Paleoclimate Investigation in the Feneos Basin, Southern Greece

by

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Certificate of Approval

This is to certify that the accompanying thesis by McKenzie Marie Elliott has been accepted in partial fulfillment of the requirements for graduation with Honors in Geology.

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May 08, 2019

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Abstract

Following the Late Bronze Age Collapse in ancient Greece around 3200 years BP, a lack of artifacts preserved following the collapse has stumped archeologists. To date, investigations into the cause of the collapse have primarily focused on archeological evidence. Suspicion that the collapse may have been a result of climate change has spurred a scientific partnership between archeologists and paleoclimate researchers. In this investigation, we build on past climate studies on the Peloponnese peninsula in southern Greece. Geochemical proxies and grain size distributions were analyzed for a sediment core taken from Paleolake Feneos in the Northeastern Peloponnese. The results can be correlated to other records in the published literature. We conclude that the microclimate of the Feneos Basin matches the record from the Asea Valley and does not closely match the record from the Lake Stymphalia core. One exception is a warm dry event which may have occurred between 3500 and 3000 years BP in both Lake Stymphalia and the Feneos Basin, around the time of the Late Bronze Age Collapse.

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Introduction

Paleoclimate study helps us understand how the climate has varied in time and space; archeology helps us understand past human civilizations. Pairing these two fields can lead to an enriched understanding of the past, and how human civilization reacted to changes in climate. Sites that include both rich archeological records and abundant climate archives are essential for this sort of research, and the Peloponnese of Southern Greece has both (Figure 1). The karstic landscape, a landscape of weathered limestone, has abundant water resources that nurtured the development of settlements and cities

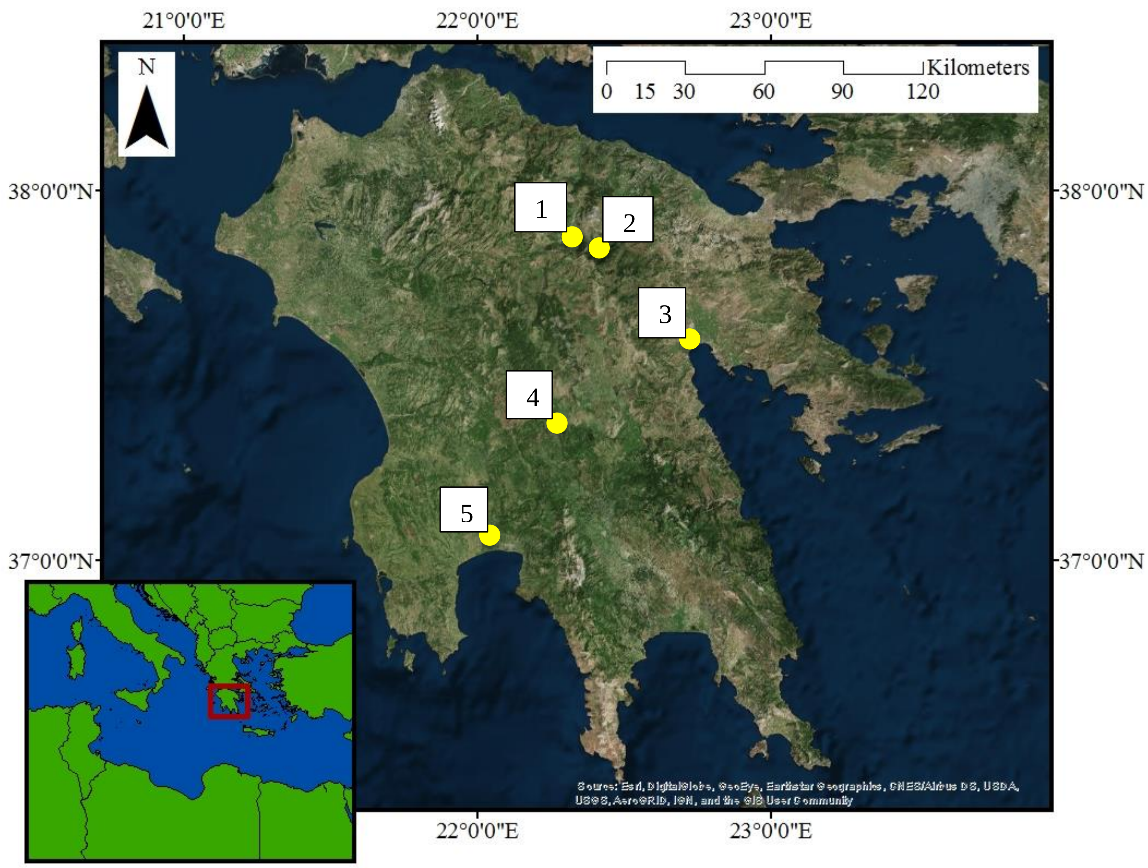

Figure 1. Map of the Peloponnese created using data from the USGS and ESRI. Note the southerly latitude of the Peloponnese and its central location in the Mediterranean Sea. Different climate archives across the Peloponnese are (1) Paleo-lake Feneos, (2) Lake Stymphalia, (3) Lake Lerna, (4) Asea Valley, and (5) Messinian Plain.

(Conners, 2016). Poljes, large flat basins found in karst landscapes, acted as sediment sinks for millennia, recording the climate during deposition.

Past paleoclimate studies in the Peloponnese have relied on sediment cores recovered from depositional basins. For example, Katrantsiotis (2016) combined geochemical proxies and diatom assemblages to reconstruct the climate of the southern Peloponnese. They found that the area experienced variable sea level and water conditions, and later transitioned to an entirely terrestrial environment starting at 4500 yrs. BP. Likely, these changes are due more to tectonic activity than to climate change. Unkel (2014) studied sediments from the Asea Valley, in the central Peloponnese, reconstructing a 6500-year record from geochemical proxies. The first continuous sediment core from the Peloponnese was cored from Lake Stymphalia by Heymann (2013) and Unkel (2011); it spans the last 15,000 years. The Little Ice Age (LIA), the 8.2-event, and the Younger Dryas, were identified from the Lake Stymphalia core using geochemical proxies.

In this study, we analyze a paleo-lake sediment core from the Peloponnese peninsula of southern Greece to (1) determine if geochemical proxies used by past studies can be used at this location and (2) compare the Feneos data to prior studies from the Peloponnese. Both grain size and geochemical data was collected from the Paleo-lake Feneos core for analysis.

Geologic Background

Feneos Basin

The Feneos Basin is a polje, a large, flat field found in karstic landscapes, in the Northeastern Peloponnese (Figure 2). The basin has an average altitude of 700 m asl, and is surrounded almost completely by mountains, the tallest peak reaching 2100 m asl. This extreme relief between basins and mountains is common across the Peloponnese (Figure 3).

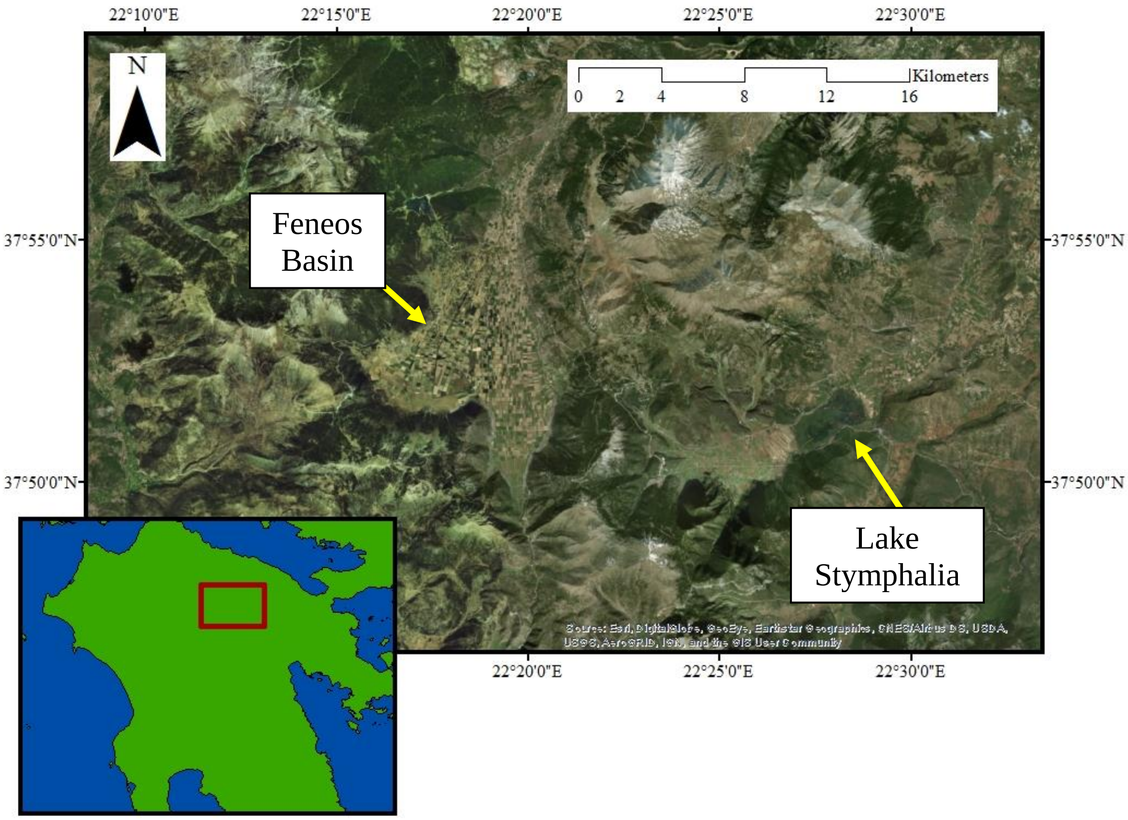

Figure 2. A satellite image of the Feneos Basin and neighboring Lake Stymphalia (both marked on the map). Map created using data from the USGS and ESRI.

In the past, the basin floor was occupied by Paleo-lake Feneos, allowing for lake sediments to accumulate. No lake exists at this location today, and the floor of the basin is covered by farmland. Due to the surrounding mountains, the lake was only fed by hillside run-off and underground springs. Similarly, no outlets existed to drain the lake, so karstic springs also drained the lake (Conners, 2016).

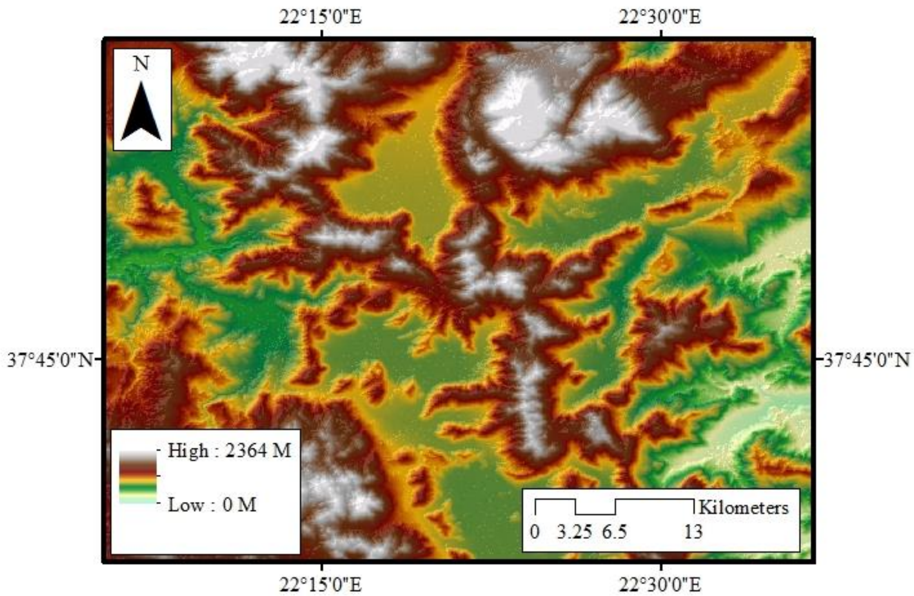

Figure 3. Digital Elevation Model (DEM) of the Feneos Basin and surrounding landscape. The Feneos Basin is in the upper center of this map. Map created using data from the USGS and ESRI.

Climate on the Peloponnese

There are strong gradients of precipitation and temperature across the peninsula. The west is typically wetter and cooler, while the east receives less rain and is typically warmer (Unkel, 2011). Figure 3 shows the changes in relief in the northeastern Peloponnese, which is typical of topography on the Peloponnese. The low-lying basins can develop microclimates very different from their neighbors (Unkel, 2011).

The climate of the Peloponnese is unique because the peninsula sits beneath an atmospheric transition zone between two climate systems, the Asian Monsoon System and the North Atlantic Oscillation (NAO). Summer winds blow from east to west, originating in the north, and their strength is associated with the intensity of the Asian monsoons (Katrantsiotis, 2019). During the winter, the NAO determines where moisture and air are carried from. The NAO can be positive or negative, and this dipole is controlled by the North Sea–Caspian Pattern (NCP), which is caused by the difference in atmospheric pressure above the North Sea and the Caspian Sea. In southern Europe, a strong NAO and weak NCP are associated with drier conditions and climate records on the west and east sides of the Peloponnese agree (NOAA, 2019) (Katrantsiotis, 2019). A weak NAO and a strong NCP are associated with cooler and wetter conditions in the northeast Peloponnese, and climate records on the west and east sides of the Peloponnese disagree (NOAA, 2019) (Katrantsiotis, 2019). Figure 4 is a map centered over the Peloponnese and shows the different climate patterns in relation to the peninsula. A strong NAO generally from the south west, hence the west to east temperature/precipitation gradient formed across the Peloponnese. A weak NAO allows

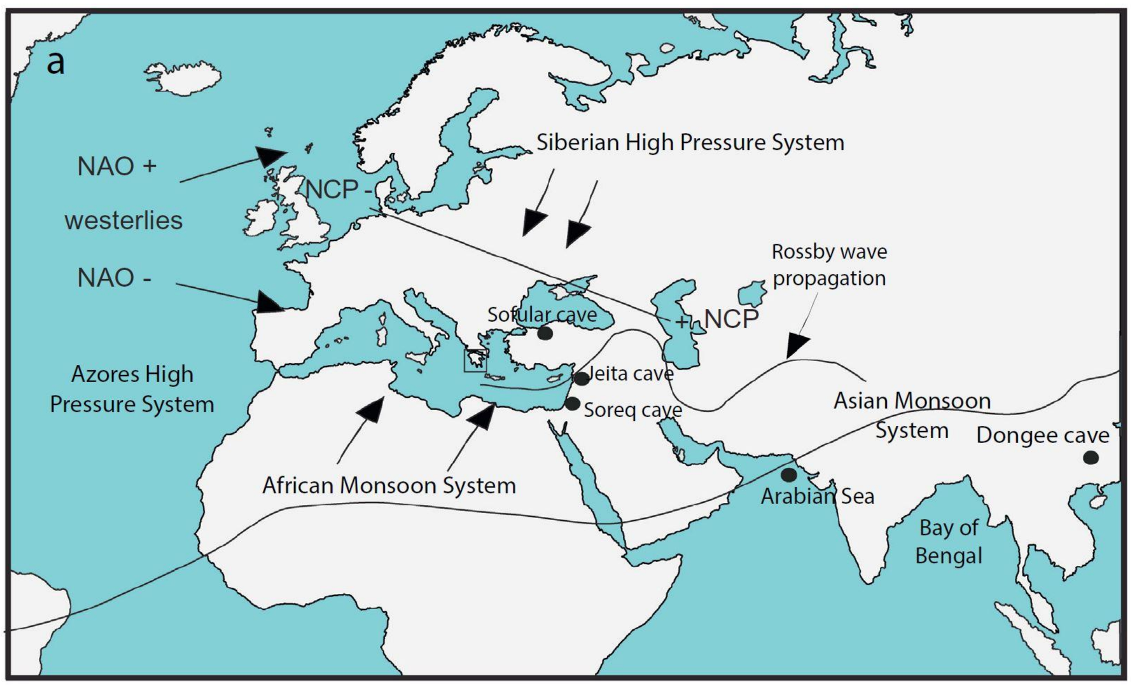

Figure 4. Map of the large atmospheric patterns that influence the climate of the Peloponnese. The NAO and the Asian Monsoon are the main influences on the Peloponnese climate. Map modified from Katrantsiotis (2019).

for air to sneak in from the north east, which is why the north east Peloponnese experiences cooler and wetter conditions during these times. Lake sediments preserve long term climate, and therefore changes in climate, so lake sediments on the Peloponnese are especially valuable because of they become archives of largescale atmospheric shifts at mid and low latitudes (Heymann, 2013) (Katrantsiotis, 2019). Lake sediment archives on the Peloponnese are sensitive enough that discrepancies appear between climate records in the southwest and records in the northeast (Katrantsiotis, 2019).

Paleoclimate studies on the Peloponnese

Heymann (2013) and Unkel (2011) performed geochemical analysis on a sediment core collected from Lake Stymphalia in the Northeastern Peloponnese. The Heymman (2013) record covers 15000 to 5000 yrs. BP and events such as the Younger Dryas and the 8.2-event were identified. They also concluded that, according to lake level fluctuations, the Stymphalian record best matches trends seen in the Eastern Mediterranean. Unkel (2011) included the last 5000 yrs. in their record and identified the Little Ice Age (LIA). Periods of increased precipitation were identified at 6800, 4000 to 3700, 3500 to 3000, and 500 to 200 yrs BP (Unkel, 2011).

Unkel (2014) collected a sediment core from the Asea Valley, a sedimentary basin in the central Peloponnese, and conducted geochemical analysis on the sediments. Pedogenic processes on the surface interrupted the climate record of the last 2000 yrs., but the record dates into the mid-Holocene. The Asea Valley experienced more humid conditions than normal, which could also be cooler conditions, from 3250 to 2700 yrs. BP, matching records in Northern Europe and Northern Italy. Rapid changes in climate, like the 4.2-event (a rapid transition into warm/dry conditions), were not observed in the Asea Valley core. This could be due to the central location of the valley, and the extreme differences in relief that create microclimates (Unkel, 2014).

Katrantsiotis (2016) conducted analysis on geochemical proxies and diatom assemblages on a sediment core from the Messinian Plain. They found evidence of variable erosional and depositional activity. At 5700 and 5300 yrs BP, an open water environment quickly developed and lasted about a decade both times. Between 4500 and 2500 yrs BP a terrestrial environment developed because of less precipitation and decreasing spring activity. Since 2500 yrs BP a wetter climate has persisted, and human activity has steadily increased (Katrantsiotis, 2016).

Katrantsiotis (2019) focused on Lake Lerna in the Northeastern Peloponnese for their geochemical analysis. Wet periods were identified at 3900 to 3300, 3200 to 3000, and 1800 to 1300 yrs. BP, while dry conditions, typical for the Northeastern Peloponnese, persist between these wet periods. It was determined that the Lake Lerna record correlated best with the Asea Valley record published by Unkel (2014) (Katrantsiotis, 2019). In this project, we correlate a new sediment core from the Feneos Basin with these existing studies of paleoclimate on the Peloponnese.

Methods

Coring

During March of 2017, field work was completed in the Feneos Basin. The result was two adjacent cores taken from paleolake sediments in the southern end of the basin (Fig. 5). The cores were split in half and preliminary sediment units determined based on color and estimated grain size. Half of each core was packaged and preserved specifically for XRF scanning, while the other half would be used for sampling. Both cores were shipped to and refrigerated at Kiel University until further analysis could be completed.

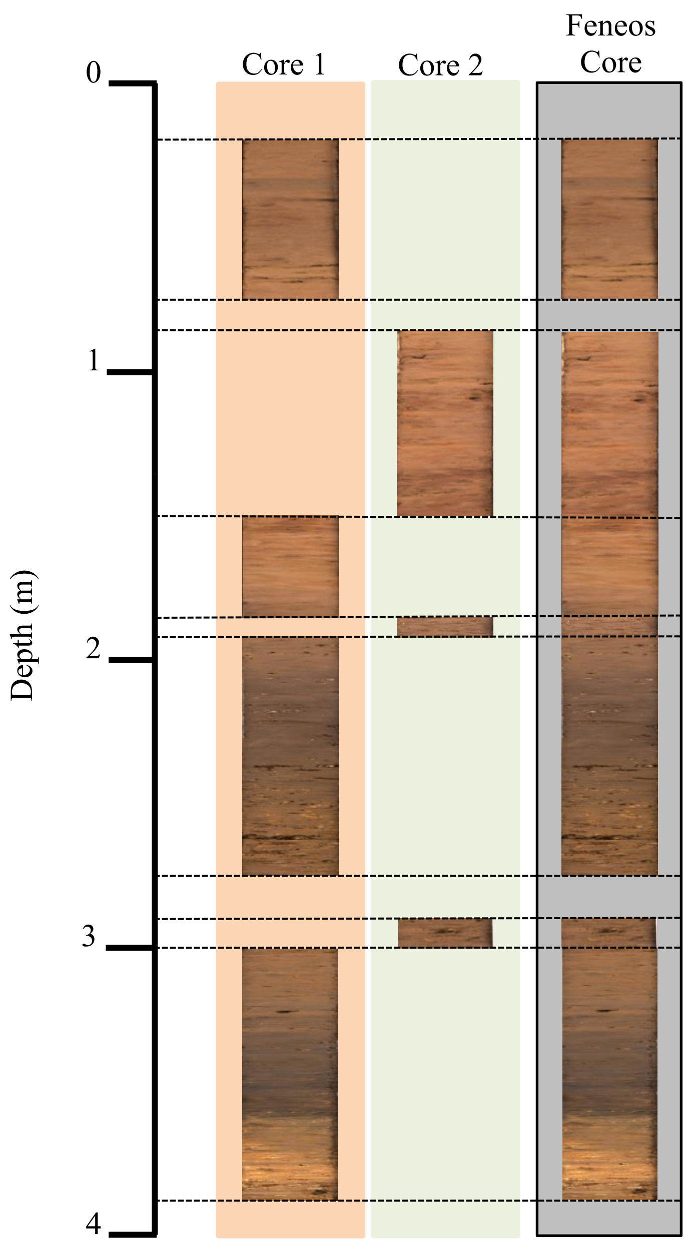

Figure 5. The construction the composite Feneos core from the two nearby cores taken from Paleo-lake Feneos.

A single, and nearly complete, core was constructed from the two nearby cores using the method in Cartier et al.

(2018; Figure 5). Material was not recovered during coring between 75-85 cm and 275-290 cm, so there are two gaps in the composite core. The top 19 cm of the core was modern soil from the plow zone and was not included in this analysis.

Line Scanning X-Ray Fluorescence

The Feneos core was scanned with an Avvatech Line Scanning X-Ray Fluorescence (XRF) instrument at the Kiel University. A measurement was taken every 5 mm for 10 seconds at 10 kV. Only the parts of the two collected cores that make up the composite core were scanned. Images of the entire core sections were collected by a camera mounted on the Avvatech scanner at this time and were later cropped to create images of the core (Figure 5).

Geochemical Proxies

Geochemical proxies take advantage of the unique behavior of different chemical elements, such as reduction potentials, solubility, and mobility. In this study we use geochemical proxies applied to the core sediments to investigate alkalinity, winter precipitation, and summer evaporation.

We used alkalinity proxy of Unkel (2014), Heymann (2013), and Unkel (2011), calculating the log ratio of Mn/Fe. Alkalinity describes the ability of water to buffer against the addition of acids and bases. This is typically to do with the concentration of specific ions within solution, which in a lake can vary due to changes in water level or a large influx of new ions. When the water becomes more basic, conditions in the water become reducing or anoxic. During these periods, metal ions with higher reduction potentials precipitate out of solution at a higher rate than metal ions with lower reduction potentials. Manganese (Mn) and iron (Fe) are two metals with different reduction potentials and can be compared in a ratio to each other as a proxy for reducing and oxidizing conditions in Paleo-lake Feneos. Fe has a higher reduction potential than Mn, so during anoxic conditions will precipitate and deposit at the bottom of the lake at higher levels than Mn (Davison, 1993). Low ratios indicate reducing conditions, while high ratios indicate oxidizing conditions. Sediment that accumulates under reducing conditions is often a darker color, sometimes even blue.

Aluminum (Al) is a relatively immobile element, so its concentration in sediments should remain constant, despite varying environmental conditions. Due to this immobility, Al can be used to normalize other elements that are mobile. Placing Al in the denominator of ratios normalizes concentrations to a constant initial volume of sediment. This is necessary for geochemical concentrations that total 100%, where the addition or subtraction of a single element would otherwise affect the relative concentration of all the remaining elements. The ratios are plotted on a log scale, so the extreme highs and lows do not dominate the plot, and because the log-transformed values have better statistical properties (Aitchison, 1982). Because the data are transformed, they cannot be directly interpreted in the same way as concentrations, but the relative changes can be compared to other relative changes seen in other archives.

To measure precipitation, we used the geochemical proxy used by Unkel (2014, Heymann (2013), and Unkel (2011), calculating the log ratio of Rubidium/Al. During the rainy winter, hillslope run off will add siliclastic sediment to the lake (Unkel, 2014). This sediment is enriched with Rubidium (Rb) relative to the carbonate precipitates that also accumulate in the bottom of the lake. During periods of increased precipitation, more physical weathering occurs on the hillslopes, washing more Rb into the lake. When plotted as a ratio with Al, higher values indicate increased precipitation.

We calculated evaporation rates with the log ratio of Sr/Al, the same proxy used by Unkel (2014), Heymann (2013), and Unkel (2011). Due to the Mediterranean climate of the Peloponnese, most of the annual evaporation occurs during the summer. As water evaporates from Feneos, carbonate minerals precipitate and deposit on the lake bottom. Strontium (Sr) commonly substitutes into the structure of the carbonate minerals, so the level of Sr in the lake sediment is a signal for evaporation rates (Unkel, 2014). When plotted as a ratio with Al, higher values indicate increased evaporation.

The winter precipitation and the summer evaporation proxies can be combined into one by plotting the log of the ratio of Sr/Rb. This proxy is used to simultaneously calculate warmer/drier (lower Sr/Rb) and cooler/wetter (higher Sr/Rb) periods (Unkel, 2014) (Katrantsiotis, 2019) (Katrantsiotis, 2016) (Heymann, 2011).

Endmember Modeling

Approximately 1.5 g of wet sediment was taken from the core, at about every 30 cm depth. Samples were dried, broken up, and then treated with hydrogen peroxide according to Gee (1986). We measured the grain size distribution of a subset of samples along the core using a Mastersizer 2000 laser diffraction instrument.

We tested whether each grain size sample could have been a composite of unique endmembers using the EMMAGeo package, written by Hartmann (2018) and initially developed by Dietze (2012), running in the data analysis environment R (R Core Group, 2018). In this context, endmembers refers to the number of sources contributing to sedimentation in Paleo-lake Feneos. The EMMAGeo package repeatedly performs analysis on the grain size data, each time modeling the data set for a whole number of endmembers. The optimal number of endmembers will explain the most variance in the data set. In other words, the package determines which number of endmembers explains the dataset best.

Results

Grain Size Composition

A table of the Feneos grain size data can be found in the appendix. The Feneos sediment is predominantly clay and silt size particles. At each sampled depth, there is a small percentage of sand sized particles. For all the samples, sand sized particles account for less than 3% of the sediment (Fig. 6). There is not a consistent fining-upward or coarsening upward trend evident from our samples.

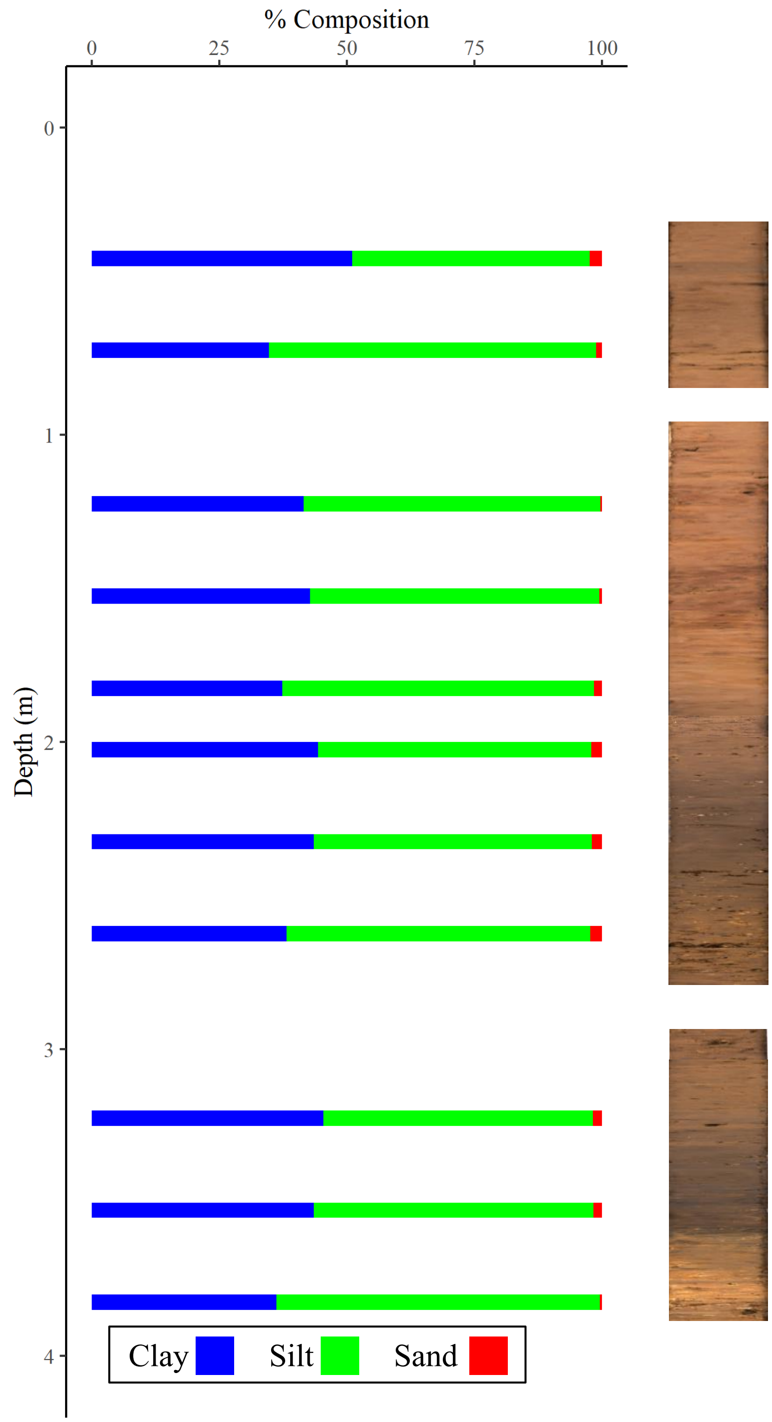

Figure 6. Grain size fractions of the Feneos core, the %composition is plotted on the x-axis and depth on the y-axis.

Endmember Modeling

Six endmembers, or six sediment sources, were identified using EMMAGeo in R. Figure 7 shows the modeled loadings of the six end members. Here, volume proportion refers to how much each size class contributes to an individual endmember's total composition. Each endmember should have a characteristic grain size loading that is added to the sediment. All the modeled Feneos endmembers are centered on or around phi size 7 and 8, which are fine silt sizes.

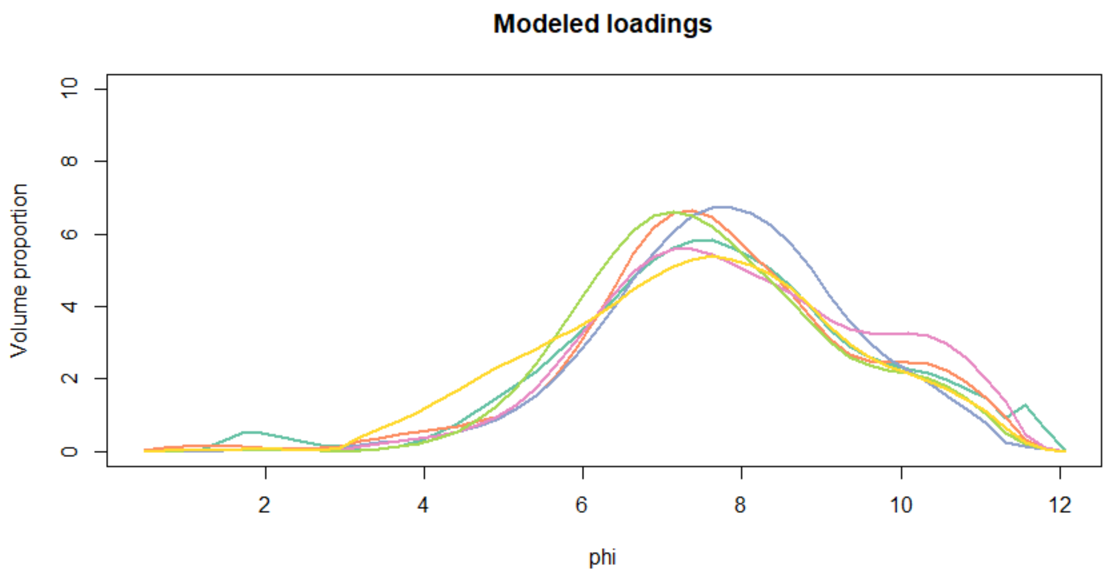

Figure 7. The modeled loadings of the 6 endmembers determined by the EMMAGeo package. Each line represents an endmember. All of the endmembers are centered over phi size 8 but have slightly different proportions of each phi size.

Geochemical Proxies

Figure 8 is the plotted log ratio of Mn and Fe, which describe the water conditions that occurred during deposition. Images of the Feneos core are plotted next to the graph. The depth is increasing down the y-axis with the relative value of the log ratio fluctuating between -2 and -5. More negative values indicate more oxidizing conditions whereas negative values closer to zero indicate more reducing conditions. In general, the Feneos core is relatively oxidized. Most of the log ratio values are centered around -3.5, and small fluctuations occur throughout the core. The most oxidizing conditions occur in the bottom meter of core. The most reduced sediments are at approximately 3.6 m in depth, just below the most oxidized sediments at about 3.5 m.

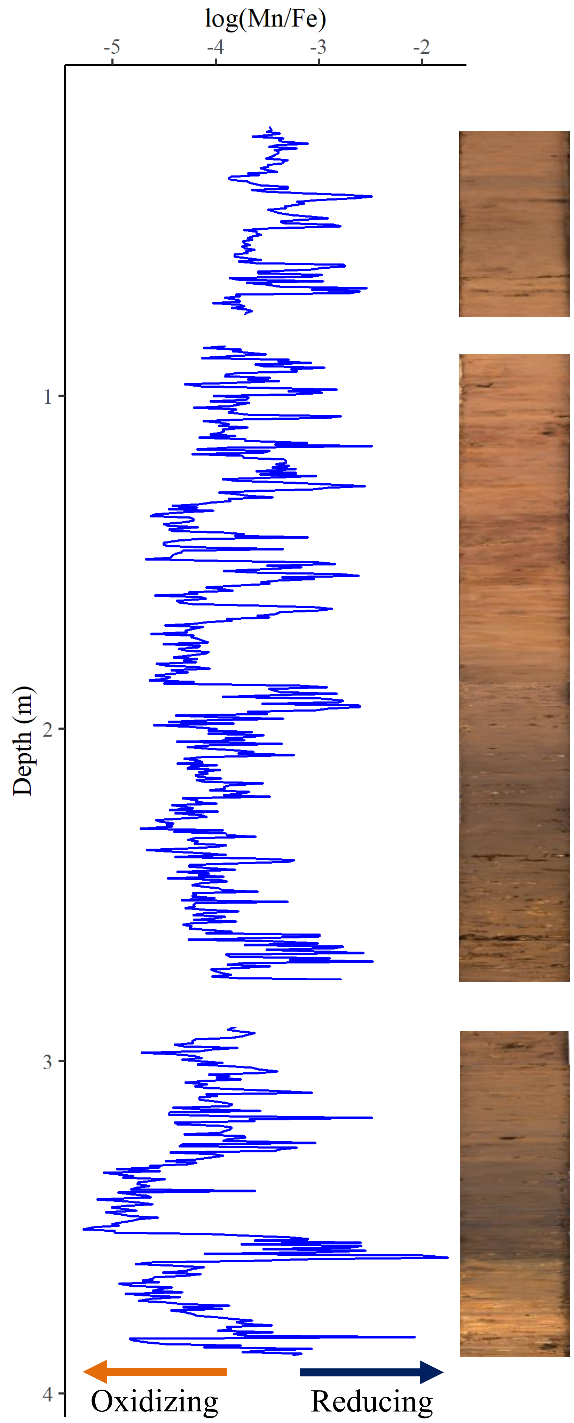

Figure 8. Alkalinity geochemcial proxy plot for the Feneos core. larger negative values indicate oxic conditions and smaller negative numbers anoxic conditions.

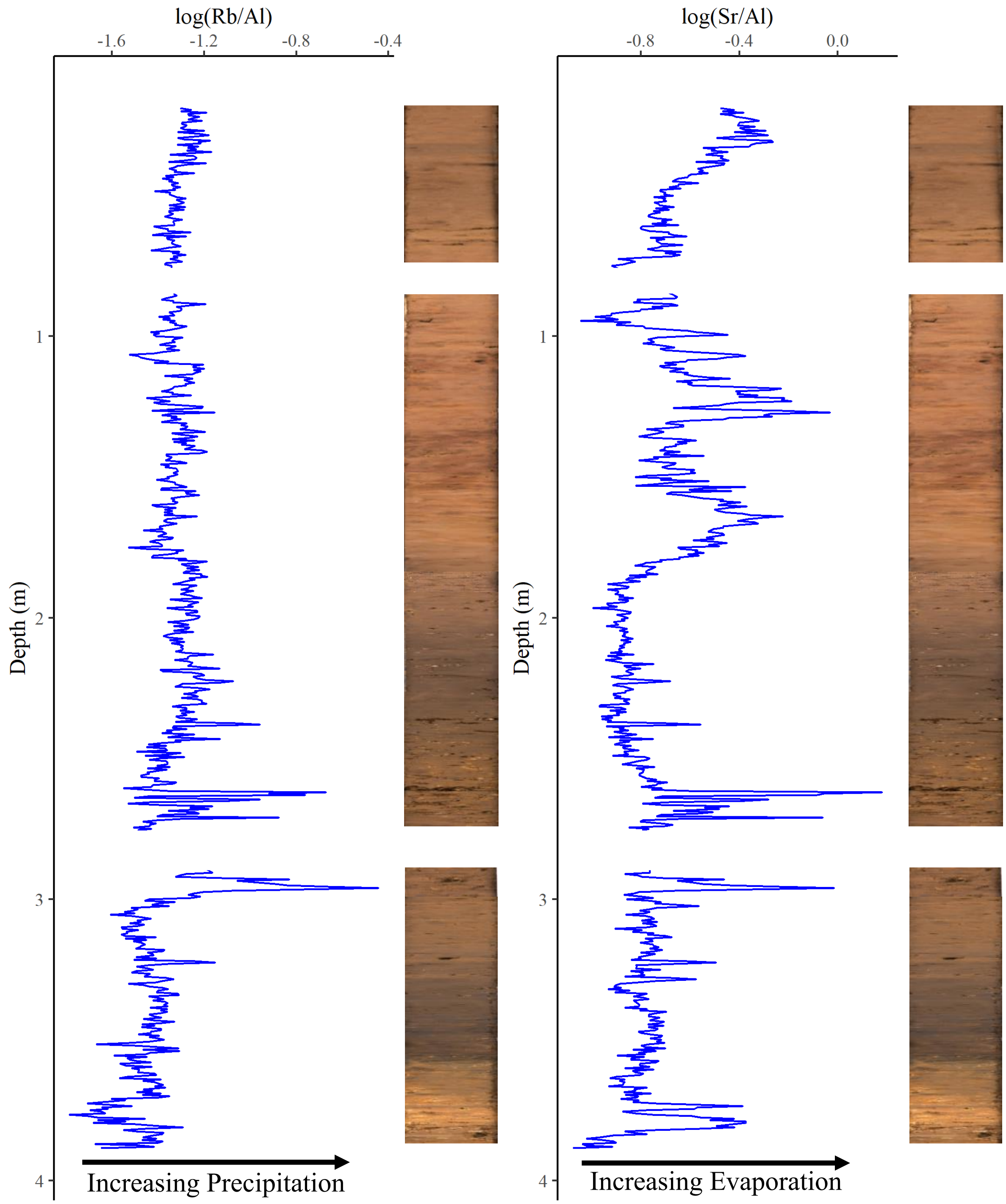

Figure 9. The winter precipitation (left) and summer evaporation (right) of Paleo-lake Feneos. Depth is on the y-axis and is equivalent to time. At the bottom of the core are the oldest sediments, and at the top the youngest.

The log ratio of Rb and Al is the proxy for winter precipitation (Fig. 9, left), with higher values indicating high precipitation, and more negative values indicating lower precipitation. This proxy is consistent throughout most of the core, with calculated values around -1.2 between 19 and 2.66 m depth and below 2.9 m depth. At 2.66 m and 2.9 m depth there are peaks indicating higher precipitation.

We calculated summer evaporation using the log(Sr/Al) proxy (Fig. 9, right), with higher values indicating high evaporation, and more negative values indicate low evaporation. Unlike winter precipitation summer evaporation is much more variable. Low evaporation values occur at 9.5 m and 1.25 m. Peaks in evaporation occur at 2.66 m, 3 m, and 3.75 m depth.

Discussion

Endmember Modeling

While the EMMAGeo package predicted 6 endmembers to be influencing the sediment in Paleo-lake Feneos, the modeled loadings of the six endmembers are not very different (Figure 7). All the predicted endmembers are predominantly silt and clay sized fractions, with very slightly different loading amounts. Therefore, we do not have enough evidence to identify more than one grain size endmember in the sediments of Paleo-lake Feneos.

Geochemical Proxies

A warm/dry and cool/wet climate plot can be created by combining the winter precipitation and summer evaporation plots (Figure 10). The resulting plot can be correlated to other published plots from archives on the Peloponnese. First, we will

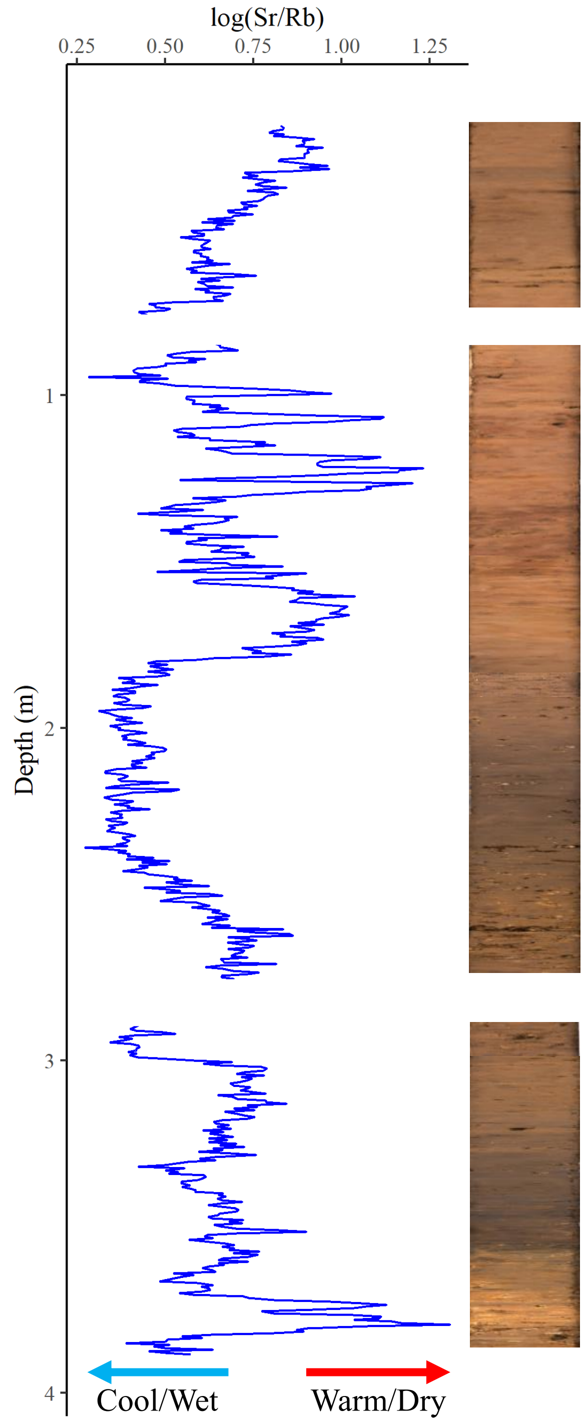

Figure 10. The dry/warm and wet/cool geochemical proxy plot from the Feneos core. Annotations point in the directions of the climate trends. Peaks point to the right for warm/dry conditions and to the left for cool/wet conditions.

compare the Paleo-lake Feneos record to the Asea Valley record (Figure 11). Periods of drier/warmer conditions in both the records are boxed, and the colors of the boxes indicate which events we predict correlate. The oldest peak (3.75 m) in the Feneos record does not have a similar peak in the Asea record. This could be for many reasons including that Feneos experienced significantly drier/warmer conditions than the Asea Valley, which could be explained with the precipitation and temperature gradient across the Peloponnese. Another explanation to explain the peak would be precipitation of carbonate at that depth, which would lead to abnormally higher amounts of Sr. A warm/dry event correlated between the two records (dark red box) appears between 3500 and 3000 yrs. BP. The next period of warmer/drier conditions (green box) appears between 2700 and 1900 yrs. BP. From 2300 to 1500 yrs. BP (purple box) a third period of warmer/drier conditions appear. A highly variable period of dry/warm conditions appears in both records (blue box) from 550 to 950 yrs. BP.

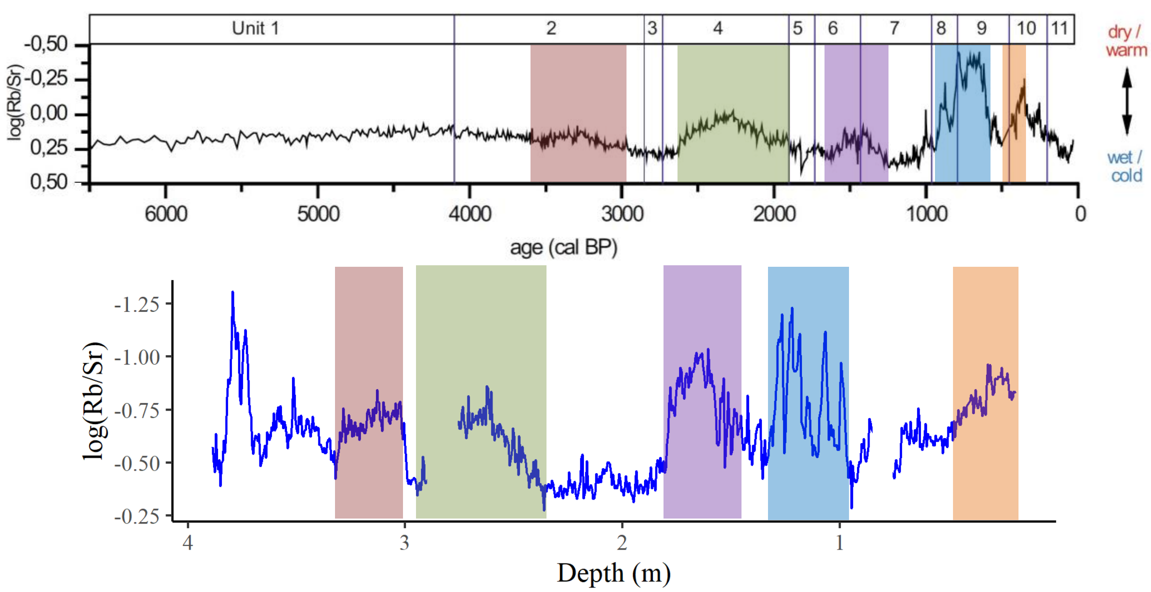

Figure 11. The Asea Valley log(Rb/Sr) plot (top) and the Paleo-lake Feneos log(Rb/Sr) plot (bottom) annotated to show similar peaks (Unkel, 2014).

The uppermost 19 cm of Paleo-lake Feneos were not collected during coring, but the uppermost sediment that was collected displays a drying/warming trend (orange box) from approximately 300 to 500 yrs. BP. Unkel (2014) suspected pedogenic processes to have disrupted the uppermost 2 m of their core. While carbon did not appear to be vertically transported in that area of the core, they could not confidently label the period of wet/cool conditions at 500 yrs BP the LIA.

We can also compare the Paleo-lake Feneos record to the record from nearby Lake Stymphalia. Both cores are lake sediments taken from basins that are adjacent to each other in the northeast Peloponnese (Figure 1) (Figure 2). A non-log ratio of Rb and

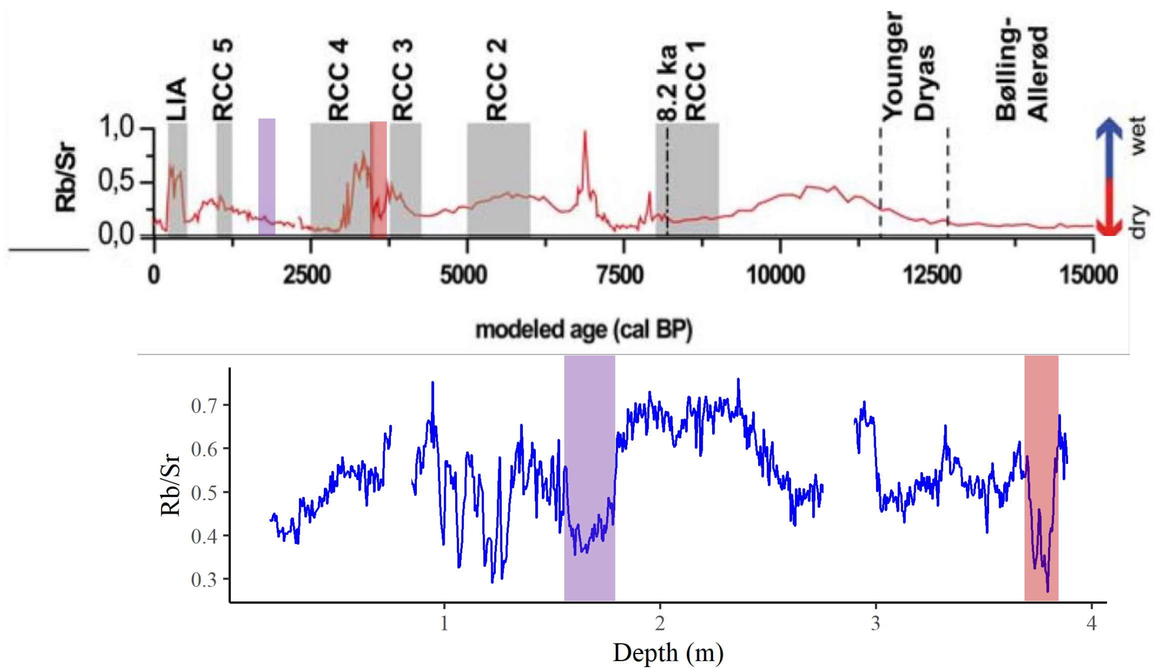

Figure12. The Lake Stymphalia climate Rb/Sr plot (top) and the Paleo-lake Feneos Rb/Sr plot (bottom) annotated to show similar peaks and discrepancies between the Lake Stymphalia, Asea Valley, and Paleo-lake Feneos record (Unkel, 2011).

Sr was used in this plot to match the graph published by Unkel (2011) (Fig. 12). Note that the y-axis is flipped from its orientation in Fig. 11, so dry/warm peaks are pointing down. The same dry/warm peaks seen in the Asea Valley record and the Feneos, between 3500 and 500 yrs. BP, record do not appear in the Lake Stymphalia record at those times

(Figure 12). The dry/warm peak correlated to 2300 to 1500 yrs. BP with the Asea Valley record (purple box) shows this best. The same peak is boxed in purple on the Feneos plot, but there does not appear to be a matching peak between 2300 and 1500 yrs. BP in the Stymphalia core. Unlike the Asea core, the Lake Stymphalia core does appear to have a peak matching the oldest warm/dry peak seen in the Feneos core (red box). In the Stymphalia timeline this peak occurs at approximately 3250 yrs. BP, which has implications for the archeological record. The LBA, a period of societal disruption and economic collapse across the Eastern Mediterranean, could have been partly caused by period of abnormally drier/warmer conditions.

The discrepancies between the Asea Valley, Lake Stymphalia, and Paleo-lake Feneos core could be attributed to the larger atmospheric patterns discussed earlier. Depending on if the NAO is positive or negative, climate records may tell opposing stories for the Peloponnese (Katrantsiotis, 2019). Future studies may be able to better calibrate the Paleo-lake Feneos record to others by constructing an age-depth model from organic material taken from the Feneos core. A timeline for the Feneos record will allow for a much better correlation, and clear up discrepancies between Lake Stymphalia, the Asea Valley, and Paleolake Feneos.

Conclusion

Sediments from Paleo-lake Feneos provide a record of the climate on the Peloponnese beginning approximately 4000 yrs. ago. Previously published records from the Asea Valley can be correlated to the Feneos Basin, and provide an age estimate for our core sediments. In general, Lake Stymphalia sediments are poorly correlated to the Feneos records. One exception is a warm/dry peak observed between 3500 and 3000 yrs. BP at both Lake Stymphalia and the Feneos Basin. Because of its timing, this event may help to explain the Late Bronze Age Collapse in ancient Greece. Further comparisons should be performed using an age-depth model for the Feneos sediments.

Appendix A

Table 1. Grain size composition of the samples taken from the Paleo-lake Feneos core.

Depth (cm)	Clay (%)	Silt (%)	Sand (%)
40	51.08103	46.57459	2.344382
70	34.75714	64.07815	1.164708
120	41.54315	58.15993	0.296922
150	42.78453	56.67277	0.542706
180	37.38143	61.04433	1.574245
200	44.32766	53.55212	2.120223
230	43.53648	54.4962	1.967319
260	38.20313	59.55241	2.244461
320	45.40536	52.79181	1.802838
350	43.48413	54.82423	1.691641
380	36.23761	63.33054	0.431852

Core No.	Section	Depth (cm)
1	1	19-75
2	1	85-150
1	2	150-185
2	2	185-192
1	3	192-275
2	3	290-300
1	4	300-388.5

Table 2. The portions of the two nearby cores taken from the Feneos Basin that constructed the composite Feneos core.

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