

**COUPLING OF OCEAN ACIDIFICATION AND OXYGEN DEPLETION  
IN THE GULF OF ALASKA**

An Undergraduate Research Scholars Thesis

by

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## ABSTRACT

### Coupling of Ocean Acidification and Ocean Depletion in the Gulf of Alaska

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Abrupt deglacial environmental changes are recorded in the North Pacific including the expansion and strengthening of the oxygen minimum zone (OMZ). Previous workers in the North Pacific proposed a link between OMZ intensification and increased ocean acidification. Understanding the relationship between oxygen depletion and ocean acidification during past intervals of climate change is crucial for forecasting and mediating the effects that the modern-day OMZ expansion will have on marine ecology. Here, I use benthic (*Uvigerina peregrina*) and planktonic (*Neogloboquadrina pachyderma*) foraminiferal size-normalized shell weights (SNW) from two Gulf of Alaska sediment core records as a proxy for carbonate dissolution, which increases with increasing acidification. If ocean acidification increased during a previously recognized low oxygen event (LOE; ~15-10 kya) should result in lower shell weights due to dissolution if ocean acidification is associated with deoxygenation. At intermediate ocean depths, planktonic SNW were generally lower while high benthic SNW increased, perhaps due to acidification in the water column affecting the planktonics, whereas, dissolution oversaturated pore waters with carbonate ion. SNW of planktonics were heavier in the intermediate than deep site, possibly due to heavier sedimentation rate or more sulfidic conditions in the pore waters at intermediate depths.

## NOMENCLATURE

OMZ	Oxygen Minimum Zone
CMZ	Carbon Maximum Zone
DIC	Dissolved Inorganic Carbon
LOE	Low Oxygen Event
SNW	Size Normalized Weight
MBW	Measurement-Based Weights
SBW	Sieve-Based Weights
AD	Area-Density

# CHAPTER I

## INTRODUCTION

The oxygen minimum zone (OMZ) is an oxygen-depleted region where aerobic respiration dominates at intermediate ocean depths (~600-1000 m) [Paulmier et al., 2009]. The OMZ varies in oxygen concentration and thickness spatially in the modern ocean [Schmidtko et al., 2017] and varies temporally as global climate, ocean circulation, and regional oceanography changes. Variation in OMZ extent and intensity may be associated with two water column processes. Increased ocean stratification would hinder the exchange between surface and bottom water masses, preventing the reoxygenation of the interior of the ocean, in turn, prolongs contact between deep water masses and the atmosphere [Du et. al, 2018; Schmidtko et al., 2017]. Additionally, increased local primary productivity and respiration would result in the consumption of oxygen and generation of CO<sub>2</sub> as the organic matter is respired.

Decreased oxygen concentrations and increased dissolved inorganic carbon (DIC) are both characteristics of modern OMZs [Wyrтки, 1962; Paulmier et al., 2011] demonstrating a key control of respiration on OMZ position and intensity. The carbonate maximum zone (CMZ) coexists within the entirety of the OMZ, and is defined by high DIC concentrations (>2225  $\mu\text{mol kg}^{-1}$ , up to 2350  $\mu\text{mol kg}^{-1}$ ) [Paulmier et al., 2011]. Thus, both oxygenation and DIC may vary with time if locally respired carbon is the driver of low-oxygen conditions. The Pacific Ocean contains the largest OMZ of the world and is continually decreasing in oxygen content in the modern [Paulmier et al., 2008; Schmidtko et al., 2017]. Decreasing oxygen in the modern Pacific Ocean is due to the increased respiration and warming-induced reduction in oxygen solubility in

the shallow depths, while deep depths are subject to meridional overturning circulation slowdown and potential increase in respiration [Schmidtko et al., 2017].

Understanding the link between the OMZ and CMZ during a period of past climate change, is the key to predicting and alleviating the effects hypoxia and acidification will have on modern marine ecology. Foraminifera collected from sediment samples can provide insight on ecological responses to low-oxygen and ocean acidification events over the past 20,000 years. Foraminifera are single-celled organisms that build their tests by secreting calcium ions which bond to freely available carbonate ions in the ocean. Availability of carbonate ions and the acidity of the water column are two important components that play into shell weight. Because shell carbonate dissolves as ocean acidification increases, shells of similar size will have lower weights with an increase in CO<sub>2</sub>. An increase in CO<sub>2</sub> reacts with carbonate in the system to produce bicarbonate, this allows for the uptake of CO<sub>2</sub> into the water column and the decreases available carbonate ion (Figure 1). This increases the acidity of the ocean, in time, leads to overall acidification of the ocean.



*Figure 1: CO<sub>2</sub> dissolves in water to produce dissolved inorganic carbon (DIC) ions and hydrogen ions. An increase in hydrogen ions would lower the water pH.*

Foraminiferal shell weight reflects both the amount of carbonate the organisms precipitated to make it shell and the dissolution of that shell after death. As such, shell weights are used as a proxy for carbonate ion concentration to reconstruct ocean acidification in palaeoceanographic records. However, weight varies with size therefore shell weights must be normalized to size to ensure captured changes are in carbonate dissolution and not in organism size. Thus, more recent studies use size normalized shell weights (SNW) or restrict weights to a

narrow size fraction [Davis et. al, 2016; Marshall et al., 2013; Pak et. al, 2018]. Therefore, I compared size-normalized weights to existing independent proxies for oxygenation (ex. redox sensitive metals such as Re and Mo) already measured on the same marine sediment samples, to test the hypothesis that SNW of foraminifera, and thus ocean acidification, decrease in response to the previously recognized low oxygen event (LOE).

In this study, I modify size-normalization methods from previous studies to examine relationship between SNW and oxygenation. Three methods are traditionally used when size-normalizing weight: measurement-based weights (MBW), area-density (AD), and sieve-based weights (SBW). MBW is a method used to size-normalize weights, which traditionally normalizes weight with a mean diameter or area silhouette. AD normalizes shell weight by taking weights and area silhouettes of individuals within a sample, which are then averaged for a sample mean. A previous study in the Santa Barbara Basin examining SNW over the past 15kyrs, did not see a relationship between SNW and oxygenation using the MBW method by normalizing with an area silhouette [Davis et. al, 2016]. The inability to see a relationship, was attributed to SNW relationships acquiring to be interpreted at a species-specific level. SBW is an additional method to size-normalize weights, which restricts samples to a narrow size fraction which then the mean of the sample is calculated. This method could skew results due to size variation within the sample not being accounted for. A different study in the Santa Barbara basin used SBW over the last 150 years, successful when finding a relationship between SNW and oxygenation [Pak et. al, 2018]. Although MBW is more efficient than SBW, SBW used sample average rather than individual weight that was used by [Marshall et al., 2013] when size-normalizing, using the AD method. Here I will use the MBW method and account for the volume of each individual rather than the area. Volume is preferred in this study over the area silhouette

used by [Davis et. al, 2016] due to volume accounting for change within the interior shell chambers.

### Site Location and Environment

The intermediate depth site 341\_U1419 was cored in the Gulf of Alaska (59.6° N, 144.2° W, 682 m) on the slope of a 25 km wide continental shelf of the Gulf of Alaska near Kayak Island. Deep-water sites 341\_U1418 and co-located EW0408-87JC (58.8° N, 144.5° W; 3703 m and 3,680 m water depth, respectively) were cored an elevated region of the proximal Surveyor Fan [Jaeger et. al, 2014] (Figure 2). The intermediate site is in the upper edge of the modern OMZ (341\_U1419) and the deep site below the OMZ (341\_U1418 and co-located EW0408-87JC) (Figure 3). Both sites record decreases in oxygenation during the last deglacial (18,000-14,000 years ago) [Davies et al., 2011; Praetorius et al., 2015; Belanger et al., 2016] and thus may also record associated changes in acidification. However, decreases in oxygenation were greater at the intermediate site than the deep site, thus we may expect to see different ocean acidification histories at each.

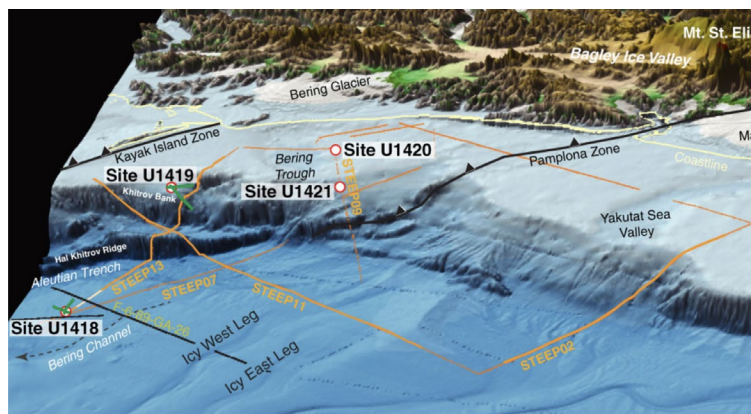


Figure 2: Map shows location of core 341\_U1418 (and co-located EW0408-85JC) and 341\_U1419 within the Gulf of Alaska and proximal geologic features [Gulick et. al, 2013].

Each site also has different expectations for changes in productivity. The intermediate depth site is located between the Copper River shelf and the Bering-Malaspina shelf, which



contribute to possible terrestrial sediment influx [Davies et al., 2011]. Nutrients can be delivered to the Gulf of Alaska during glacial retreat, such as during the last deglacial in the past of warm summers in the modern, when runoff is high [Davies et al., 2011]. Seasonal productivity near 341\_U1419 is limited in the winter in the modern due to low light and vertical mixing. However, spring is the beginning of moderate productivity and grades into high productivity within the early summer. Summer is a period of high sun light, nutrient upwelling and nutrient flux from fluvial systems, the Cooper River and rivers branching off the Bering and Malaspina glaciers [Jaeger et al., 1998]. Moreover, when spontaneous, non-annual, amounts of nutrients are presented to the system, this can be tied to the effect of environmental or climatic changes such as a warming event. The deep site is located between Aleutian Trench Channel and Bering Channel, that could contribute to terrestrial and nutrient influx [Jaeger et. al, 2014]. Additionally, eddies within the westward-flowing Alaska Current provide seasonal high productivity [Jaeger et. al, 2014].

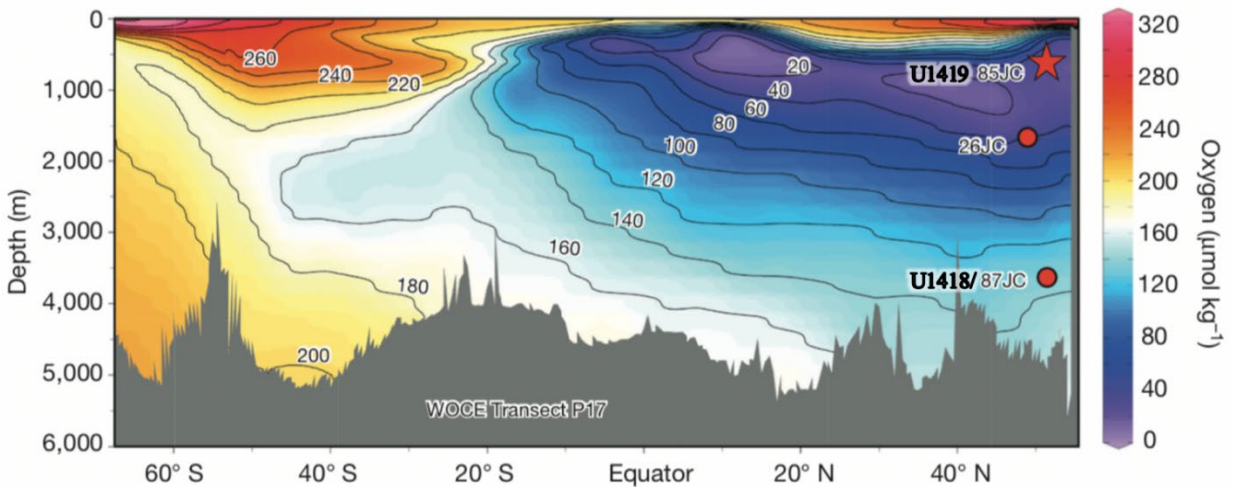


Figure 3: EW0408-87JC and U1418 are shown to be at different depths and oxygen concentrations than U1419 [Praetorius et al., 2015].

## CHAPTER II

### METHODS

#### Sample Preparation

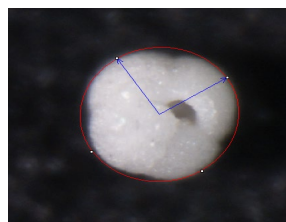
Twenty-five samples were selected from 341\_U1419 and 26 samples from both EW0408-87JC and 341\_U1419 over the past 20,000 years. Each sample was freeze dried, disaggregated in DI water, and wet sieved over a 63 $\mu$ m sieve. I picked a range of 7-10 (mean: 9.4) individuals of two species: *Neogloboquadrina pachyderma*, a planktonic foraminifer used in both sites and *Uvigerina peregrina*, a benthic foraminifer picked only in the intermediate depth. All individuals are from the 250-125 $\mu$ m size fraction, have no filling and are complete, well-preserved specimens.

*Uvigerina peregrina*



$$V = \pi r^2 h$$

*Neogloboquadrina pachyderma*



$$V = \frac{4}{3} \pi r^3$$

Figure 4: Morphological dimensions of each species are depicted with the associated geometry equation used.

#### Size Weight and Normalization

I weighed individuals to the nearest .1  $\mu$ g of each species for each sample using a Sartorius Ultramicro Balance for the overall sample weight ( $W_T$ ). Individual shell dimensions were digitally measured along the x-y plane using a Nikon SMZ 1500 stereoscope at 30x

and the software program NIS Elements BR. These taxa have morphologies resembling a cylinder (*U. peregrina*) and sphere (*N. pachyderma*), therefore their radii and diameters were acquired by measuring the length and width in 2-D (*Figure 4*). These dimensions were then used to calculate volume of each individual which were then summed together for the total sample volume ( $V_T$ ). Each sample was size normalized using the SNW formula:

$$\text{SNW} = \frac{W_T}{V_T}$$

### **Redox Metals**

Redox sensitive elements such as Molybdenum (Mo), and Rhenium (Re), can be used as paleo-environmental redox proxies to help reconstruct past OMZs, due to the insolubility of elements at different levels of oxygenation [Moffitt et al., 2015]. Molybdenum is associated with anoxic (sulfidic) conditions, while Rhenium is associated with the onset of suboxic conditions, or intermediate oxygen levels [Moffitt et al., 2015].

Mo and Re concentrations were collected from  $\sim 60 \pm 2.5$  mg of each sample using ICP-MS at Oregon State University. In order to determine excess amounts of redox metals precipitated from seawater rather than due to influx from terrestrial sediment, elemental concentrations were standardized to the aluminum concentration. Once the terrestrial influx was removed, the concentration redox sensitive trace elements were used as oxygenation proxies.

### **Relationship Between SNW and Redox Metals**

Weight and diameter data of planktonic and benthic foraminifera samples of deep and intermediate sites were rank-order correlated to analyze relationship between organism size and weight. Normalized redox metals (Re/Al and Mo/Al) and SNW of planktonic/benthic foraminifera from intermediate and deep sites were rank-order correlated to test for a relationship between redox concentrations and SNW. Spearman rank-order correlation was preferred over a

Pearson correlation due to abnormal distribution and nonlinearity between SNW and redox metal data. Online statistical computation, Vassar Stats, was used to compute correlation and p-tail values using the Spearman rho and Mann-Whitney correlation method.

## CHAPTER III

### RESULTS

Weight and diameter data of planktonic and benthic foraminifera samples of deep and intermediate sites have a strong correlation (Table 1). *N. pachyderma* range in weight from ~10 to ~90  $\mu\text{g}$  at both sites, but had a larger size range in the deep (Figure 5). At larger diameters of *N. pachyderma* shell weights are generally heavier in the intermediate than the deep. *U. peregrina* shells weights were heavier than *N. pachyderma* with a given diameter.

Table 1: Spearman rho rank-order correlations between weight and diameter of planktonic and benthic foraminifera samples of deep and intermediate sites.

	<b>INTERMEDIATE <i>Neogloboquadrina pachyderma</i></b>	<b>Deep <i>Neogloboquadrina pachyderma</i></b>	<b>INTERMEDIATE <i>Uvigerina peregrina</i></b>
<b>Spearman Rho</b>	0.9077	0.9152	0.8792
<b>P (one-tailed)</b>	<.000001	<.000001	<.000001

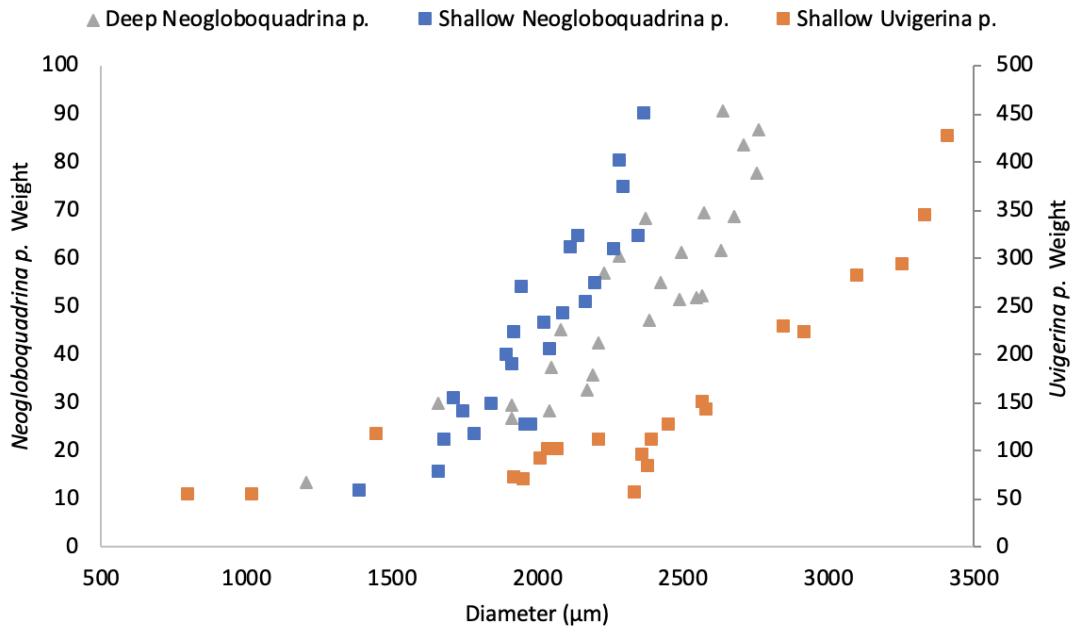


Figure 5: Shell diameter and weights *Neogloboquadrina pachyderma* from the deep site (gray triangles) and intermediate site (black circles) and intermediate site sample of *Uvigerina peregrina* (orange squares).

## SNW of Foraminifera Over the Past 20,000 Years

Spearman rho values for SNW and Re/Al in both sites are marginally correlated (Table 2). Planktonic SNW data sets of both sites were negatively correlated with Re/Al, while deep benthic SNW are positively correlated. Mo/Al were poorly correlated with Mo/Al of both sites. Moreover, Mo/Al values of the intermediate showed positive correlation while deep site showed negative (Table 2).

The interval of time were Re/Al values exceeded .6 and were continuous through the deglacial from 15,460-10,320yrs in the intermediate and 14,789-10,678yrs in the deep, defined the Low Oxygen Event (LOE). Re/Al values were consistently higher during the LOE than during the glacial and Holocene of the intermediate (M-W test  $U= 1191$ ,  $p = <.0001$ ) and deep site (M-W test  $U= 175$ ,  $p = <.0001$ ). However, Re/Al and Mo/Al concentration values in the intermediate site exceed those of the deep site during the LOE (*Figure 6*).

Table 2: Rank order correlation between SNW planktonic or benthic species of the intermediate and deep sites.

	<b>INTERMEDIATE</b> <i>Neogloboquadrina</i> <i>pachyderma</i>		<b>Deep</b> <i>Neogloboquadrina</i> <i>pachyderma</i>		<b>INTERMEDIATE</b> <i>Uvigerina Peregrina</i>	
<b>Redox metal</b>	<b>Re/Al</b>	<b>Mo/Al</b>	<b>Re/Al</b>	<b>Mo/Al</b>	<b>Re/Al</b>	<b>Mo/Al</b>
<b>R<sub>s</sub></b>	<b>-.32</b>	<b>.095</b>	<b>-.33</b>	<b>-.14</b>	<b>.29</b>	<b>.16</b>
<b>P- 1 tail</b>	<b>.06</b>	<b>.32</b>	<b>.05</b>	<b>.25</b>	<b>.22</b>	<b>.25</b>

Benthic SNW values in the intermediate site are low in the early glacial (*Figure 7*). SNW increases prior to the LOE and remain consistent until a sharp increase at 13,355 yrs. Throughout the LOE and ~1,100 years after, intermediate benthic SNW weights remain consistently high. Intermediate site benthic SNW values in the late Holocene are low and consistent with low SNW during the glacial. Intermediate site *U. peregrina* data have no significance between SNW values within and outside of the LOE (M-W test  $U=105.5$ ,  $p=.102$ ). However, SNW values

remain consistently high from 13,335 to 9,193 years during an initial period of high Re/Al for ~3,000 yrs, into an ~1,100 yr period of low Re/Al.

Planktonic SNW in the intermediate site are high in the glacial and remain high until an abrupt drop in SNW in the early LOE at 14,218 years. SNW values remain low in value, compared to the glacial, throughout the LOE and ~1,800 years after. Late Holocene SNW values are low compared to higher SNW in the glacial. Intermediate *N. pachyderma* data had no significant difference in SNW values within and outside of the LOE (M-W test  $U=65$ ,  $p=.356$ ). However, from 14,218 to 8,456 yrs SNW remain moderate in value during a period of high Re/Al for ~5,700 yrs, into a ~1,800yr period of low Re/Al. Planktonic SNW in the deep site was variable through the glacial, deglacial, and Holocene. Deep *N. pachyderma* data had no significant difference in SNW values within and outside of the LOE (M-W test  $U=57$ ,  $p=.117$ ).

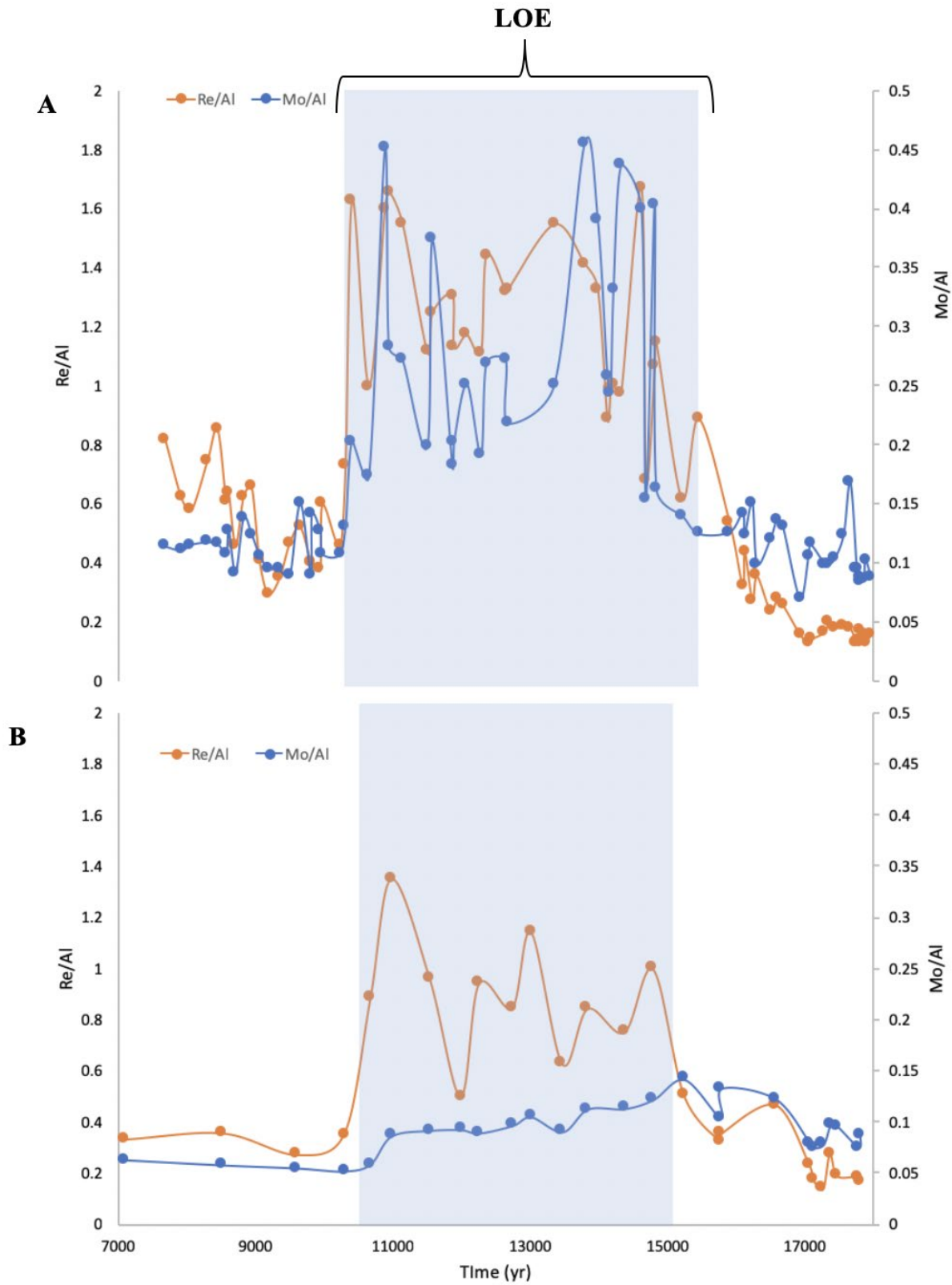


Figure 6: Redox metal data (Re/Al and Mo/Al) through time from: (A) intermediate water site (341\_U1419) and (B) Deep water sites (341\_U1418 and EW0408-87JC); Shaded blue area represents defined Low Oxygen Event (LOE).



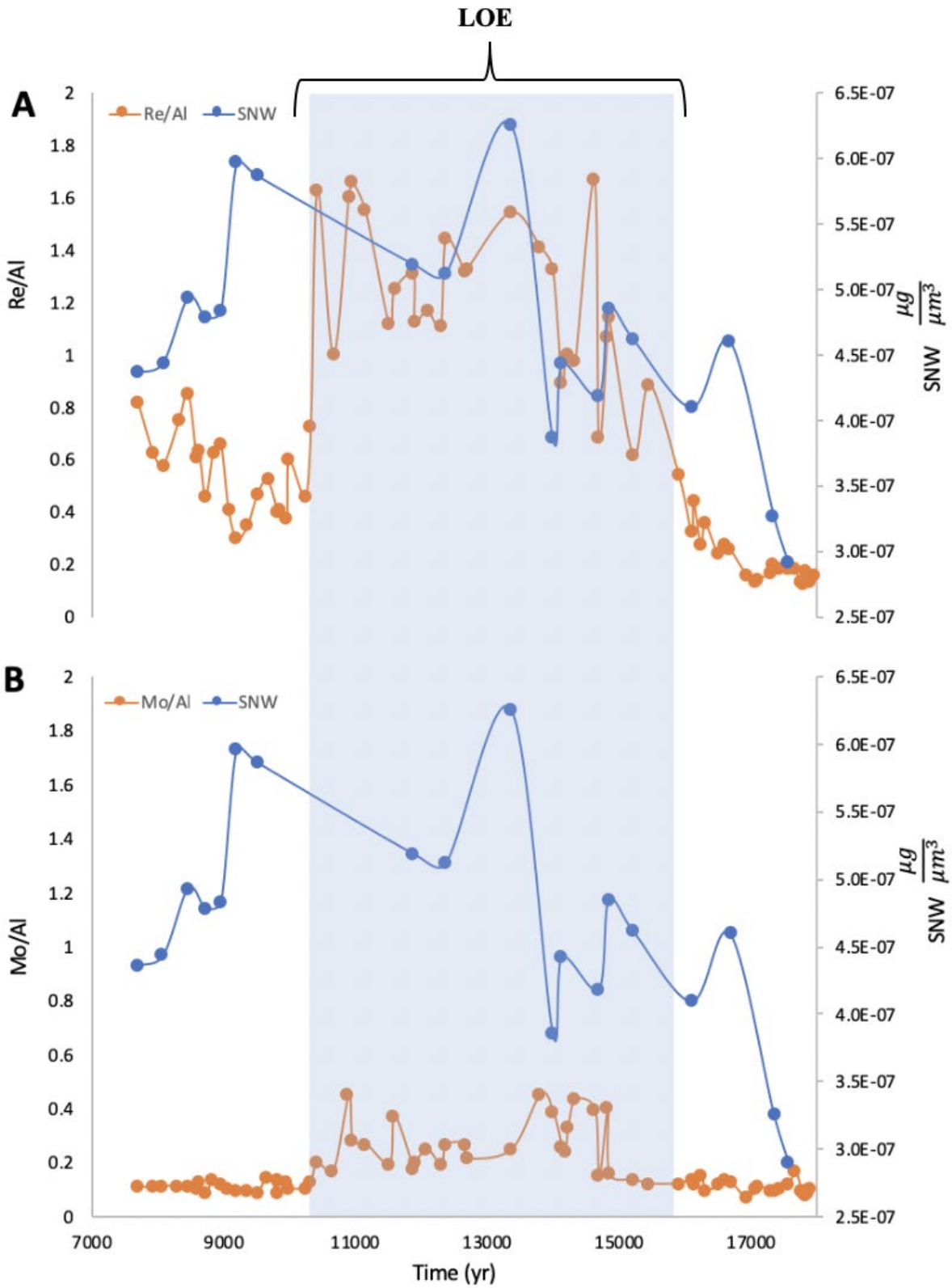


Figure 7: Intermediate site benthic species (*Uvigerina peregrina*) SNW over time compared to redox metal data: (A) Re/Al and (B) Mo/Al. Shaded blue area represents defined Low Oxygen Event (LOE).

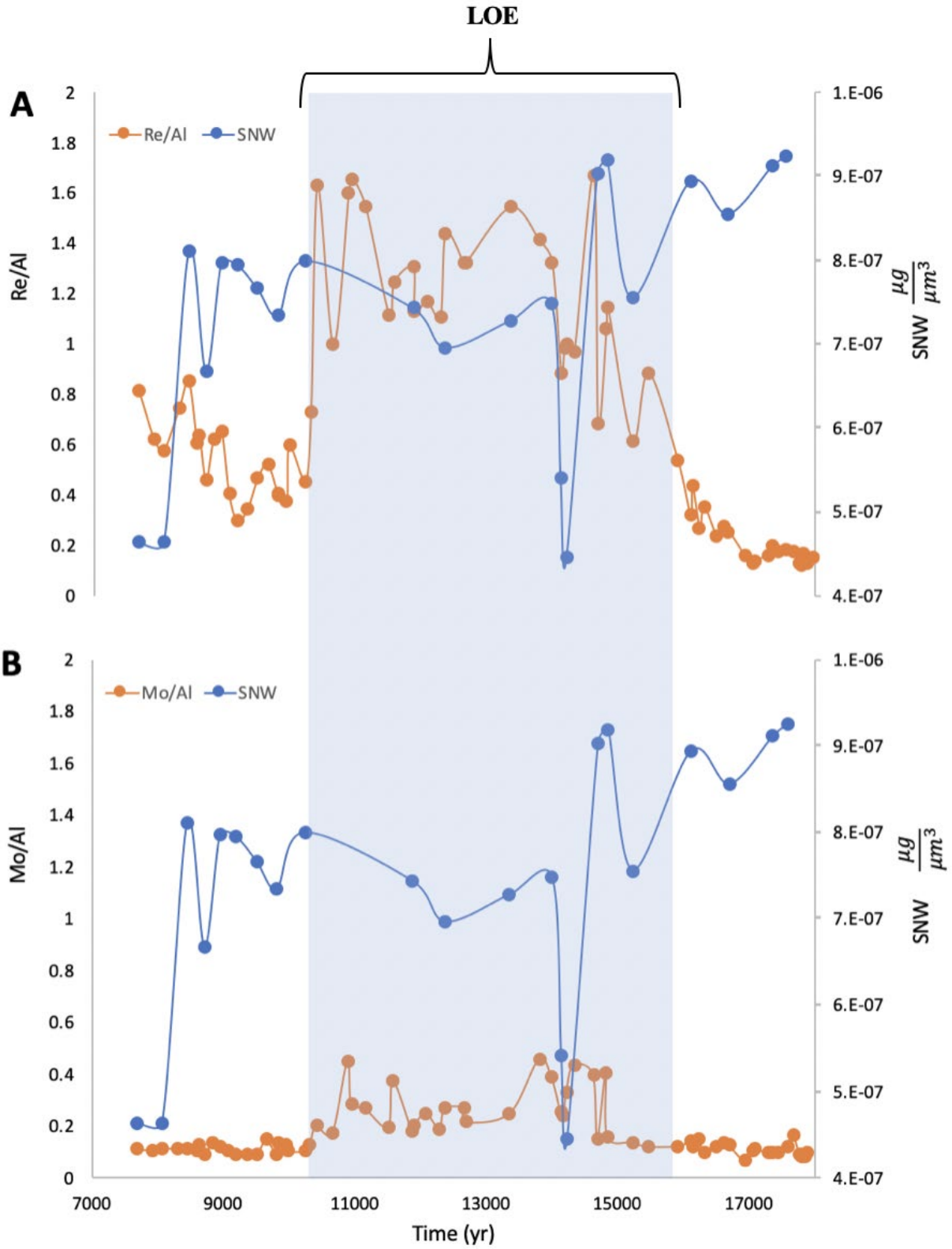


Figure 8: Intermediate site planktonic species (*Neogloboquadrina pachyderma*) SNW over time compared to redox metal data: (A) Re/Al and (B) Mo/Al. Shaded blue area represents defined Low Oxygen Event (LOE).

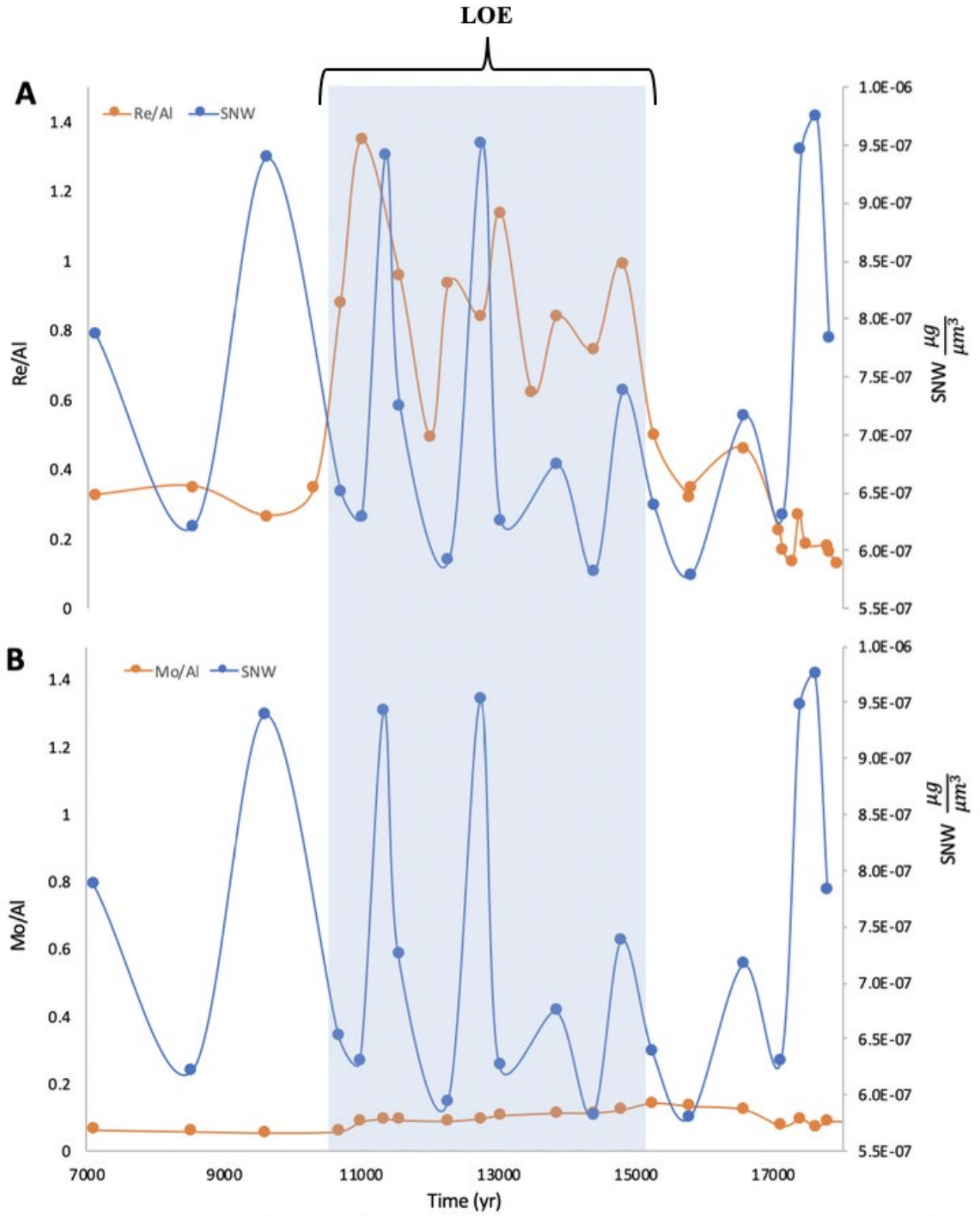


Figure 9: Deep site of planktonic species (*Neogloboquadrina pachyderma*) SNW over time compared to redox metal data: (A)-Re/Al and (B)- Mo/Al. Shaded blue area represents defined Low Oxygen Event (LOE).

## CHAPTER IV

### DISCUSSION

The strong relationship between shell size and shell weight demonstrates that the majority of shell weight variation is due to differences in size (Figure 5, Table 1). Thus, it is important to control for size variation when assessing changes in shell weight in this record. Unlike previous studies, I normalize shell weights using volume to account for changes that could be occurring due to changes in shell thickness or growth conditions [Keating-Bitonti, 2017].

#### **Planktonic Foraminifera at Intermediate and Deep Sites**

*N. pachyderma* are generally heavier for a given size at the intermediate site than at the deep site. In the North Pacific, carbonate saturation declines with water depth and thus we would expect more dissolution on average at the deeper site [Schmidtke et al., 2017]. Interestingly, the size of *N. pachyderma* are also larger at the deep site than at the shallow site (Figure 5). This may reflect differences in productivity in the two regions whereas individuals at the deep site can grow faster due to a greater food source. Differences in dissolution between the sites could also be driven by differences in sedimentation rates. High sedimentation rates bury dead shells faster, effectively removing them from the zone of active dissolution, and variation in dissolution may also be controlled by changes in the rate of burial. Indeed, foraminifera are not generally well preserved in the North Pacific due to its corrosive deep waters, however U1418 and U1419 have high sedimentation rates that lead to good preservation of calcite fossils [Gulick et. al, 2013; Belanger et al., 2016]. On average, U1419 has higher sedimentation rates than U1418 [Gulick et. al, 2013], thus the better preservation at U1419 could also be due to more rapid burial.

The two sites are also very different in their oxygenation histories (Figure 6). While both have elevated Re/Al during the LOE, only the intermediate depth site has an increase in Mo/Al. This suggests that the intermediate site experience strong dysoxia and sulfidic conditions in the pore waters, but the deep site did not. During sulfidic conditions, oxygen is not available for respiration and other redox processes dominate; these redox processes do not produce CO<sub>2</sub> and thus do not contribute to acidification [Cranston et. al, 1990]. Thus, shell weights may be higher at the intermediate site during the LOE than at the deep site if dissolution is related to oxygenation.

SNW of *N. pachyderma* decreases at ~17 kyrs at the deep site, but does not decline sharply until ~14.5 kyrss at the intermediate depth site. At the deep site, SNW values remain consistently low until 13 kyrs at which point the values fluctuate between minimum and maxima equivalent to SNWs during the glacial (Figure 9). At the intermediate site, SNW values increase at ~14kyrs, but are not as high as during the glacial (Figure 8). In neither case, do the low SNW values correspond with the LOE interval suggesting that low-oxygen conditions are not directly related to SNW. This suggests that changes in carbonate ion are unrelated to changes in oxygenation and not the primary control of SNW.

### **Benthic vs. Planktonic Foraminifera at the Intermediate Site**

Also, unlike previous studies, I examine both planktonic and benthic foraminifera from the same samples in the intermediate depth site. *U. peregrina* is generally heavier at a given diameter than *N. pachyderma* which is expected given differences in shell shape (Figure 5). SNW reflects both changes in calcification and dissolution while the organism is alive or authigenic precipitation of carbonate of the shell after the organism dies [Higgins et. al, 2009]. Thus, a decrease in SNW could be driven by decreased biologic calcification, increased

dissolution, or decreased authigenic precipitation of carbonate. For planktonic foraminifera, biologic calcification occurs in the surface waters whereas for benthic foraminifera biologic calcification occurs in sedimentary pore waters. The majority of dissolution should occur in the sedimentary pore waters or in bottom waters just above the sediment surface for both benthic and planktonic foraminifera. Thus, if both taxa are experience similar conditions after death, differences in shell weight through time should be due to biologic processes unique to their living conditions rather than the water chemistry they encounter on the sea floor after death.

Both planktonic and benthic foraminifer have a low in SNW at 14,218 years and 13,992 years, respectively, at the onset of the LOE and an immediate increase in SNW in the flowing sample that persists into the Holocene. This suggests a strong acidification event that increased dissolution followed by a recovery. However, during the LOE planktonic foraminifera generally have lower SNW than in the older glacial sediments whereas the benthic foraminifera have generally higher SNW than during the glacial. This difference in response suggests that the lower SNW of the planktonic foraminifera is not driven by dissolution after death in the sediments but is instead related to changes in biologic calcification during life or dissolution in the water column as the dead shell falls to the seafloor. A difference in carbonate ion availability between the water column and sedimentary pore waters could occur because as carbonate is dissolved in the pore waters carbonate ion will increase such that the pore waters can be oversaturated even if the water column and bottom waters are undersaturated. Thus, planktonic foraminifera may experience low carbonate ion in the water column during life and while they sink to the benthos at the same time benthic foraminifera experience carbonate ion saturation in both life and death.

In the Holocene, both benthic and planktonic foraminifer decrease in SNW, suggesting that more dissolution is occurring in the Holocene than during the LOE or the glacial. This may

be driven by decreased sedimentation during Holocene and thus longer exposure times to corrosive water. As glaciers retreated and formed tidewater glaciers, sediment is trapped in fjords and overall sedimentation to the Gulf of Alaska decreased [Davies et al., 2011].

## CHAPTER V

### FUTURE WORK

While others have used SNW as a proxy for ocean acidification, measuring additional geochemical proxies would allow us to test the hypothesis that differences in SNW are due to changes in sedimentation rate rather than carbonate ion concentrations in the water column or pore waters. A previous study in the North Pacific measured boron isotope composition to reconstruct the pH record from 24,000 - 8,0000 years ago [Gray et. al, 2018]. Higher values of  $\delta^{11}\text{B}$  coincide with high pH, vice versa. During the glacial  $\delta^{11}\text{B}$  values were the highest, while deglacial  $\delta^{11}\text{B}$  values were the lowest of the 16kya time span. Therefore, if I were to compare  $\delta^{11}\text{B}$  values to SNW data set in both sites, I would expect to see low  $\delta^{11}\text{B}$  values during the LOE and early Holocene, and high  $\delta^{11}\text{B}$  values in the glacial and mid-Holocene. Alternatively, comparing SNW directly to sedimentation rates would allow me to test if SNW tracks sedimentation rate.

Moreover, multiple techniques can be used to analyze the surface of shells within my data set to better understand whether dissolution or calcification is occurring at a set time interval. SEM-scanning individual foraminifera in selected samples would allow would me to analyze the shell surface, focusing on the pores, to determine whether dissolution or calcification is occurring [Pak et. al, 2016]. SEM-scanning of planktonic and benthic individuals of the would strengthen my argument that authigenic calcification is not occurring post-mortem, if shell surface were absent of authigenic calcite crystals in both sites. Additionally, if planktonic shells of the intermediate site were smooth and absent of spine bases during the LOE [Pak et. al, 2016], this would be consistent with my hypothesis that respiration is the cause for low SNW. CT



scanning would let me compare test thickness of individuals over the palaeoceanographic record, capture more precise volumetric measurements on each individual, and capture variations in shell thickness of interior chamber walls. If shell thickness is consistent throughout the palaeoceanographic record, CT scanning would strengthen my argument that shell-surface dissolution is occurring rather than changes in growth conditions during the life of the foraminifer.

## CHAPTER VI

### CONCLUSIONS

In summary, SNW does not appear well related to oxygenation as hypothesized based on the modern relationship between the OMZ and the CMZ. However, this water column pattern does not consider differences in pore water chemistry and sedimentation rates, which can control the intensity of dissolution.

1. SNW of *N. pachyderma* were heavier in the shallow than the deep during the LOE which could be due to U1419 having: heavier sedimentation rates, or more extreme low-oxygenations in the pore waters than U1418, causing redox processes to dominate respiration.
2. SNW of *U. peregrina* exceed that of *N. pachyderma* during the LOE due to acidification in the water column affecting the planktonics, whereas, dissolution oversaturated pore waters with carbonate ion.
3. Low SNW of *N. pachyderma* and *U. peregrina* during the Holocene suggested, more exposure time to corrosive waters, due to decreased sedimentation during glacial retreat.

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