy form containing ^{18}O. The two forms of bicarbonate have different chemical reactivity which is temperature sensitive. The result is that the light and heavy bicarbonate undergo fractionation and are not equally incorporated in the secrete carbonate of the shell. The degree of fractionation is temperature sensitive so that as temperature drops an increasing proportion of the heavy bicarbonate is incorporated. If we compare the ratio of ^{16}O:^{18}O in the shell we can estimate the temperature at which the clam was producing aragonite, and essentially growing.

The process for finding the ^{16}O:^{18}O ratio from the clam is described in the procedure section of this paper. For now I will discuss how we relate that ratio to sea surface temperature. First the ^{18}O:^{16}O ratio of the seawater is determined. That value is compared to a standard ^{18}O:^{16}O ratio:

$$\delta^{18}O = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{seawater}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}}. \tag{1}$$

This equation provides the values of the local seawater isotopic ratio.
From the shell we find $\delta^{18}O_{shell}$. Subtracting the $\delta^{18}O$ values relates the ratios to temperature.

$$T = 17.4 - 3.3(\delta^{18}O_{shell} - \delta^{18}O). \tag{2}$$

The above equation relates a temperature measurement in degrees centigrade to the oxygen isotope ratios we sampled form the clam.

Mesodesma donacium

We will use oxygen isotope measurements from the growth bands of the clam species *M. donaicum*. This species is a surf clam that lives off the coast of Peru with southern most extent of

43°20'S. Modern specimen experience sea surface temperatures ranging from 8° to 26°, and the organism does not migrate (Loubere, Creamer, 2009, ref Tarifeno 1980)

M. donacium records its growth in a series of growth bands along its surface. This species of clam can live up to 10 years. As the clam grows the shell develops a ridging and trough pattern that reflects the temperature of the water the clam was living in. In warmer water the clam's growth is stunted and a ridge pattern results. This literally means that there is a raised surface on the clam's shell. In colder water *M. donacium's* growth is faster and a trough pattern results. As *M. donacium* grows it develops a banding pattern of alternating trough and ridges that record the annual cycle of sea surface temperatures. It is this pattern that can help us build a record of past ocean temperatures with great accuracy. Powdered samples of $CaCO_3$ are obtained by drilling into the shell. The ^{16}O:^{18}O ratio is measured to find a determination of past temperature. We have found that the ratios correspond to the growth patterns. That is we see colder temperatures measured using ratios correspond with trough patterns on the shell. A detailed examination of this process has shown that temperature can be determined with an accuracy of ±1.5°C (Loubere, Creamer, 2009, ref. Carre, 2005).

There are several issues regarding the accuracy of using isotope ratios in *M. donacium* that have been addressed. There was a question that the surface water in the equatorial Pacific Ocean did not have a uniform oxygen isotope ratio value. This was addressed by sampling the water from the beaches where the shells were collected. There are small oxygen isotope differences in different areas. The differences of oxygen isotope values in the sea water rendered an uncertainty of ±0.5°C. This is a small enough error that shells from different beaches can be compared to one another (Loubere, Creamer, 2009).

Another issue of concern was the preservation of shells that are thousands of years old. Due to the dry conditions in Peru, preservation is excellent. Human artifacts such as fabrics and human remains display exceptional preservation. We are confident that trough-ridging pattern of the shell is well preserved (Loubere, Creamer, 2009).

The specimens of *M. donacium* were used as a food source by human civilizations living on the coast of Peru in the past. A concern was that boiling of the shells would alter the isotope ratios preserved in the shells. Boiling of shells was done for a reasonable cooking time of 10-15 minutes. It was found that boiling posed no significant effect on the isotope values in the shell (Loubere, Creamer, 2009).

Modern isotope profiles from *M. donacium* have produced sea surface temperature results that are consistent with what we expect for coastal Peru (Loubere, Creamer 2009).

We have collected and will continue to collect *M. donacium* specimens from coastal Peru. The shells date from 5,000 to 500 years before present. They are commonly found in archeological structures constructed by ancient people living in this region (Loubere, Creamer, 2009). The shells are collected from several time periods: Archaic Period (5000-3800 calendar years before present), Initial Period (3800-2200 calendar years before present), Late Intermediate Period (1000-1475 A.D), and over the last half century. Individually each shell provides sea surface temperature data for 3 to 8 years of time. Analyzing a number of individuals will provide a more complete record of paleo sea surface temperatures. The age of each shell can be determined via radiocarbon dating with an accuracy of ±50 years. We can group shells based on time correlation in order to understand the frequency of El Nino events for a century's worth of time. It is anticipated that a minimum of 20 shells are needed to build sea surface temperature records for one century (Loubere, Creamer, 2009).

Procedure

The first portion of the procedure deals with preparing the shell for drilling of calcium carbonate. The second portion of the procedure outlines how the drilling was conducted. The third part of the procedure discusses the mass spectrometer and how we find oxygen isotope ratio values. Finally the last part of this discussion deals with data processing.

The first step in the process was cutting the shells into thin, cross-sections (figure 10-13). The shells were cut using an 11-1180-160 low speed saw serial number 256-IS-1291 made by Behler LTD. Evanston, Illinois USA. The saw blade was a diamond wafering blade number 11-4254 series 15LC Diamond USA. The saw parameters were 115 volts and 1.5 amperes. The saw speed was 5.

The shells needed to be cut into sections, thus two cuts were made. First the shell was cut lengthwise in such a way as to try and maximum the amount of growth layers in the section. This usually meant cutting the shell at an angle down the longest axes. The cut side of the shell, or in other words the flat side, was then adhered to a glass slide using epoxy glue. The glue dried for at least 24 hours before the second cut was attempted. The second cut was made parallel to the first cut so that the shell on the slide was only a couple millimeters wide.

A magnified image of the clam sections were taken. Pictures were taken using the MiniVID LW Scientific Inc microscope camera: Nikon 67378 Tokyo, Japan, NIU serial #82432. The computer program used to process the images was Scopephoto 2.0.4 (2003-2005). The magnified images were taken in sections using the Scopephoto program and then merged using Adobe photoshop.

The drilling process was done in order to collect powder samples of the calcium carbonate in the clam shell at different points of clam growth. Ideally we will have a drill point for every trough and ridge or essentially two drill points for each year of clam growth. The shells were drilled using Micromill. The powder sample was weighed and then collected in test tubes for analysis in the mass spectrometer. A mark was made at each drill point indicating where every sample came from.

The outer edge of the clam shell was digitized using Engauge Digitizer Version 4.1 (2002) by Mark Mitchell. The x, y coordinates were determined absolutely in centimeters. The magnified image was used to accurately outline the edge of the shell. The digitizing process was a way to digitally record the ridge, trough pattern of the shell. In order to clearly see the trough-ridging pattern on the shell we removed all of the curvature so the shell. We did this by fitting a polynomial to the graphed outline of the shell. We then subtracting the polynomial fit from the graph of the shell. The difference was any point on the shell that deviated from the smooth polynomial fit. This difference represented trough-ridge pattern on the shell's surface. Once the outer surface of the shell was made we could mark the drill points along the shell (see appendix, graphs 1, 3, 5, 7).

NIU's MAT-250 mass spectrometer is an instrument that can measure the isotope ratios of oxygen in carbon dioxide, CO_2, gas. Reacting samples of calcium carbonate from the clams shell with phosphoric acid, H_3PO_4, produces CO_2 gas. That gas is then imbedded into a stream of inert helium gas and transported to the mass spectrometer. Inside the mass spectrometer the gas is first ionized, so that the CO_2 is now charged. It is then placed in an eclectic field where it is focused and accelerated along a tube. The gas passes through a magnetic field where it is bent around a curve. The curved path that the gas follows is proportional to its mass. In this way the heavy CO_2, The CO_2 containing ^{18}O is separated from the light CO_2. Finally the gas collides with electromagnetic plates that have a certain electric potential across them. When the ionized CO_2

particles collide with plates they cause a change in the electric potential across the plates which is recorded by the instrument. The mass spectrometer is sensitive enough to count each molecule of ionized CO_2 individually.

There are three different plates that catch the different masses of carbon dioxide. The plate closest to the outer bend of the curve measures the heaviest weight, and the plate closest to the inner bend of the curve measures the lightest weight. In nature there are three weights of carbon dioxide gas. CO_2 can be composed of ^{12}C, ^{16}O, ^{16}O. With a total mass of 44 this is the lightest variety. CO_2 can also occur in a mixture of ^{13}C, ^{16}O, ^{16}O and have a total mass of 45. Finally CO_2 can be made of ^{12}C, ^{16}O, and ^{18}O. This is the heaviest form with a total mass of 46. All other combinations of CO_2 are so rare or nonexistent in nature such that they can be ignored. Once the software for the mass spectrometer counts the amount of heavy ^{18}O containing CO_2 and lighter ^{16}O versions it finds a ratio of ^{18}O:^{16}O. We compare our ^{18}O:^{16}O from the shell to a reference CO_2 gas that we also run through the machine. The reference CO_2 is pure and contains no water.

The mass spectrometer finds oxygen isotope ratio numbers that are relative to the reference CO_2 gas. We convert these measurements into an internationally recognized scale known as the PDB scale. Along with the samples we also test a reference carbonate called NSB-19 in the mass spectrometer. In this experiment we used 6 reference tubes of varying sizes. We first correct for any amplitude effects in the NBS-19. We can then find the PDB value that correlates to the NBS-19 sample and convert all sample measurements to PDB.

Data

This semester I worked with several shells, four of which I was able to collect viable sample. The shells were labeled BERF5D, BERF5F, BERF8F, and BERF10D. The surface each shell was digitized. The drilling points on the digitized shell was marked. Finally the oxygen isotope values for the shells were graphed. The hypothesis was that a trough pattern on the digitized surface would correspond to higher O-18 values. The clam preferentially uptakes more O-18 from the water during fast growth in cold water. A ridge would correspond to lower values of O-18 indicating the clam was growing in warmer water and in taking less O-18.

Shell number BERF5D afforded the best resolution of oxygen isotope data. This shell was drilled in 14 places along the length of the shell. See appendix graph 1 for the digitized image of the shell with drill points marked. We were able to collect viable sample for each of the 14 drilled locations. The oxygen isotope data is recorded in appendix graph 2. See appendix table 1 for oxygen isotope PDB values.

Shell number BERF5F was also sampled. This shell was drilled in only 8 places. See appendix graph 3 for the digitized image of the shell with the drill points marked. The oxygen isotope data is recorded in graph 4. See appendix table 2 for the oxygen isotope PDB values.

Shell number BERF8D was drilled in 6 places. See appendix graph 5 for the digitized image of the shell with the drill points marked. The oxygen isotope data is recorded in graph 6. See appendix table 3 for the oxygen isotope PDB values.

Finally shell number BERF10D was drilled in 15 places. See appendix graph 7 for the digitized image of the shell with the drill points marked. The oxygen isotope data is recorded in graph 8. See appendix table 4 for the oxygen isotope PDB values.

Results

As of yet the data is inconclusive. I am unable to draw any conclusions regarding the frequency of El Nino events during the Initial Period. Not enough shells were sampled. Also for each shell more oxygen isotope data is needed. Despite this, the data does provide some meaningful information. While similar techniques are employed using other organisms, the process of using *Mesodesma donacium* as a past sea surface temperature indicator has never been done before. The graphs 1-6 in the appendix section outline the relationships between oxygen isotope ratios to the shell morphology (trough-ridge pattern). Some correlation between shell morphology and O-18 levels was present in each shell. Shell BERF10D showed the most correlation between the two graphs. The shells drilled so far from the Initial appear to be showing a more variability in the oxygen isotope values than shells previously drilled from the Archaic. While it is much too early to say, the data thus far provides enough evidence to proceed with this work.

Conclusion

This year we were able to successfully establish a viable procedure for this work. For example I organized a system for digitally recording the shell's surface. This involved finding a program, understanding how to use it, and adapting it to our needs.

This project involves a variety of challenges that had to be overcome. As with any research project, I encountered unforeseen obstacles. However we are beginning to build a substantial record of sea surface temperatures in the east equatorial Pacific for the Initial Period. While my capstone project is concluding, I will continue to collect sample through next year. Our goal is to produce a complete record of ENSO during the Initial and submit a publication.

FIGURES

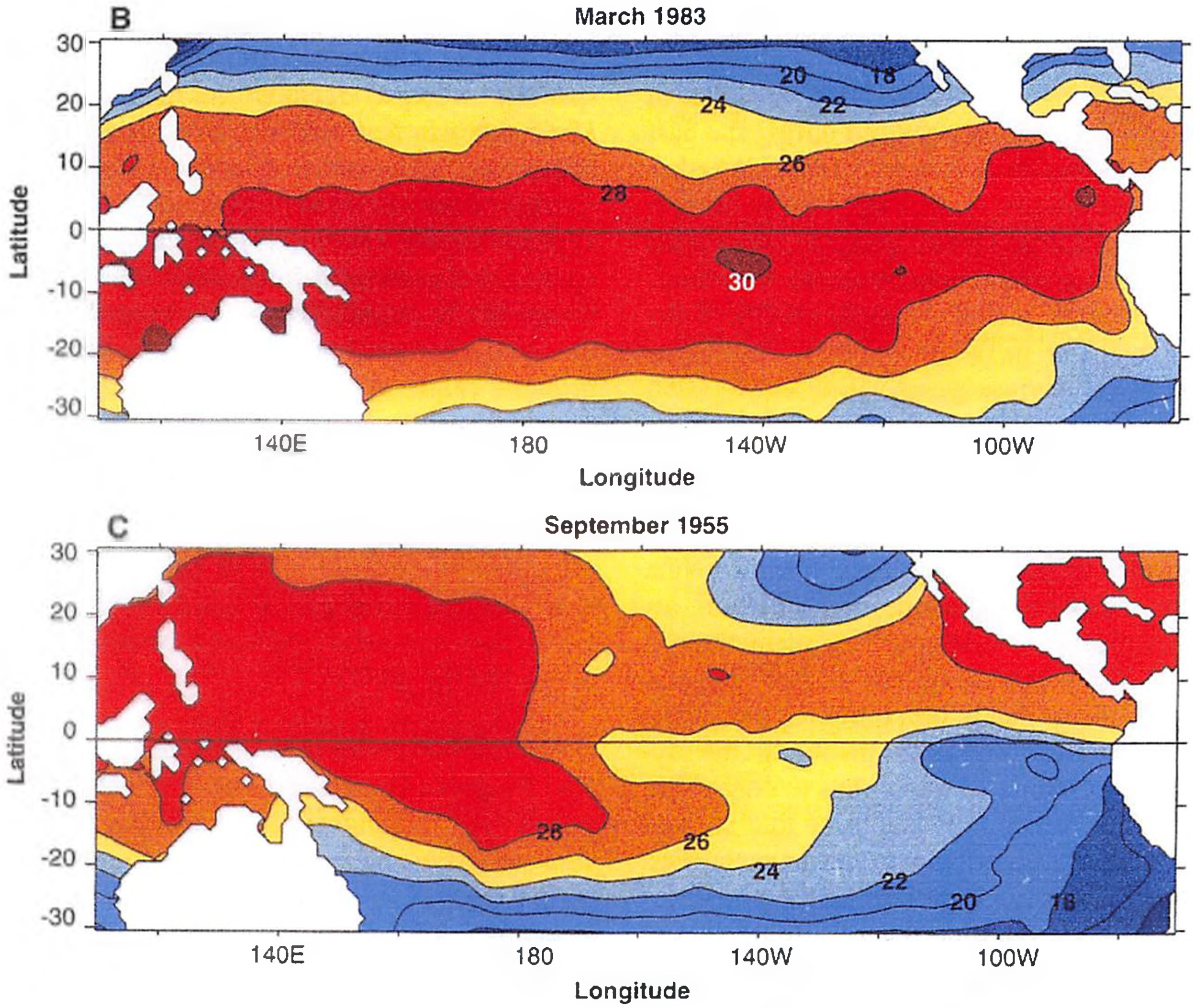


Figure 1: end member states. (Top figure) displays the sea surface temperatures in degrees centigrade across the equatorial Pacific Ocean during an El Nino event. Notice that warm water stretches fully across the basin. (Bottom figure) display sea surface temperatures in degrees centigrade across the Pacific Ocean during a La Nina event. Notice the stratification with cold water in the east and warm water in the west. Source: Federov, A., and Philander, S., 2000, Is El Nino Changing?, Science, v. 288, p. 1997-2002

FIGURES

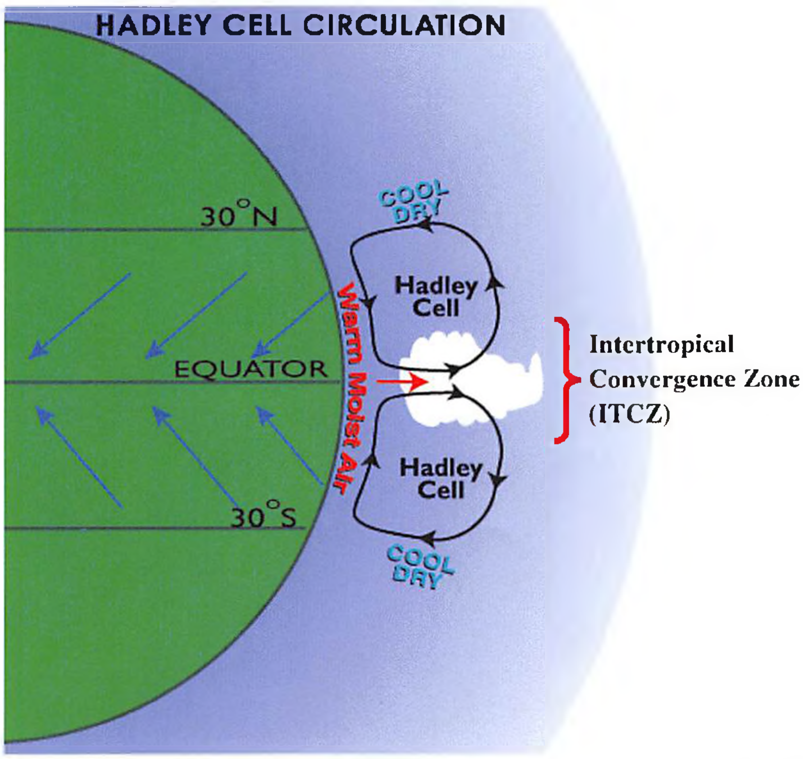


Figure 2. A simplified model of the Hadley Cell. Warm, moist air rises at the equator producing rain. The dried air then moves north and south towards higher latitudes where it cools and sinks at latitude 30°. Source: www.newmediastudio.org

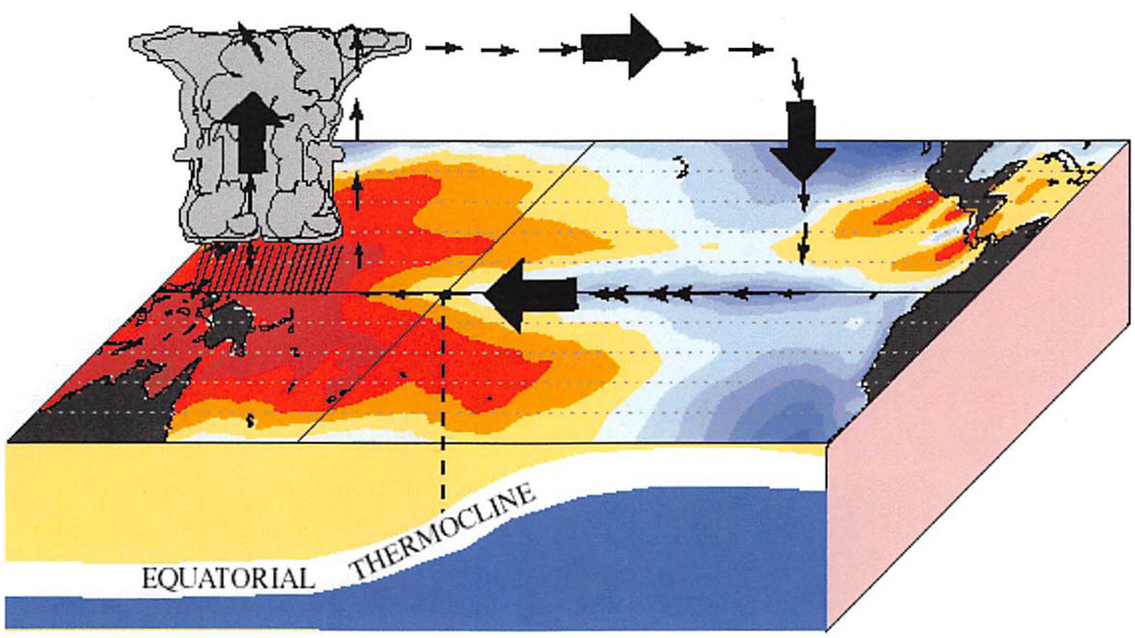


Figure 3: An example of the Walker Circulation moving air across the Pacific Ocean. On the surface air moves east to west. In the upper atmosphere air moves west to east. Thus there is a continual loop of moving air across the basin. Source noaa.gov

FIGURES

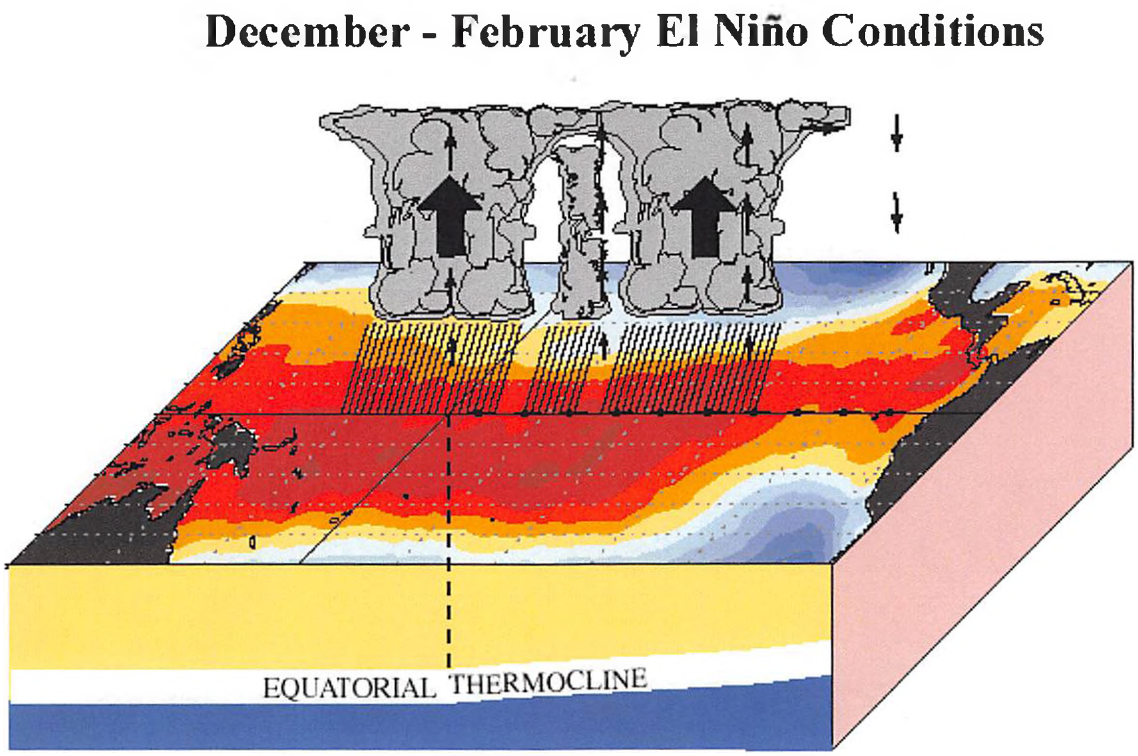


Figure 4: In El Nino the Walker Circulation patter stretches out across the equatorial Pacific as the sea surface temperatures across the basin equalize. This brings rain to the normally dry eastern equatorial pacific. Source noaa.gov

FIGURES

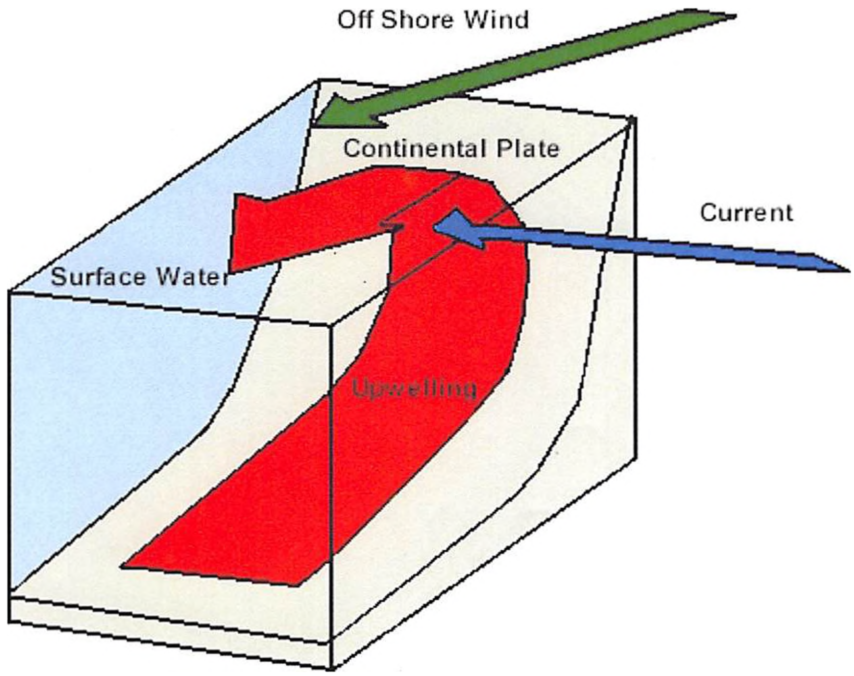
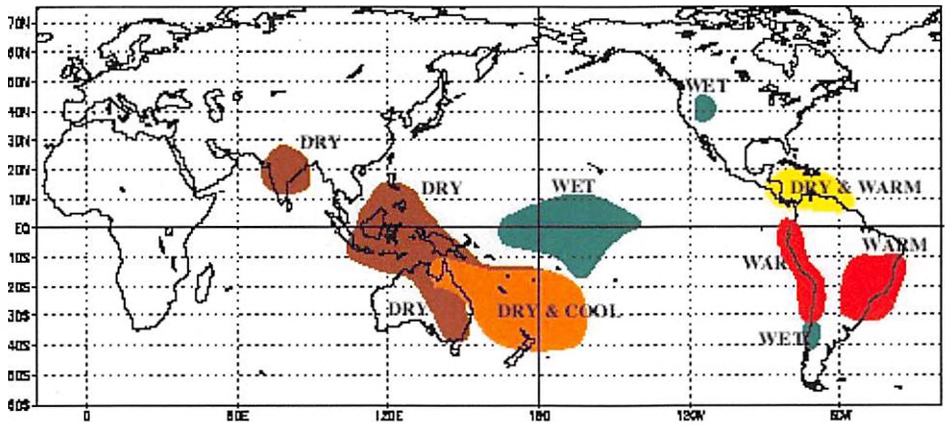


Figure 5. Upwelling is a process by which wind pushes the surface water away from the continent and cold, bottom water rises to the surface to replace the removed surface water. Source: www.galapagosonline.com

FIGURES

WARM EPISODE RELATIONSHIPS JUNE - AUGUST



WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY

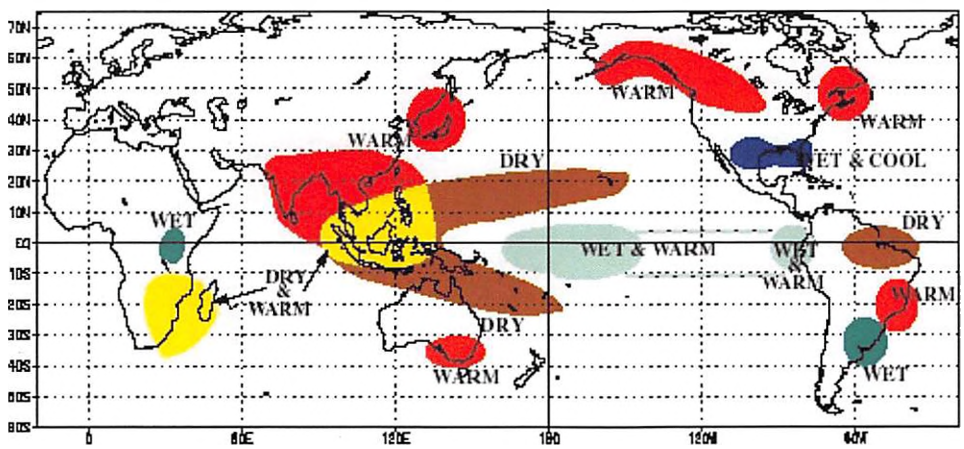


Figure 6. El Nino has a global impact on temperature and precipitation.

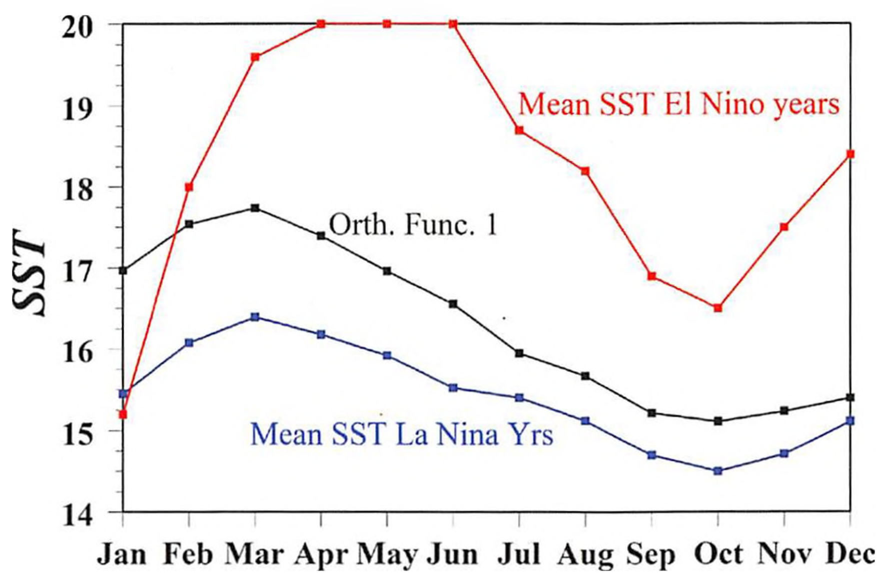


Figure 7. First orthogonal function of annual SST cycle at Callao, compared to mean cycle for El Nino and La Nina years. The black represents normal annual sea surface temperature variation. The red represents El Nino sea surface temperature.

Figure 8. Mesodesma donacium showing surface ridging marking the annual growth cycle.

FIGURES

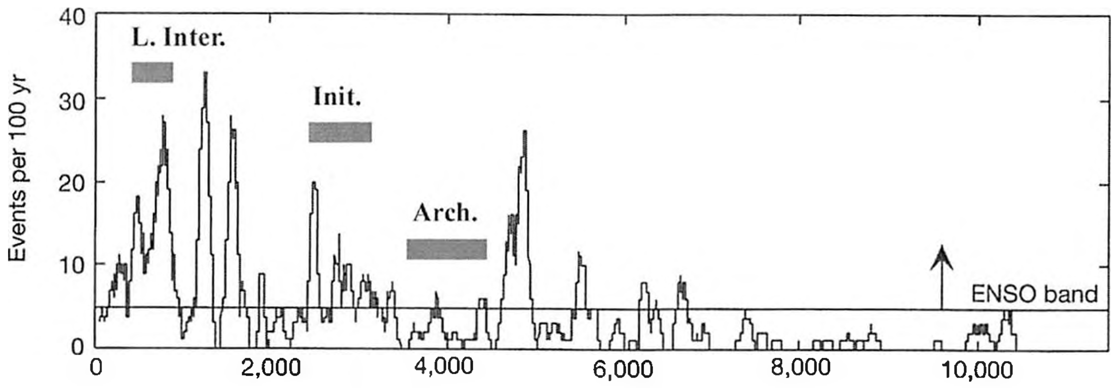
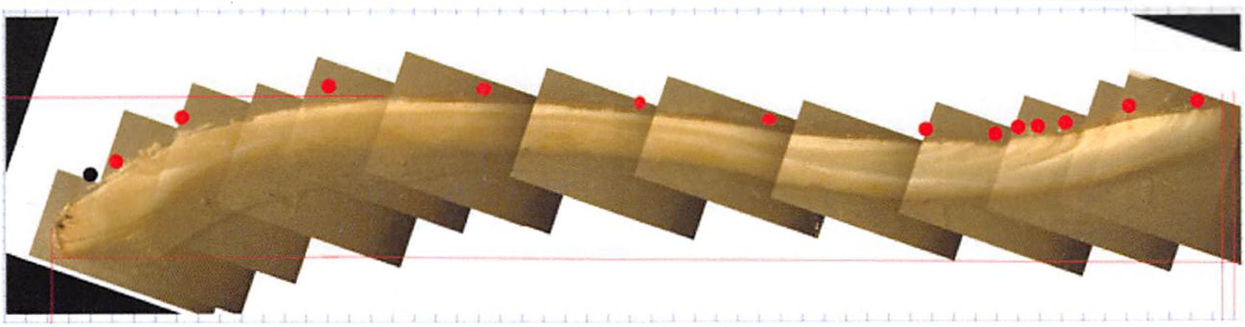


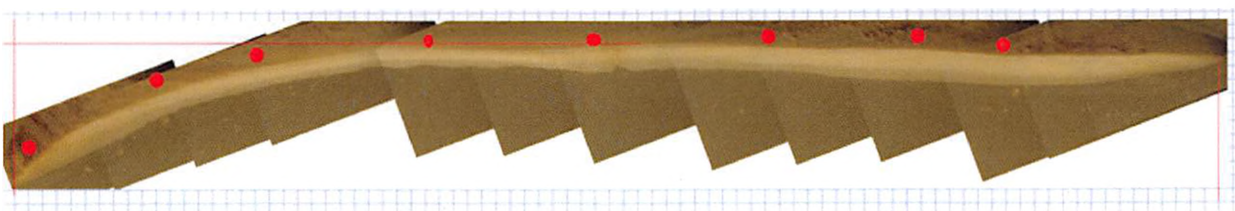
Figure 9. Interpreted frequency of El Ninos based on lake deposits in Ecuador (Moy et al., 2002). Grey bars mark age date intervals for archeological sites we will sample for this study. Init. Stands for initial and it is the time period that I specifically work with

Figures 10-13. Magnified images of the cut shells.

BERF5D



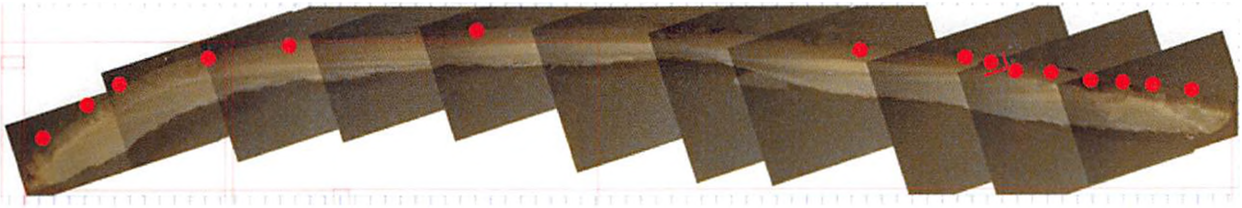
BERF5F



BERF8D

FIGURES

BERF10D



APPENDIX

Table 1

OXYGEN ISOTOPE DATA FOR BERF5D		
BERF	Distance*	del O-18
5D-1	0.197049	0.48
5D-2	0.354803	0.81
5D-3	0.694161	0.54
5D-4	1.42667	0.66
5D5	2.21625	1.08
5D6	3.00951	1.07
5D7	3.66127	0.95
5D-8	4.47161	0.78
5D-9	4.84068	0.18
5D-10	4.95661	1.01
5D-11	5.05531	0.61
5D-12	5.20378	0.78
5D-13	5.53115	1.06
5D-14	5.86855	0.62

Table 2

OXYGEN ISOTOPE DATA FOR BERF5F		
BERF	Distance*	del O-18
5F-1	0.103911	0.84
5F-2	0.801117	0.91
5F-3	1.34413	0.89
5F-4	2.26592	1.01
5F-5	3.1743	0.92
5F-6	4.12961	0.66
5F-7	4.95419	1.02
5F-8	5.42346	0.92

*Distance refers to distance in cm along bottom of the shell

APPENDIX

Table 3

OXYGEN ISOTOPE DATA FOR BERF8D		
BERF	Distance*	del O-18
8D-1	6.03514	0.75
8D-2	5.67218	1.25
8D-3	5.48262	0.88
8D-4	5.35132	1.11
8D-5	4.98994	0.87
8D-6	3.50186	1.06

Table 4

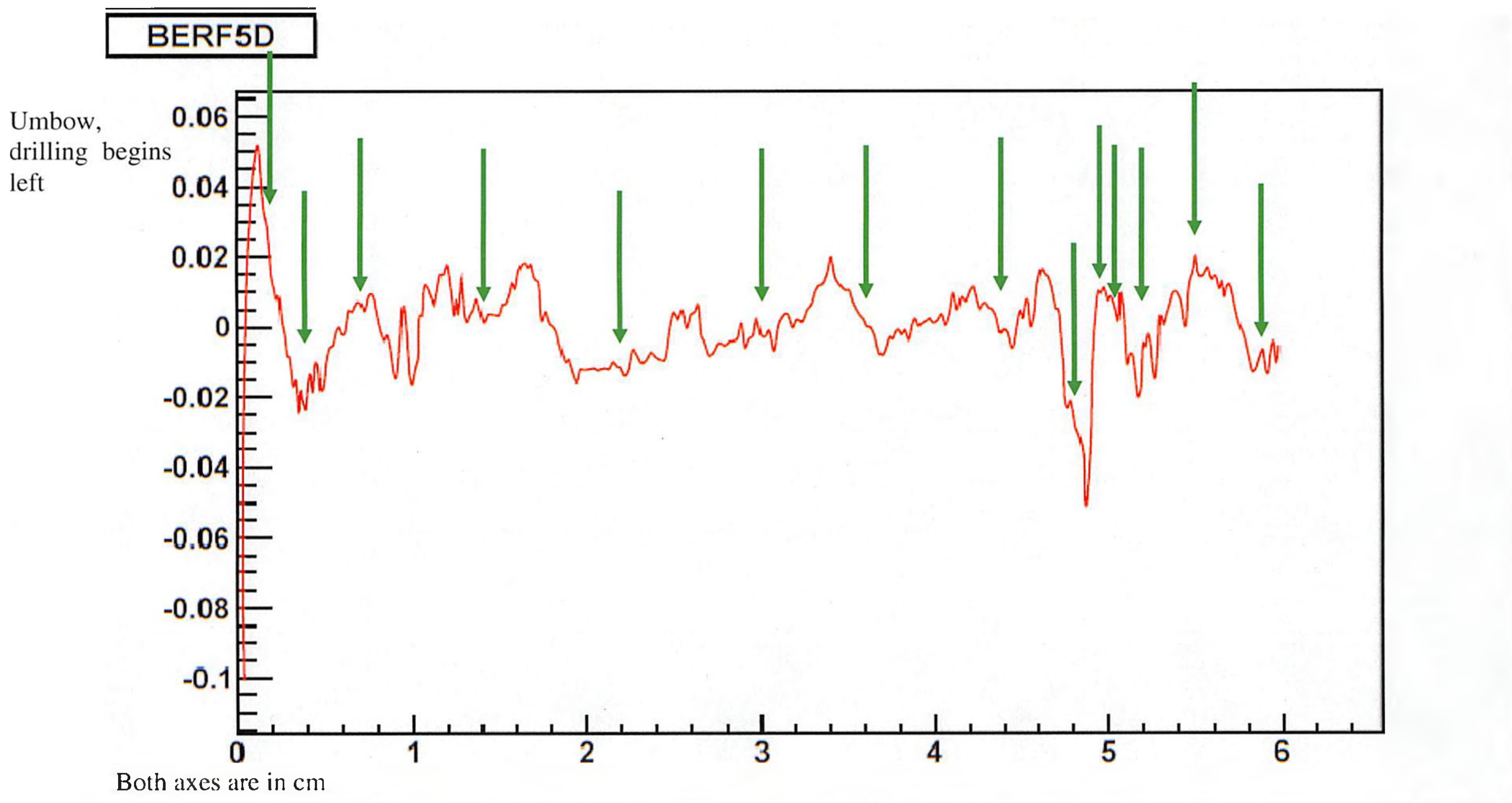
OXYGEN ISOTOPE DATA FOR BERF10D		
BERF	Distance*	del O-18
10D-1	0.144138	0.85
10D-2	0.369397	0.6
10D-3	0.549618	0.39
10D-4	0.998025	0.67
10D-5	1.42594	0.53
10D-6	2.44308	0.91
10D-7	4.50048	0.8
10D-8	5.05324	0.56
10D-9	5.18929	0.69
10D-10	5.33212	0.8
10D-11	5.51974	0.59
10D-12	5.73181	1.17
10D-13	5.90846	0.38
10D-14	6.07492	1.1
10D-15	6.29299	0.5

*Distance refers to distance in cm along bottom of the shell

APPENDIX

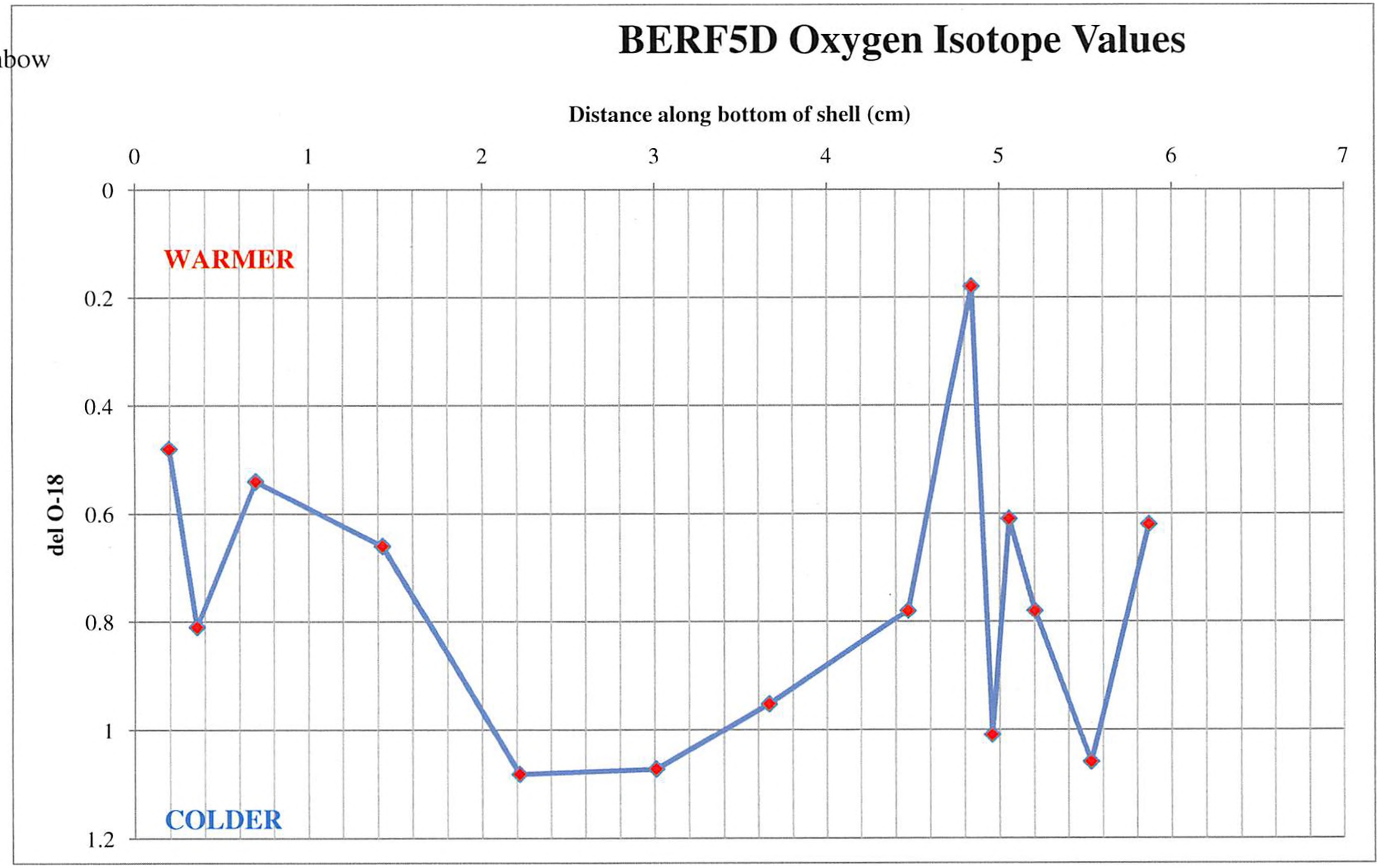
Graph 1. A digital representation of the outer surface of clam number BERF5D. The ridges of the shell are represented by positive points on the graph. The troughs of the shell are represented by negative points on the graph. The green arrows indicate drill points on the shell.

GRAPH 1



GRAPH 2

Umbow



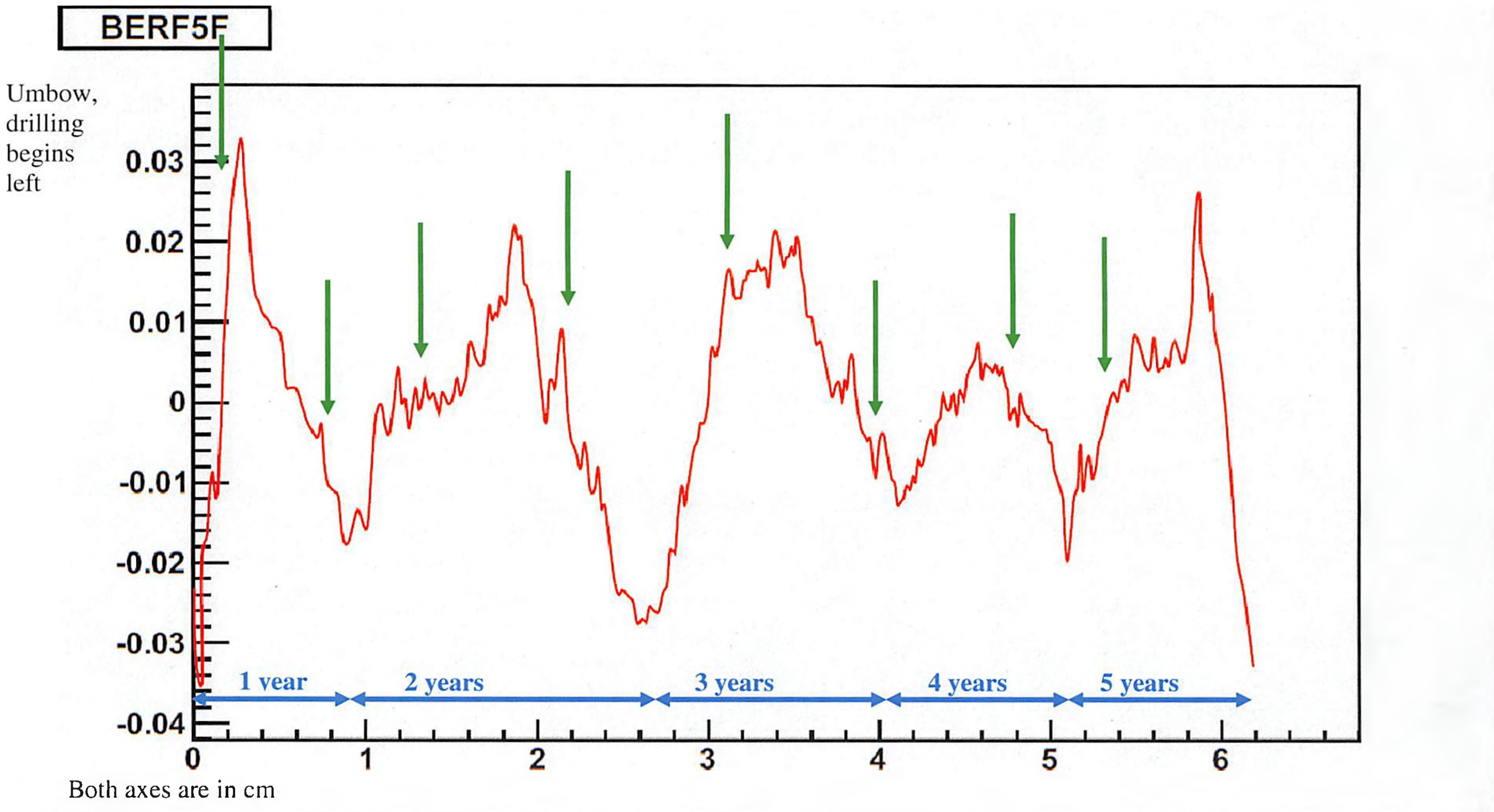
Drill spot 1 left, counts numerically up from left to right

Graph 2. O-18 values for shell BERF5D. Higher O-18 values correspond to colder sea surface temperatures. Lower O-18 values correspond to warmer sea surface temperatures. There are some similarities between the graphs. Between spot 1 and 2 a trough is present and this correlates to higher O-18 values. From 4.5 to 5 there is a ridge followed by a trough which is reflected in the O-18 values.

APPENDIX

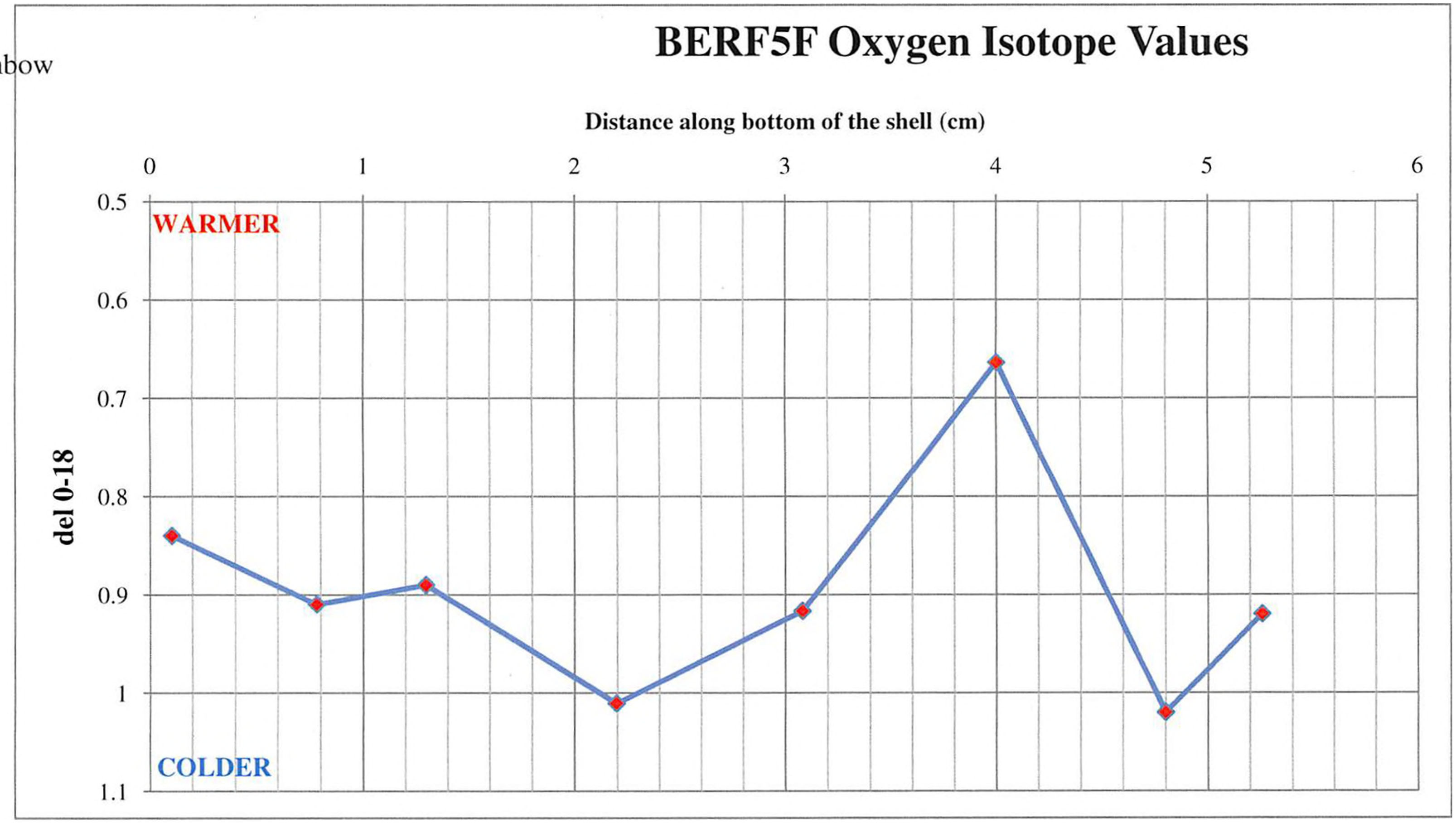
GRAPH 3

Graph 3. A digital representation of the outer surface of clam number BERF5F. One thing to notice in this shell is the definite trough to ridge pattern. Each trough-ridge set indicates a year of growth. During the Austral winter the *Mesodesma donacium* grows quickly and a trough appears. Durring the Austral summer the clam grows slowly and a ridge appears. This shell was approximately 5-5.5 years old when it died.



GRAPH 4

Umbow

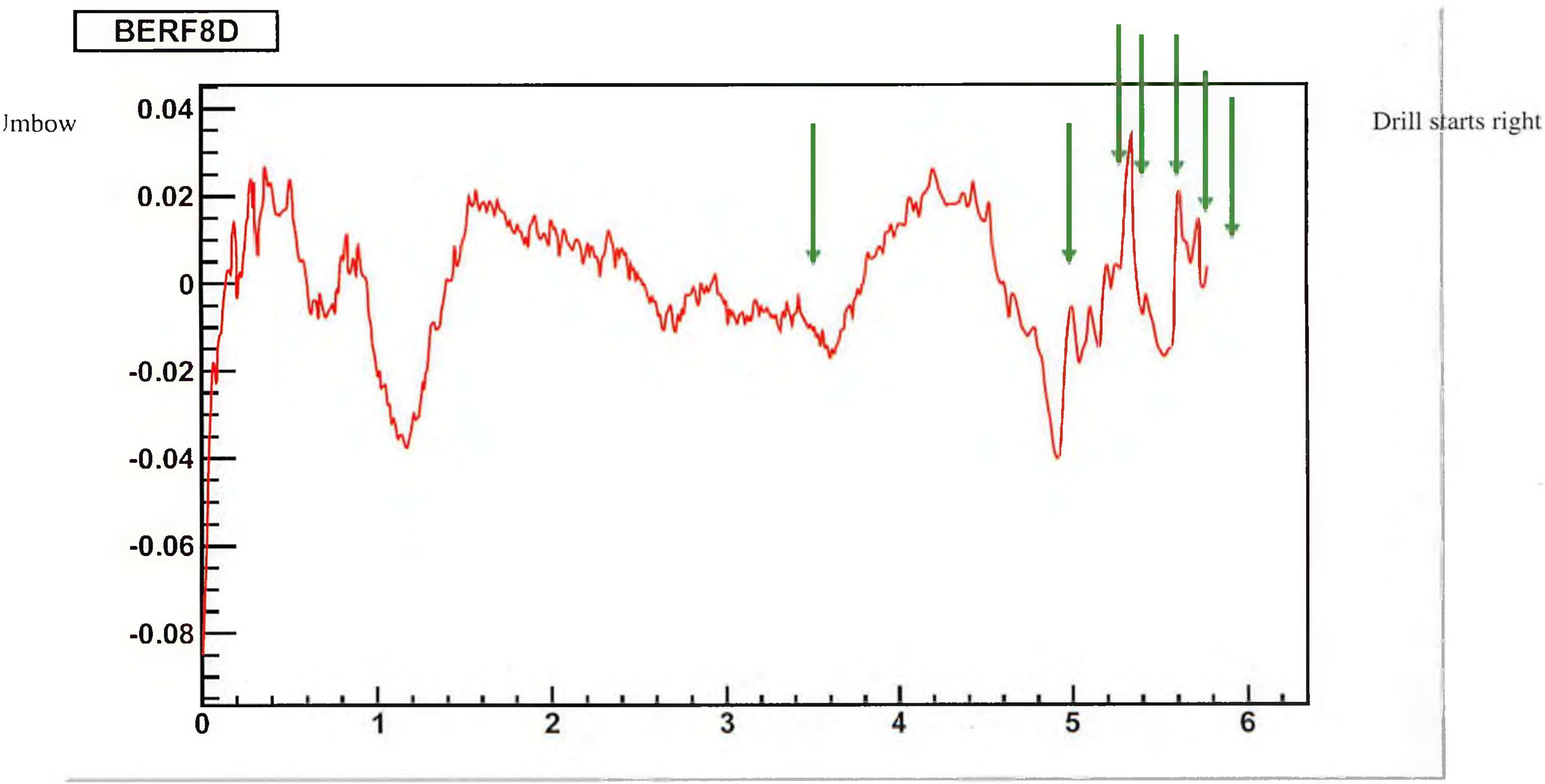


Drill spot 1 left, counts numerically up from left to right

Graph 4. This graph represents the oxygen isotope values for BERF5F. Overall any correlation of the oxygen isotope values with the trough-ridge pattern of the shell is difficult to see. If more del O-18 sample were collected from BERF5F, some correlation may be found. It may be that the lack of correlation is attributed to the poor resolution of the oxygen isotope values.

GRAPH 5

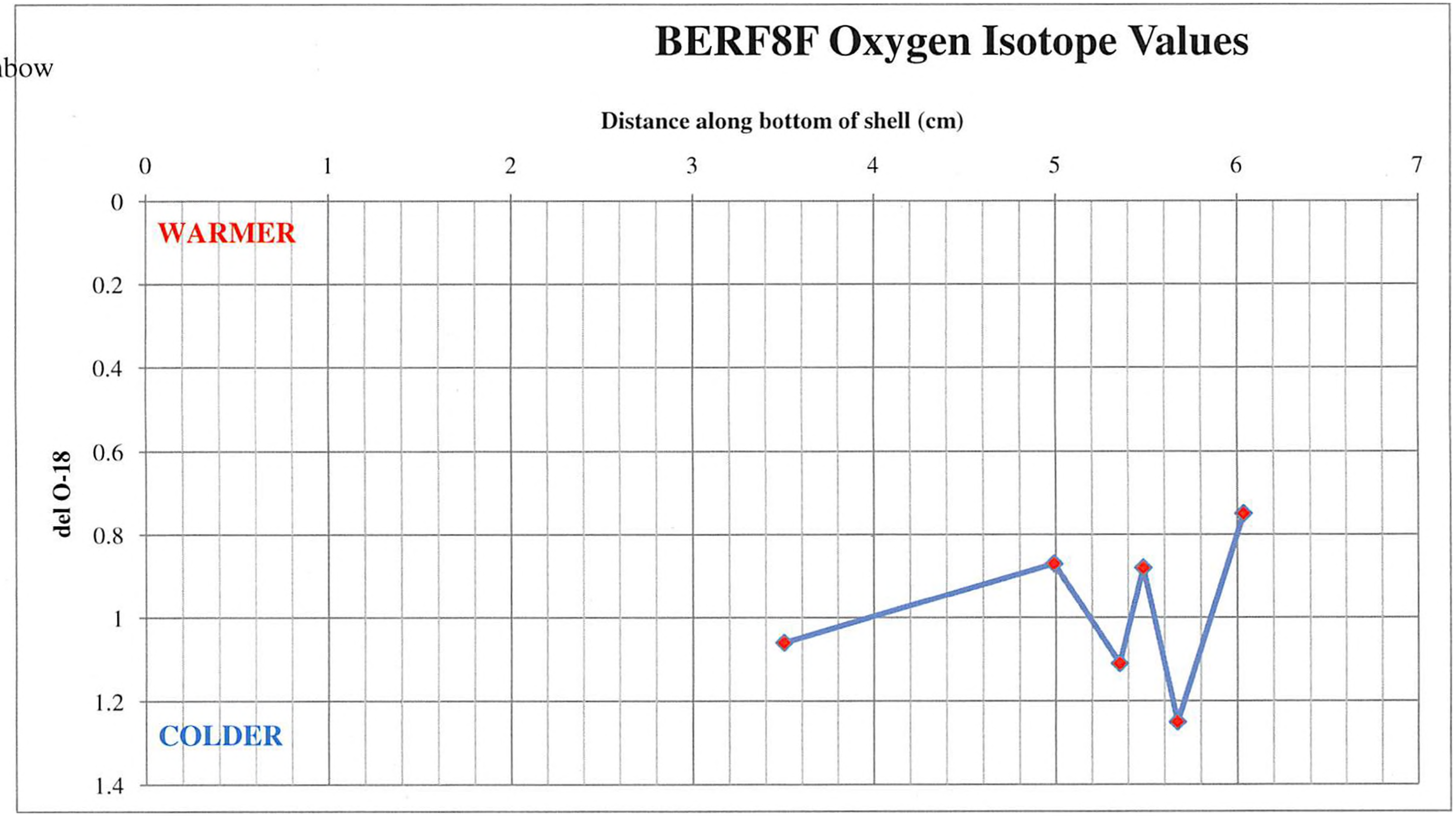
Graph 5. A digital representation of shell number BERF8D. The green arrows are indicating drill points.



APPENDIX

GRAPH 6

Umbow

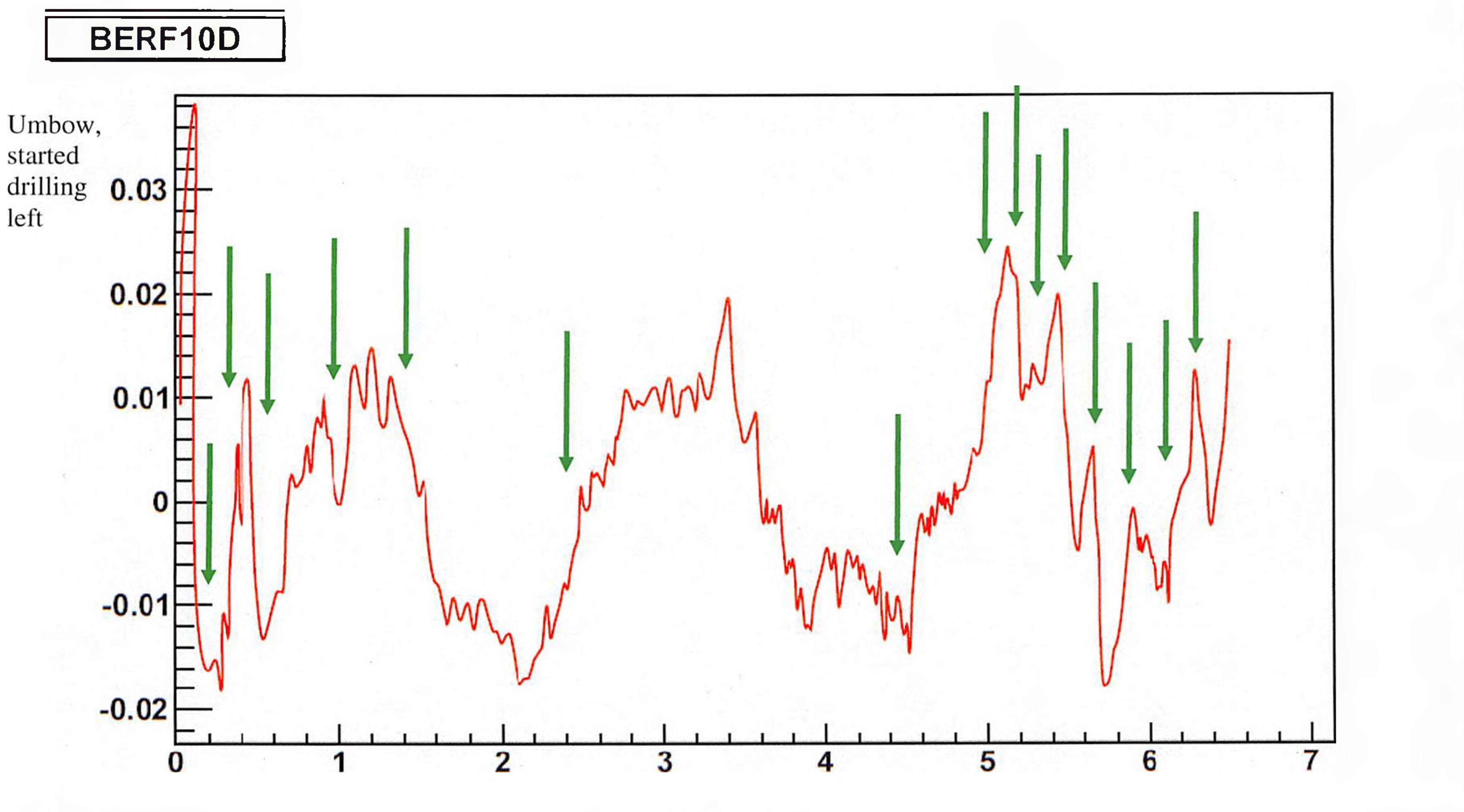


Drill spot 1 right, counts numerically up from right to left.

Graph 6: While incomplete the O-18 values for shell BERF8D do show some correlation with the trough-ridge pattern of the shell. A ridge followed by a trough occurs from 5.4-5.6. The O-18 data reflects that with lower O-18 values during the period of the ridge and higher O-18 values during the period of the trough.

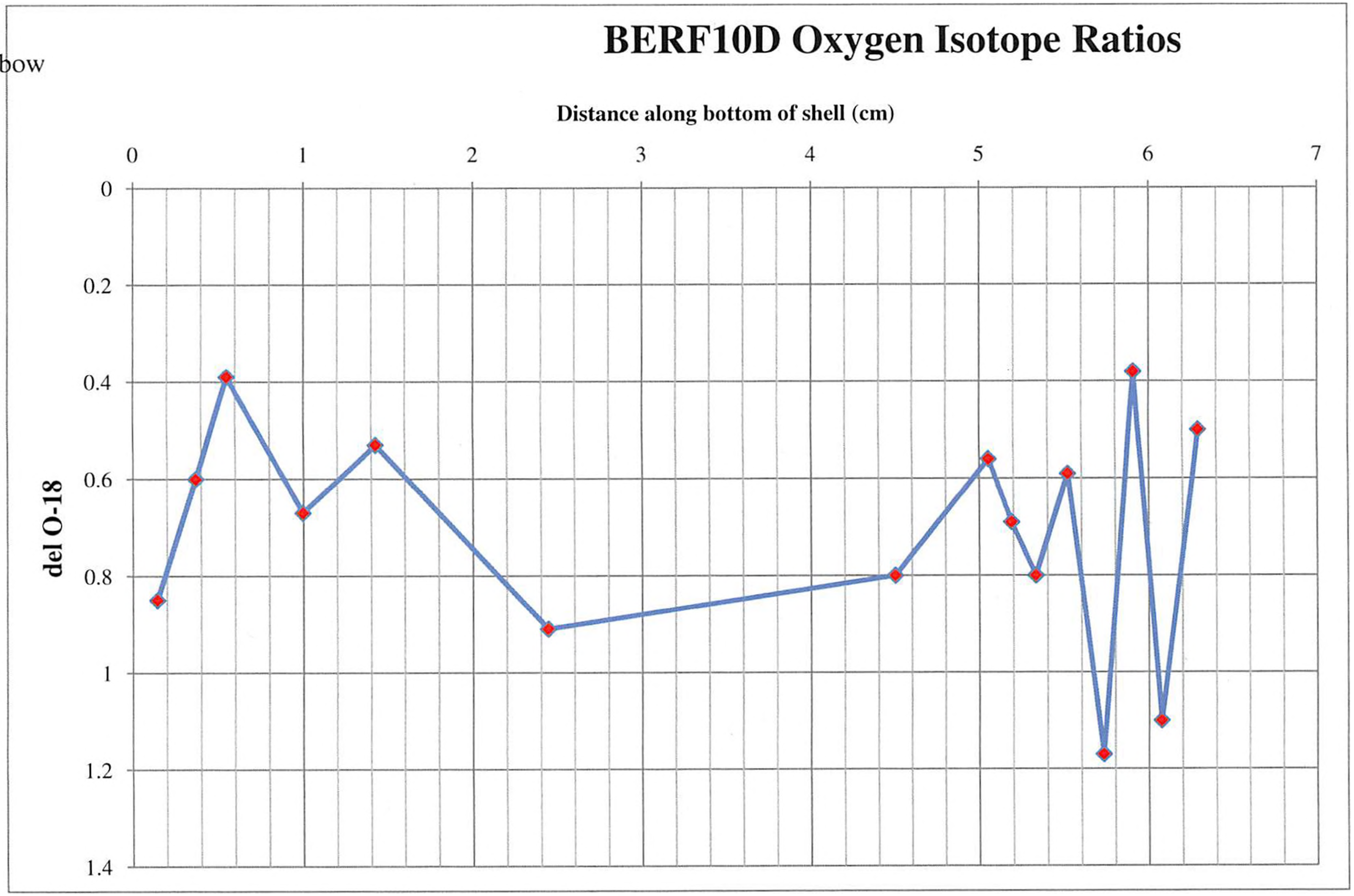
GRAPH 7

Graph 7. A digitized image of the shell morphology for shell number BERF10D. The oxygen isotope data and shell morphology match well in BERF10D.



GRAPH 8

Umbow



Drill spot 1 left, counts numerically up from left to right

Graph 8. The oxygen isotope data from shell BERF10D clearly correlates with the shell morphology. For example there is a trough pattern occurring at 2 cm in the shell and again at 4 cm in the shell. This corresponds to higher amounts of O-18. Furthermore at spot five there is a ridge pattern in the shell morphology which correlates with lower O-18 values.

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