Title

A record of abundance of fish teeth and shark denticles during the Pleistocene

Author
Wilson, Alexis

Publication Date
2024-07-01

A record of abundance of fish teeth and shark denticles during the Pleistocene

Alexis Wilson

Master of Advanced Studies Candidate- Marine Biodiversity & Conservation

Scripps Institution of Oceanography, University of California San Diego

Capstone Advisory Committee:

Signature: [redacted] Date: June 14, 2024

Dr. Richard Norris, CAC Chair

Scripps Institution of Oceanography

Signature: [redacted] Date: June 13, 2024

Dr. Dahiana Arcila

Scripps Institution of Oceanography

Signature: [redacted] Date: 06/13/24

Dr. Brice Semmens

Scripps Institution of Oceanography

Abstract

As many marine species face dwindling populations due to the effects of climate change, it is vital to gain crucial information on what this means for the future of these organisms and their surrounding ecosystems. In order to gain insight to what ocean ecosystems might look like with shifting climate variability, we can look to the past. The goal of this project is to produce a two-million-year record of abundance of pelagic fish and sharks in the waters off Cape Town, South Africa. A Ichthyolith Accumulation Rate (IAR) was established to identify fish and shark production over the span of 2 million years. Results from this study show significant fluctuations of IAR, potentially contributing to the glacial-interglacial cycles that characterize the Pleistocene. When compared to complementary data, IAR data from this site is significantly higher compared to other subtropical regions. This increased IAR may be attributed to the behavior of the Agulhas Current that flows around the southern end of the Cape of Good Hope. This project aims to expand the geological history of fish abundances, providing baseline data to fill gaps in knowledge and guide future management efforts.

Introduction

The Pleistocene epoch, ranging from 2.58 million to 11,700 years ago, was a time period that was filled with significant environmental changes to our planet (Lisiecki & Raymo, 2006). These alterations were driven by glacial-interglacial cycles causing significant temperature influxes (Elderfield, et al. 2012). Marine ecosystems were profoundly impacted by the temperature variations and the resulting consequences. During these glacial cycles of the Pleistocene, the planet experienced significant environmental shifts that are similar to shifts we are witnessing today. Temperature shifts led to oscillations of melting and formations of ice sheets which altered ocean salinity and ocean acidity. The formations of ice sheets and glaciers led to alterations of coastlines (Qin et al., 2022). These glacial cycles also had an effect on ocean current circulations which impacted distribution and migration patterns of marine life (Qin et al., 2022). As marine ecosystems and organisms dealt with these changing oceans, they either learned to adapt or face extinction.

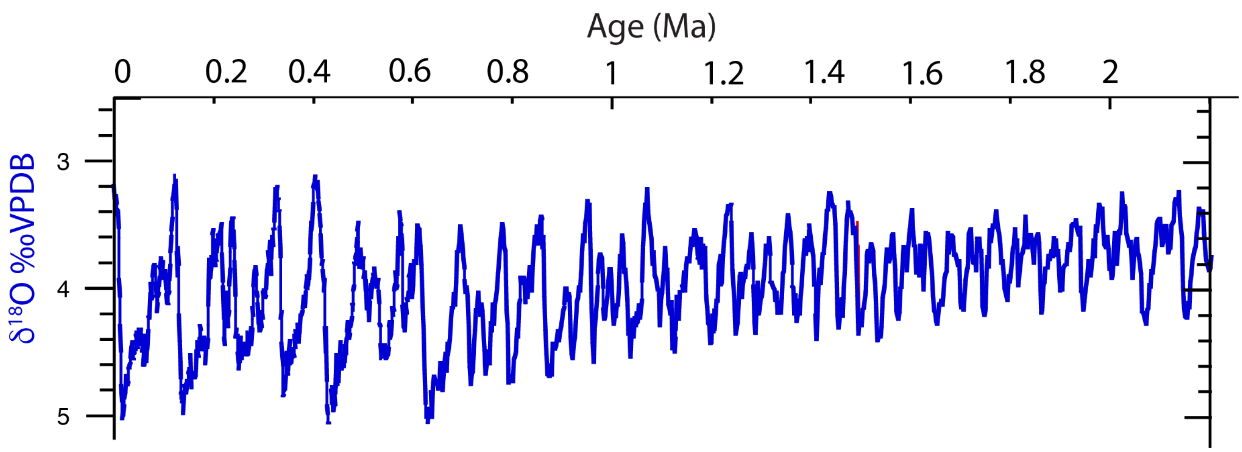

Figure showing the oscillation between glacial climate periods (down) and interglacial climate periods (up) in the deep sea. The amplitude of the glacial-interglacial climate system has increased over the last several million years, mainly because of expansion of glaciers in Europe and North America. The illustrated record is from a global compilation of isotope data by Lisiecki & Raymo (2006).

An interesting adaptation that has been debated throughout the years is the immense size of the great whales. A recent theory attributes the large body size of the biggest whales to the considerable distances they must travel between food resource patches (Slater et al., 2017). Great whales, such as Blue and Fin whales, are evolutionarily young—the last 2-3 million years at most—suggesting that their large sizes reflect the increased climate variability and resource patchiness of the Pleistocene glacial-interglacial climates (Slater et al., 2017). This relatively young evolution coincides with the cooling of the Earth's climate as this period faced a significant increase in glacial intensity (Raymo & Lisiecki, 2007). If this theory is correct, this should be reflected in the increasing variability in fish abundance over time in the IAR data.

The changing climate of the Pleistocene period is similar to the human driven climate change that is occurring today. Although today's changing climate is occurring at an unprecedented rate, it is still extremely useful to look to the past to see how organisms dealt with similar changes in climate. Our current atmospheric CO_2 (pCO_2) resembles the concentrations of the Miocene, with our current pCO_2 already surpassing mid Pleistocene concentrations (Steinthorsdottir et al. 2020). Pleistocene pCO_2 averaged 279 ppmv (Wang et al. 2012). This is far from our current pCO_2, which has reached 426.23 ppm at the time of writing, according to the Mona Loa Observatory. Still, the Pleistocene is a good proxy to evaluate how Earth's systems might react with changing climates. Targets set out by the Paris Agreement include goals to limit global average temperature increase to below 2°C from pre-industrial levels (Steinthorsdottir et al. 2021). Although this goal seems unattainable and ambitious, it is crucial for mitigating further impacts of climate change. Interestingly, the mid-Pliocene is a reflection of what Earth's temperature would look like if this goal of the Paris Agreement is reached (Burke et al. 2018). By looking at Earth conditions within this period, scientists can gain a better understanding and can better prepare on how the future of Earth might look if goals from the Paris Agreement are successfully implemented.

In order to gain a better understanding of the past oceanographic conditions, sediments from the deep sea can be utilized. Sediment cores can be used as proxies and can give us insight on physical properties of the ocean at any given period. By looking at layers of the sediments that have accumulated over the history of the Earth, we can date the sediments to specific time periods and gain information about physical properties at designated times. For this study, we are focused on fossils–specifically fish teeth and shark dermal denticles–that we find in the sediments. By counting and analyzing these fossils, it will allow us to reconstruct past ecosystems and act as important baseline data (Dillon et al., 2021). This baseline data of shark denticles and fish teeth are important for a multitude of reasons. It allows us to gain a better understanding of fish and shark abundances which can grant insight on how marine ecosystems evolved over time. It is also useful to identify how marine organisms react to environmental changes. This can include temperature changes, acidification changes, etc. This baseline data is also valuable so that we can see how ecological systems behaved before there was any anthropogenic impact. This key information is especially important today and can assist with informing conservation efforts and policy changes.

For this study, we utilized preserved sediment samples collected from a research cruise completed in 2016 which surveyed the Cape Basin, South Africa. These samples were collected with the use of sediment cores which are used to capture stratigraphic layers of sediment. Analyzing sediments in the deep sea is a valuable tool to gain a better understanding of how ocean conditions looked like in the past. As organisms in the ocean complete their life cycle, the dead organic carbon will eventually sink to the bottom of the ocean. From large great white sharks to microscopic radiolarians, we are able to get a glimpse of their abundances from fossil records recovered from sediment collections.

Cape Basin, South Africa was the chosen location for this study due to the expected high productivity, the significant shark populations that reside here, and the intersection of whale migrations (Anderson & Sachs 2005). Some sharks that can be found in this location include great white sharks, mako sharks, blue sharks, among numerous other species. Sharks are particularly challenging organisms to survey due to their migration patterns and elusive behavior. This is why sediment analysis is especially valuable for gaining baseline data on this species. Cape Town, South Africa, which is the city closest to our sampling site, relies heavily on ecotourism led by shark tours and cage diving with great white sharks (Bowlby et al. 2023).

Unfortunately, there has been a decrease in white shark sightings in the area, prompting the first regional trend assessment of white sharks to be completed (Bowlby et al. 2023). Other recent studies completed in this location indicate a shift in predator-prey dynamics. With the significant reduction of white sharks, there have been behavioral changes exhibited in their prey (Hammerschlag et al. 2022). As an apex predator, sharks play a crucial role in food webs and trophic cascades, making it essential to understand how surrounding ecosystems react to population shift (Hammerschlag et al. 2022).

Currently, there is no geological history of fish or shark abundance in the Atlantic during a 7-8-million-year long period. This study aims to fill this gap in knowledge. By looking into the past and establishing a record of abundance of fish, we can gain valuable information about current and future marine ecological processes. This geological record will allow us to gain a better understanding of ecosystem dynamics, evolutionary history, and how these factors change in relation to a changing climate. Fish are a crucial part of the marine environments and changes in their abundance can have cascading effects on the rest of the food chain and surrounding ecosystems.

Methodology

Site Selection

Icthyoliths were retrieved from a preserved deep sea sediment core in the Atlantic and was collected in 2016. The sediment core was collected from International Ocean Discovery Program (IODP) leg 361 at Site U1479. This core was completed in the Cape Basin about 85 nmi southwest of Cape Town, South Africa at a water depth of about 2,615 m below sea level (Hall et al., 2017).

Sample Processing

The preserved samples were processed in order to isolate fish teeth and dermal denticles. Processing the samples began with weighing the dry sample to obtain the total dry weight (g). They were then washed through a 38 µm sieve and placed in the oven at 50°C until dry. Once dried, samples were sieved again in a 150 µm sieve to separate the larger microfossils which were saved in vials. The finer portion—38-150 µm–was dissolved in 5% acetic acid. This acid wash was completed to get rid of calcium carbonate and any other unwanted materials in order to concentrate the teeth. After the acid wash is completed, this insoluble fraction should contain just the desired portion which is the fish teeth and shark denticles.

Unfortunately, it was determined that there was a significant amount of biosilica in our samples which could make it hard to make an accurate count of teeth and denticles. So, to isolate the ichthyoliths, the samples underwent a heavy liquid separation step. Once the samples were re-dried in the oven, the samples were placed in 15 ml eppendorf tubes along with non-toxic LST (heavy liquid for density of separation) with a specific gravity of -2.4. The tube was placed in a centrifuge and once the centrifuge reached the max rpm, the centrifuge was stopped. Once the samples were taken out of the centrifuge, the desired ichthyoliths were at the bottom of the tube and the light unwanted opal fraction of diatoms and radiolaria (density about 2.0 g/cm2) was floating on the top. The unwanted top fraction was discarded by pouring it over a 38 µm sieve and bucket to save the heavy liquid solution. The heavy portion of the samples that contained the ichthyoliths were rinsed with deionized water to remove any of the heavy liquid solution that remained. After the samples were rinsed, they were placed in the oven to dry and evaporate any remaining water.

Once the samples were dried, they were weighed and placed in vials. Next, samples were counted with an inverted binocular microscope. Each sample was sieved through a 125 µm sieve and the larger material was placed in a dish filled with deionized water and placed under the microscope to be counted. Teeth, denticles and skeletal fragments were recognized by their distinct pale-yellow color in plane light–a color distinctive of calcium apatite. This protocol closely followed similar procedures that were previously completed to isolate ichthyoliths from marine sediments (Sibert et al., 2017).

Data Analysis

Raw tooth and denticle counts were converted into accumulation rates. The accumulation rate or "ichthyolith accumulation rate" of some authors, is a measure of how many teeth and denticles fall onto the seafloor each thousand years. This was completed by utilizing the following formula:

Ichthyolith Accumulation Rate = Abundance * Dry Bulk Density * Sedimentation Rate

To establish the age model, the depth in meters of each sample was determined using the LIMS database in the IODP. Top depth for each sample of CSF-B was chosen for depths. The depth of each sample was then associated with the corresponding age by looking at the age/depth relationship described in the cruise report (Hall et al., 2017). The biostratigraphic calcareous nannofossil datum data was chosen to be used as the age model because it had the highest quality of reliability compared to the other microfossil or magnetostratigraphic age models. The nannofossil age/depth relationship was reported at depths of CCSF-A (m). To adjust for this, the original CSF-B depths were converted to the CCSF scale by adding the cumulative offset.

The dry bulk density (g/cm^3) of each sample was calculated from the physical properties measurements that were made on the ship. The sedimentation rate (cm/ky) was based on the age-depth relationship from planktonic foraminifera, calcareous nannofossils, diatoms, and magnetostratigraphy from the cruise report.

Results

Raw counts of fish teeth and shark denticles recovered from sediment cores from Cape Basin were established and turned into a cumulative accumulation rate. Fish teeth abundance varied significantly, ranging from a high of 73.81 fish teeth/cm^2/kyr to a low of 1.87 fish teeth/cm^2/kyr (Fig. 1). Shark denticles also had a significant range with a maximum of 1.66 denticles/cm^2/kyr to a minimum of 0 denticles/cm^2 /kyr (Fig. 2). There is a significant spike in ichthyolith accumulation rate at around 0.25 Ma, peaking at 65.16 fish teeth/cm^2 /kyr. There are significant fluctuations throughout this time scale, possibly due to the glacial-interglacial cycles occurring throughout the Pleistocene. The highest peak in this period reaches 73.81 fish teeth/cm^2 /kyr at 1.25 Ma indicating a significant event.

When looking at shark denticles accumulation rates, they are similar to the fish teeth accumulation rates in terms of large fluctuations. Accumulation rates are much lower in the denticles with the average being 0.13 denticles/cm^2/kyr while the mean fish teeth accumulation rate was 18.40 fish teeth/cm^2 /kyr. There is a significant spike of denticles at 1.19 Ma of 1.02 denticles/cm^2/kyr. This spike occurs at the same time that there is a sharp increase of fish teeth, 49.82 fish teeth/cm^2/kyr. There is also the largest spike of denticles at 1.93 Ma.

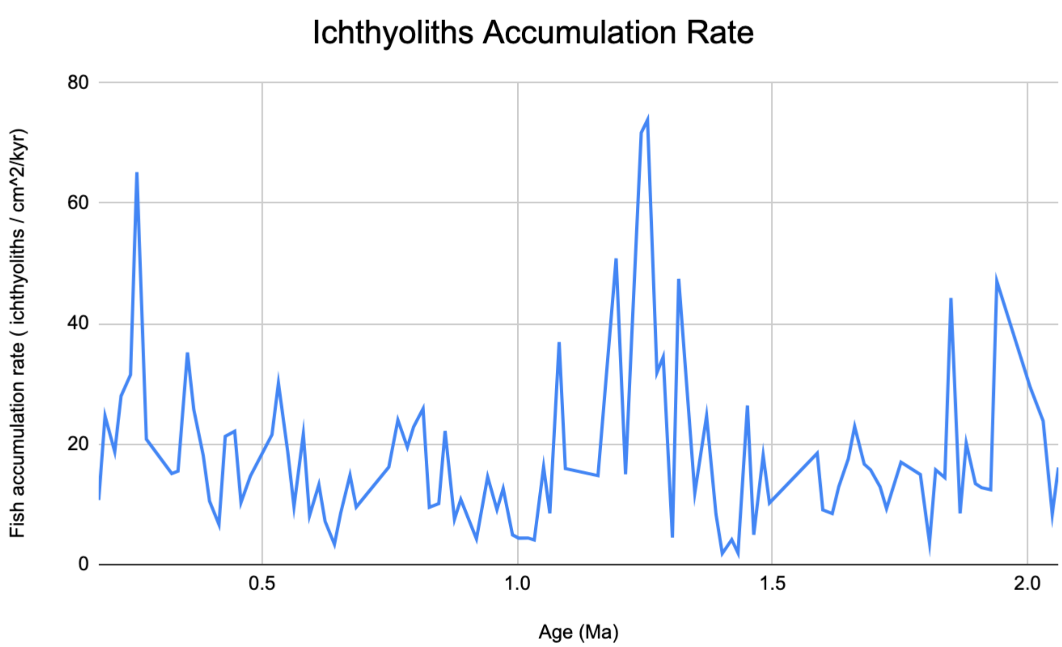

Figure 1. IAR vs. Age for Cape Basin Site. Cumulative rates of ichthyoliths (fish teeth and shark denticles) spanning up to 2.06 Ma from site 1479.

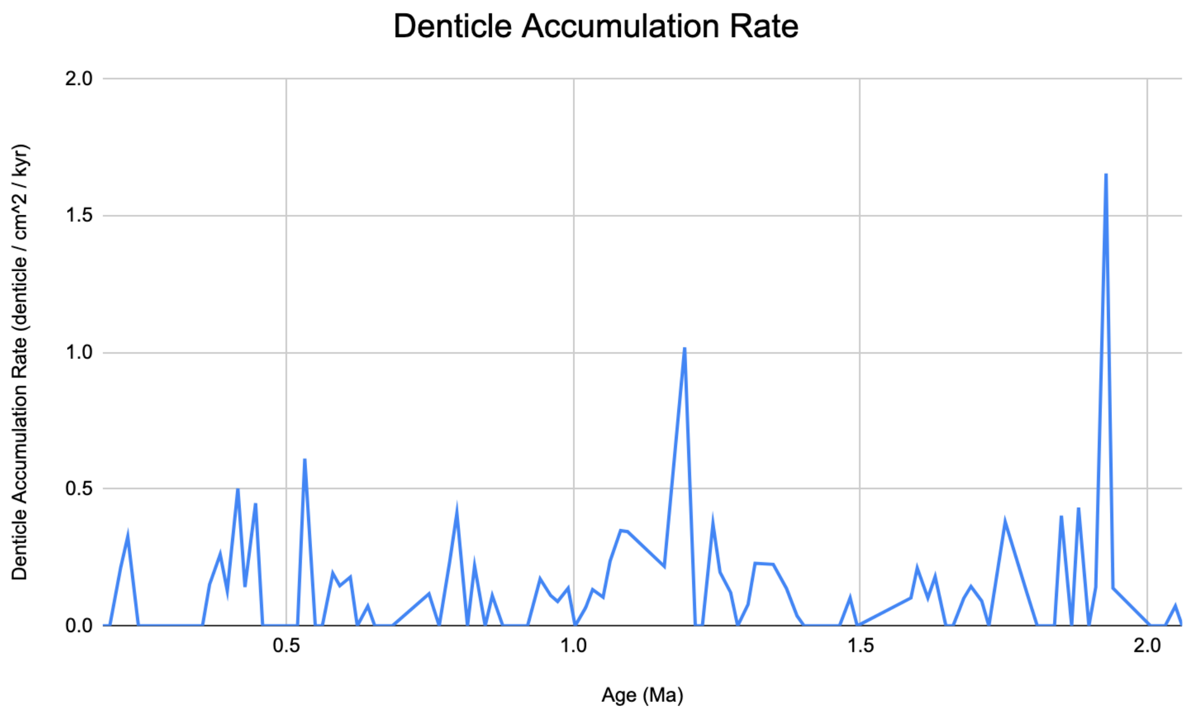

Figure 2. Dermal Denticle Accumulation Rate vs. Age. Data from the Cape Basin, South Africa.

IARs from Site 1479 were compared to previous IAR data collected from six different sites throughout the Pleistocene. Data collected from Site 1479 complements the published record of a former MS student, Leah Werner, who collected data for 6 ocean drill cores over the past 2 million years (Werner & Norris, 2019). These locations range from the Southern Ocean to the tropics as well as polar regions (Fig. 3). For the most part, there is a higher accumulation rate in tropic areas compared to polar regions. Overall, these data suggest that ichthyolith accumulation rates are correlated with latitude. Since our site is located in the subtropics, we expected IARs to be similar to other sites that are located in the subtropics like ODP 1123. Site 1479C does reflect an increase in accumulation rate compared to polar regions, but at a significantly higher rate compared to the other tropic IARs (Fig. 4, Fig. 5). It is hypothesized that this might be due to the Agulhas leakage process that occurs in this area which has led to an enhanced primary productivity in the area.

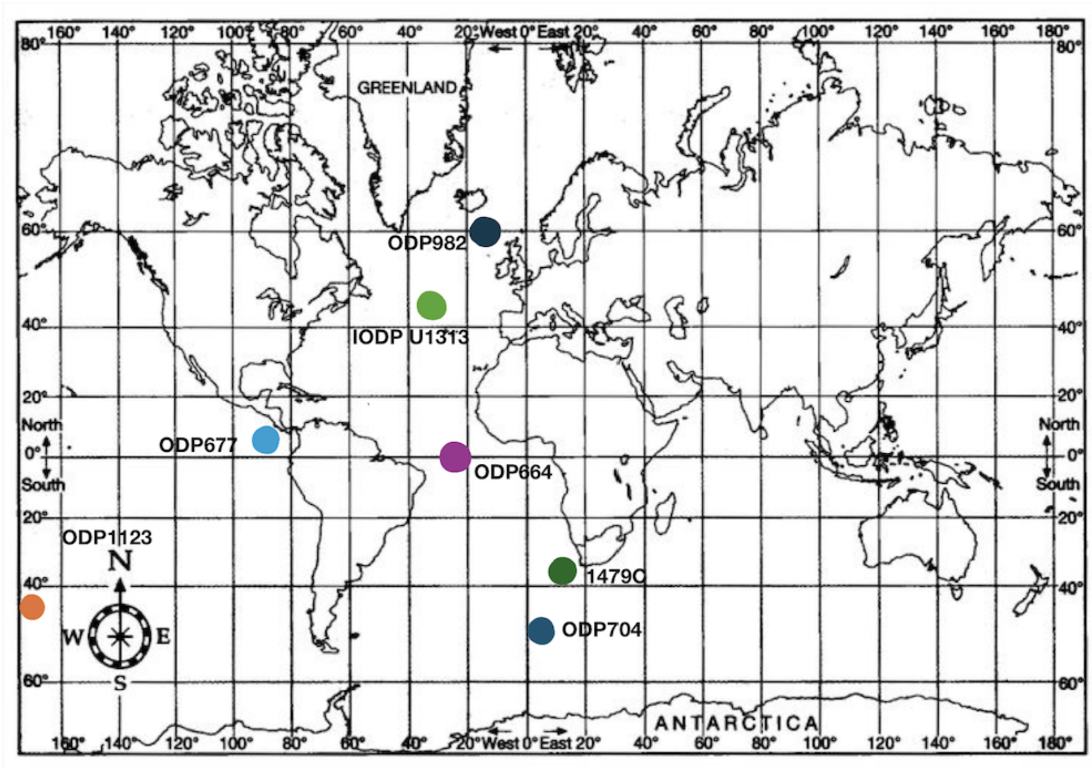

Figure 3. Map of Site Locations. Paired with previous IAR analysis, six other sites with varying latitudes were surveyed.

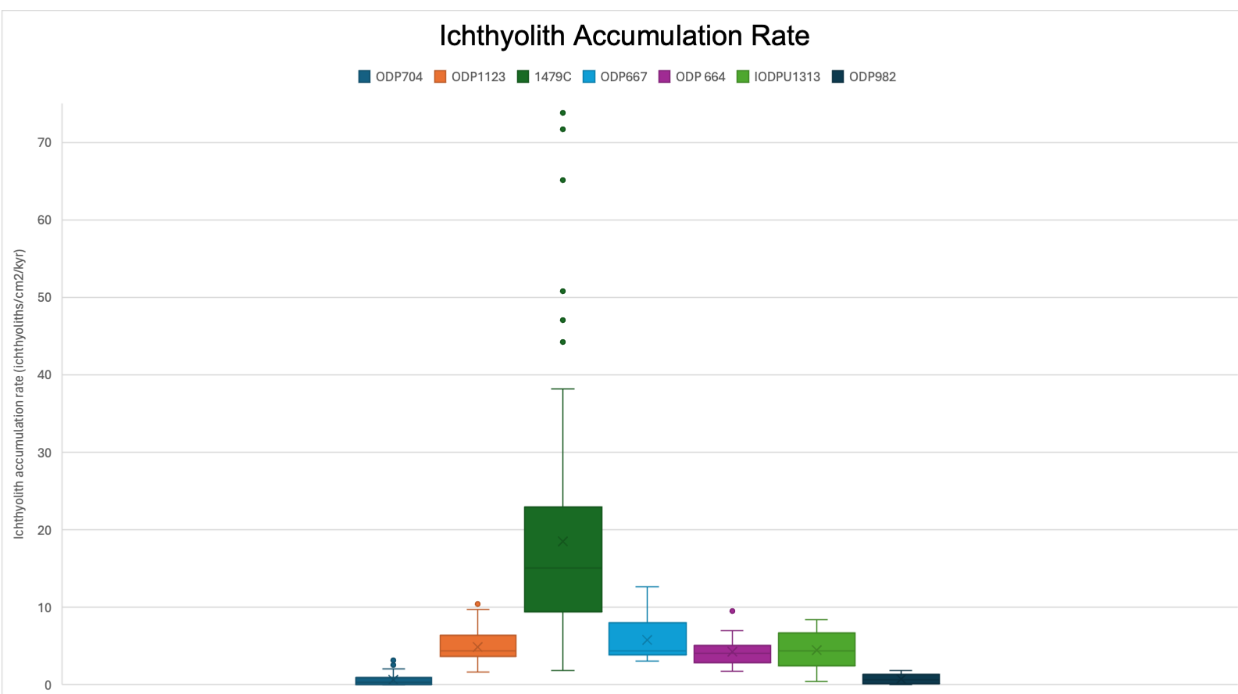

Figure 4. Ichthyolith Accumulation Rate Comparison. Site locations are color coordinated and correspond to site locations from Fig. 2. Starting from the left is the site with the lowest

latitude, with increasing latitude going from left to right. These box plots include interquartile ranges, the median which is the solid line in the box, whiskers, and outliers.

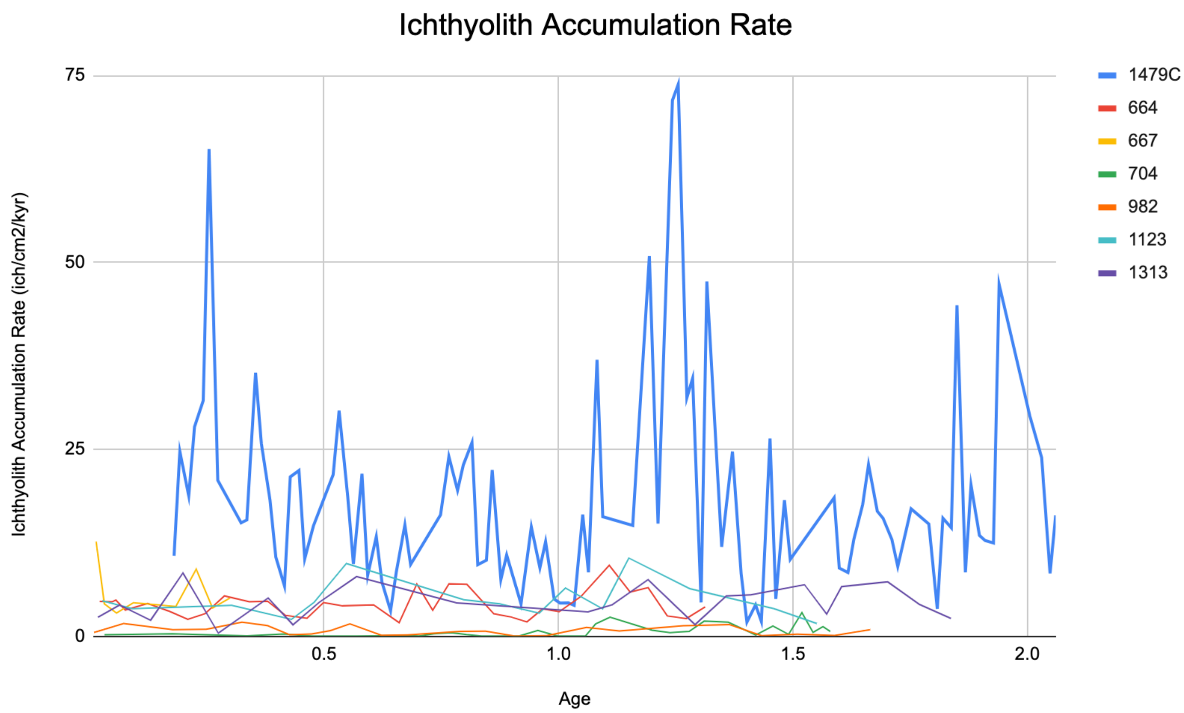

Figure 5. Icthyolith Accumulation Rate Comparison vs. Age.

Discussion

Ichthyolith accumulation rate in the Cape Basin, South Africa has experienced significant variability over the past 2 million years. The significant peaks visualized in both fish teeth and shark denticles are likely a reflection of the changes occurring in surrounding ocean environments. Further analysis is needed in order to determine the specific factors that are driving these large spikes in IAR.

When looking at the Werner data, there is consistency in that polar fish production is significantly lower compared to rates in the subtropical and tropical regions. Data collected from this study is consistent with this correlation. Interestingly, site 1479 IAR rates were significantly higher than the other tropic locations. One reason for this could be attributed to the intersection of this site with the Agulhas current. The Agulhas Current is an important ocean current that transports water in the Eastern direction from the Indian Ocean into the South Atlantic (Hall et al., 2017). Near the Cape Basin, the current retroflects and occasionally releases Agulhas rings into the area (Dencausse, et al 2010). This leakage, known as the Agulhas leakage, is significant to the water composition of the Cape Basin area (Hall et al. 2017). This variability of the

Agulhas Current is reflected in the IAR data, indicating a dynamic system with decent variability.

Future aims for this study include completing the Cape Basin, South Africa record of abundance so that it encapsulates an even longer timespan. It has been hypothesized that pelagic productivity has become more variable over the Plio-Pleistocene (the last 3-5 million years) causing resources like fish and krill populations to become patchier in the global ocean. This increased patchiness supports the hypothesis that great whales evolved their large body size to travel long distances to find prey. Data from this study aligns with this hypothesis, showing significant variability in productivity. By extending this record, we will be able to gain an even deeper understanding of fish abundances and how they react to changing oceanic conditions.

In conclusion, this study was built to improve the geological history of fish and shark abundances in the Cape Basin, South Africa over the past 2 million years. Filling this gap in knowledge and establishing this record of abundance has granted us valuable insights into past ecological dynamics. This geological record will help enhance our understanding of ecosystem dynamics, evolutionary history and adaptations, and how climate plays a part in driving these changes. Establishing and building onto this record is key to understanding historical baselines which in turn will eventually assist and guide future management.

ArcGIS StoryMap

An important aspect of this project is to reach a broad audience. To achieve this, I have developed a StoryMap on ArcGIS that serves as an accessible and informative resource for this research project. The StoryMap highlights the significance of ocean sediments and presents the research findings in an easy-to-understand format. By using this tool, it makes it possible to make complex scientific information accessible and engaging. Effective communication of scientific research is essential and this StoryMap helps bridge the gap between the scientific community and the public, which fosters greater awareness and understanding of our oceans. The QR code and link to access the StoryMap can be found below.

Link: https://storymaps.arcgis.com/stories/9e02851bc352487db26e5c4aa9fed27b

References

Anderson, F.R. & Sachs, J.P. (2005) Increased productivity in the subantarctic ocean during Heinrich events. Nature. 434, 1118-11121.

Bowlby, H., Dicken, M., Towner, A., Waries, S., Rogers, T., Kock, A. (2023) Decline or shifting distribution? A first regional trend assessment for white sharks (*Carcharodon carcharias)* in South Africa. Ecological Indicators 154. https://doi.org/10.1016/j.ecolind.2023.110720

Burke, K. D., Williams, J. W., Chandler, M. A., Haywood, A. M., Lunt, D. J., & Otto-Bliesner, B. L. (2018). Pliocene and Eocene provide best analogs for near-future climates. Proceedings of the National Academy of Sciences, 115(52), 13288–13293. doi:10.1073/pnas.1809600115

Dencausse, G., Arhan, M., & Speich, S. (2010). Routes of Agulhas Rings in the southeastern Cape Basin. *Deep Sea Research Part I:* Oceanographic Research Papers, *57*(11), 1406–1421. doi:10.1016/j.dsr.2010.07.008

Dillon, E. M., McCauley, D. J., Morales-Saldaña, J. M., Leonard, N. D., Zhao, J., & O'Dea, A. (2021). Fossil dermal denticles reveal the preexploitation baseline of a caribbean coral reef shark community. Proceedings of the National Academy of Sciences, 118(29). doi:10.1073/pnas.2017735118

Elderfield, H., Ferretti, P., Greaves, M., Crowhurst, S., McCave, N., Hodell, D., Piotrowski. (2012) Evolution of Ocean Temperature and Ice Volume Through the Mid-Pliestocene Climate Ttransition. Science. 337 (6095), 704-709. DOI: 10.1126/science.1221294

Hall, I. R., Hemming, S. R., LeVay, L. J., Barker, S., Berke, M. A., Brentegani, L., … Zhang, H. (2017). Site U1479. Proceedings of the International Ocean Discovery Program. doi:10.14379/iodp.proc.361.108.2017

Hammerschlag, N., Fallows, C., Meÿer, M., Seakamela, S. M., Orndorff, S., Kirkman, S., Kotze, D., Creel, S. (2022). Loss of an apex predator in the wild induces physiological and behavioural changes in prey. Biology Letters. *18*(1). doi:10.1098/rsbl.2021.0476

Lisiecki, L.E & Raymo, M.E. (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography. 20.

Raymo, M.E. & Lisiecki, L.E. (2007) Plio-Pleistocene climate evolution: trends and transitions in glacial cycle dynamics. Quaternary Science Reviews. 26 (1-2), 56-59.

Qin, B., Li, T., Xiong, Z., Algeo, T. J., Jia, Q., Nürnberg, D., & Shi, J. (2022). Influences of atlantic ocean thermohaline circulation and Antarctic Ice-sheet expansion on Pliocene Deep Pacific carbonate chemistry. Earth and Planetary Science Letters, 599, 117868. doi:10.1016/j.epsl.2022.117868

Raymo, M.E. & Lisiecki, L.E. (2007) Plio-Pleistocene climate evolution: trends and transitions in glacial cycle dynamics. Quaternary Science Reviews. 26 (1-2), 56-59.

Sibert, E., Cramer, K., Hastings, P., Norris, R. (2017) Methods for isolation and quantification of microfossil fish teeth and elasmobranch dermal denticles (Ichthyoliths) from marine sediments. Palaeontologia Electronica. 20, 1-14.

Sibert, E., Norris, R., Cuevas, J., & Graves, L. (2016). Eighty-five million years of Pacific Ocean Gyre Ecosystem structure: Long-term stability marked by punctuated change. Proceedings of the Royal Society B: Biological Sciences, 283(1831), 20160189. doi:10.1098/rspb.2016.0189

Slater, G.J., Goldbogen, J.A., Pyenson, N.D. (2017) Independent evolution of baleen whale gigantism linked to Plio-Pleistocene ocean dynamics. Proc. R. Soc.

Steinthorsdottir, M., Coxall, H. K., de Boer, A. M., Huber, M., Barbolini, N., Bradshaw, C. D., et al. (2021). The Miocene: The future of the past. Paleoceanography and Paleoclimatology, 36, e2020PA004037. https://doi.org/10.1029/2020PA004037

Wang, Y., Momohara, A., Wang, L., Lebreton-Anberrée, J., & Zhou, Z. (2015). Evolutionary history of atmospheric CO2 during the late cenozoic from fossilized metasequoia needles. PLos ONE 10(7). doi:10.1371/journal.pone.0130941

Werner, L., & Norris, R., (2019). A Pleistocene record of global fish production and implications for sustainability of polar fisheries.