Response of foraminifera *Ammonia confertitesta* (T6) to ocean acidification, warming, and deoxygenation -

An experimental approach

Elsa Muller

Dissertations in Geology at Lund University,
Master's thesis, no 667
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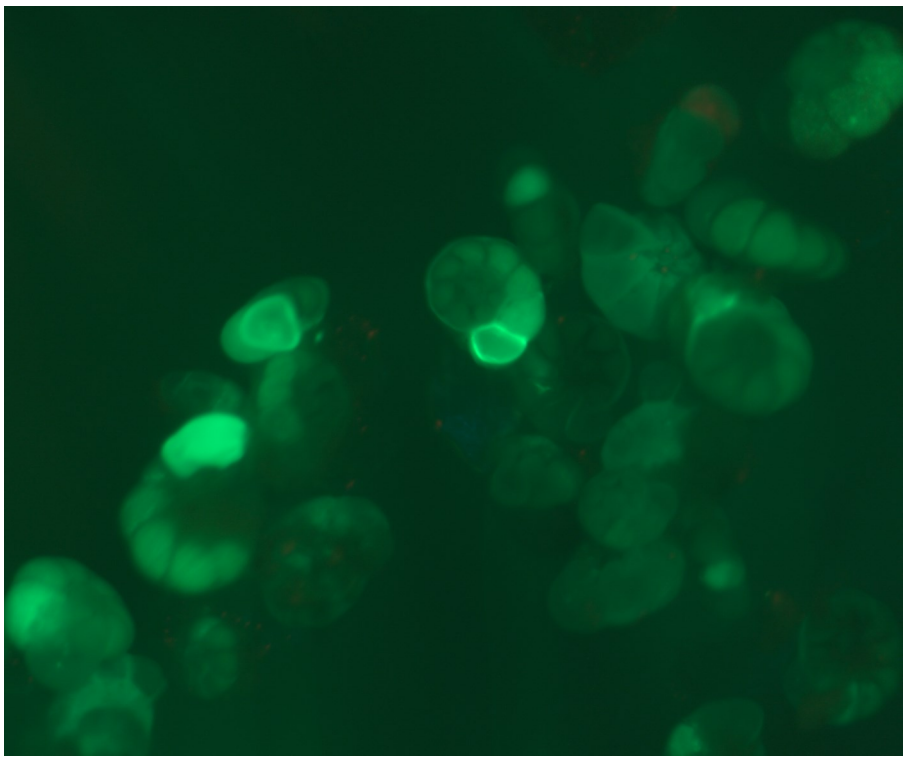

Department of Geology
Lund University
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Contents

Cover Picture: Newly formed chambers of *Ammonia confertitesta* (T6) that calcified during incubation in the Calcein fluerogenic probe, experiencing fluorescence under epiflurorescence microscopy. Photo: Elsa Muller

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Abstract: Ocean acidification, warmer temperatures, and the expansion of hypoxic zones in coastal areas are direct consequences of the increase in anthropogenic activities. However, so far, the combined effects of these stressors on calcium carbonate-secreting marine microorganisms - foraminifera are complex and poorly understood. This study reports the foraminiferal survival behavior, and geochemical trace elements incorporation measured from the shells of living cultured benthic foraminifera from the Gullmar fjord (Sweden) after exposure to warming, acidification, and hypoxic conditions. An experimental set-up was designed with two different temperatures (fjord's in-situ 9 ˚C and 14 ˚C), two different oxygen concentrations (oxic versus hypoxic), and three different pH (control, medium, and low pH based on the IPCC scenario for the year 2100). Duplicate aquariums, meaning aquariums displaying the same conditions and same number of species, were employed for the controls and the two lower pH conditions at both temperatures. The stability of the aquariums was ensured by regular measurement of the water parameters and confirmed by statistical analysis. The species *Ammonia confertitesta*'s (T6) survival (CTB-labeled), shell calcification (calcein-labeled), and geochemical analyses (laser-ablation ICP-MS) were investigated at the end of the experimental period (48 days). Investigated trace elements (TE) ratios were Mg/Ca, Mn/Ca, Ba/Ca, and Sr/Ca. Results show that *A. confertitesta* (T6) calcified chambers in all the experimental conditions except for the most severe combination of stressors (i.e., warm, hypoxic, low pH). Survival rates varied by up to a factor of two between duplicates for all conditions suggesting that foraminiferal response may not solely be driven by environmental conditions but also by internal or confounding factors (e.g., physiological stress). A large variability of all the TE/Ca values of foraminifera growing at low pH is observed suggesting that *A. confertitesta* (T6) may struggle to calcify in these conditions. Thus, this study demonstrates the vulnerability of a resilient species to the triple-stressor scenario in terms of survival, calcification, and trace element incorporation. Overall, the experimental set-up yielded coherent results compared to previous studies in terms of ontogeny, trace elements ratios, and partition coefficient making it advantageous for environmental reconstructions.

Keywords: Acidification, Warming, Deoxygenation, Foraminifera, *Ammonia confertitesta* (T6), Culture Experiment, Trace elements.

Supervisor(s): Helena L. Filipsson, Constance Choquel

Subject: Quaternary Geology

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Svar från foraminiferarten *Ammonia confertitesta* (T6) på havsförsurning, uppvärmning och syrebrist -

Ett experimentellt tillvägagångssätt

ELSA MULLER

Muller, E., 2023: Svar från foraminiferarten *Ammonia confertitesta* (T6) på havsförsurning, uppvärmning och syrebrist - Ett experimentellt tillvägagångssätt. *Examensarbeten i geologi vid Lunds universitet*, Nr. 667, 31 sid. 45 hp.

Sammanfattning: Havsförsurning, högre temperaturer och utvidgningen av syrefattiga zoner i kustområden är direkta konsekvenser av pågående klimatförändringar tillsammans med övrig mänsklig påverkan. Hittills har förståelse av de kombinerade effekterna av dessa stressvariabler på kalkskaliga marina mikroorganismer - foraminiferer - varit undermånliga. Min studie redovisar överlevnaden hos foraminiferer samt geo-kemiska data från skalen hos levande, bottenlevande foraminiferer från Gullmarsfjorden (Sverige) efter att ha utsatts för uppvärmning, försurning och syrefattiga förhållanden. Vi har utfört ett stort experiment med två olika temperaturer (in-situ 9 °C och 14 °C), två olika syrgaskoncentrationer (syresatt jämtemot syrefattigt) och tre olika pH-värden (en kontroll samt två låga pH-värden baserade på IPCC-scenarier fram till år 2100, -0,4 och -0,6 pH-enheter). Vi hade duplicerade akvarier för kontrollgruppen och för de två lägre pH nivåerna vid båda temperaturerna. Foraminiferarten *Ammonia confertitestas* (T6) överlevnad (via CTB-märkning), skal-byggnad (via calcein-märkning) och geokemiska analyser (laser-ablation ICP-MS) undersöktes vid slutet av experimentperioden (48 dagar). De spårelementförhållanden som undersöktes var Mg/Ca, Mn/Ca, Ba/Ca och Sr/Ca. Experimentets stabilitet i akvarierna säkerställdes genom regelbunden mätning av vattenvariablerna och bekräftades genom statistisk analys. Resultaten visar att *Ammonia confertitesta* (T6) byggde kamrar under alla förhållanden förutom den mest påfrestande (det vill säga varmt, syrefattigt, lågt pH-värde). Mellan duplicerade prov kunde överlevnadsgraden variera med upp till faktor två för samtliga förhållanden, vilket tyder på att foraminiferernas reaktion inte bara påverkas av miljöförhållanden utan också av interna eller samverkande faktorer (t.ex. fysiologisk stress). En stor variation i TE/Ca-värden observerades för foraminiferer som växte vid lågt pH, vilket tyder på att *A. confertitesta* (T6) har svårt att bilda skal under sådana förhållanden. Sammantaget visade den experimentella uppställningen positiva resultat och samstämmiga resultat vad gäller ontogeni, spårelementförhållanden och partitionskoefficienter, vilket gör den lämplig för miljörekonstruktioner. Ytterligare geokemiska analyser kommer att utföras för att förbättra resultatens noggrannhet. här testpublikationen skall visa hur ett examensarbete skall vara disponerat samt vilka formatmall som skall användas för de olika delarna.

Nyckelord: Marin försurning, uppvärmning, syrebrist, foraminiferer, *Ammonia confertitesta* (T6), experiment, geokemi, spårämnen.

Handledare: Helena L. Filipsson, Constance Choquel

Ämnesinriktning: Kvartärgeologi

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1 Introduction

Increases in anthropogenic activities lead to a global rise in carbon dioxide emissions which has severe consequences on coastal areas and marine ecosystems. The rise in atmospheric pCO_2 subsequently increases oceanic pCO_2 which in turn decreases the oceanic pH and leads to ocean acidification (OA) (Gattuso & Hansson 2011; Strong et al., 2014). The global increase in temperature induces stronger vertical stratification of the oceans driven by intensified surface warming and reduced vertical exchange of gas, heat, carbon, dissolved oxygen, and nutrients between the surface and deep water (Gruber, 2011; Li et al., 2020). Anthropogenic activities and land use induce excessive nutrient loading into coastal ecosystems which promotes algal productivity and thus eutrophication (Valiela, 2009). The microbial consumption of this organic matter reduces the oxygen level and contributes to hypoxia (Cloern, 2001; Heisler et al., 2008). The water stratification and eutrophication in coastal environments consequently favor bottom-water deoxygenation (Keeling et al., 2010). When combined, these effects lead to a triple-stressor situation (i.e., warming, acidification, and deoxygenation) previously coupled with past mass extinctions (Bijma et al., 2013). These threats especially affect high latitudes and sub-polar regions (IPCC 2022). Climate reports (i.e., IPCC 2022) focus on understanding the consequences of these threats on natural environments by investigating several warming scenarios (e.g., +4 ºC; +2 ºC) and their direct effects. The main aim of this study was to understand the severity of the combined anthropogenically induced stressors on one group of important calcifying marine organisms based on the IPCC 2022 assessments.

Marine calcium carbonate-secreting microorganisms, namely foraminifera, are one of the most ubiquitous calcifying organisms in the oceans. They play a significant role in the ocean's carbon reservoir system which in turn is crucial in atmospheric pCO_2 regulations (Siegenthaler & Sarmiento, 1993). Furthermore, they act as bioindicators of environmental changes because of their extensive geographical distribution and rapid growth (Murray, 2006), their dependency on biotic and abiotic parameters, and their species-specific response to environmental changes (De Rijk et al., 2000; Schafer, 2000; Gooday et al., 2000; Annin, 2001; Licari et al., 2003; Murray, 2006; Jorissen et al., 2007; Milker et al., 2009). Furthermore, during shell (referred to as test) calcification, foraminifera incorporate chemical elements from the surrounding seawater as trace elements making them excellent recorders of ambient seawater conditions and powerful tools in paleo-oceanographic studies (Lea et al., 1999). Thus, the study of trace elements (TE) to Calcium (Ca) ratios in foraminiferal tests offers valuable proxies for elemental water composition (Emiliani, 1955; Delaney et al., 1985; Boyle, 1988). In this study, the ratios of interest are Mg/Ca, a well-known reconstruction tool for seawater temperature, displaying a positive correlation with increasing temperature (Dissard et al., 2010a, b). Secondly, due to Manganese's redox sensitivity, the Mn/Ca ratio is considered a potential geochemical proxy for bottom waters (BW) oxygen concentrations (Groeneveld & Filipsson, 2013; Limburg & Casini, 2018; Schöne et al., 2021) and demonstrates a positive correlation with oxygen depletion (Brinkmann et al., 2023). The Ba/Ca ratio has recently been demonstrated as a reliable proxy for past riverine discharge due to a decrease in near-continent Barium concentration from river run-offs during droughts events (Brinkmann et al., 2022). Finally, Sr/Ca is known to be influenced by salinity, temperature, seawater carbonate chemistry, and pH (Mojtahid et al., 2023). Some studies link the incorporation of Sr to increasing $[CO_3^{2-}]$, which in turn is closely linked to increasing pH. (Dissard et al., 2010a, b, Elderfield et al., 1996, Rosenthal et al. 2006). However, in those studies $[CO_3^{2-}]$ positively correlates with other environmental factors, making the interpretation of Sr in foraminiferal calcite challenging. Thus environmental changes directly impact the water chemistry and consequently the TE/Ca ratios in foraminiferal calcite. The carbonate system parameters are in turn also impacted such as the dissolved inorganic carbon (DIC; dissolved carbonic dioxide + carbonic acid + bicarbonate + carbonate ions = CO_2 aq + H_2CO_3 + HCO_3^- + CO_3^{2-}), calcium carbonate saturation state of seawater (Omega Calcite Ωc) and partial pressure of CO_2 (pCO_2). Understanding the severity and outcomes of environmental changes on microorganisms' geochemistry and physiological behavior is fundamental for supporting effective environmental management strategies.

However, in natural environments, all stressors are combined, and attributing their impacts on foraminifera is challenging due to co-varying parameters such as temperature, salinity, oxygen concentration, or nutrient input (Hillebrand & Matthiessen, 2009). Laboratory-based multiple stressors studies allow the deconvolution of the combined parameters controlling foraminiferal response (Zeebe and Wolf-Gladrow, 2001; Bernhard et al., 2021). This study was designed to culture sub-polar benthic foraminifera under a decoupled (T, pH, and O_2) experimental design. The set-up was based on the IPCC SSP3-7.0 (+4 ˚C) scenario which anticipated a water warming of 2.9 ± 1 ˚C, a pH level drop of -0.35 pH units, and lowered O_2 concentration of -0.09 ± 0.06 µmol L^{-1} (potentially reaching the hypoxic threshold of $[O_2] < 63$ µmol L^{-1}; Breitburg et al., 2018) for the year 2100. We hypothesized that the foraminiferal calcification would be affected by the experimentally assessed conditions. Survival percentages, growth percentages, and TE/Ca ratios (for Mn/Ca, Mg/Ca, Ba/Ca, and Sr/Ca) were investigated. The species considered were typical fjords species (Choquel et al., 2021) with a focus on the intertidal species *Ammonia* T6 recently named *Ammonia confertitesta* (Hayward et al., 2021). The genus *Ammonia* sp. is commonly used in culturing experiments (e.g., van Dijk et al., 2017; Mojtahid et al., 2023) for acidification (Keul et al., 2013; Le Cadre et al., 2003; Charrieau et al., 2018) warming (Dissard et al., 2010a, b) and deoxygenation (Geslin et al., 2014). This consequently offers a large comparable

database. To improve the monitoring of the set-up, the experiment was performed at the Kristineberg Centre for Marine Research and Innovation (Sweden) using 16 aquariums displayed in two thermoregulated rooms, and at high, medium, and low pH. De-oxygenation was also investigated at high and low pH. Additionally, duplicate aquariums were set up to ensure experimental consistency. Each duplicate consisted of petri dishes with the same species placed in separate aquariums, which displayed similar water parameters. These were performed for high pH, medium pH, and low pH conditions within each experimental room but not for the low oxygen tanks.

The general objectives of the study were (1) to test our experimental method and introduce the use of duplicate aquariums. (2) To investigate the combined effects of single, double, and triple stressors on foraminifera's survival and calcification. We were interested in observing if there is a synergistic response, meaning if the combined effect of multiple stressors would be greater than the sum of their individual effects. (Boyd et al., 2018). (3) To assess the potential for environmental reconstruction through ontogeny, which is defined by the changes in metabolic rates during the foraminiferal life history (ontogenetic effect) (Schumacher et al., 2010) (4) Investigate the trace elements to calcium ratios for Mg, Mn, Ba, and Sr incorporation. We hypothesized changes in the temperature and oxygen-based proxies (i.e., Mg and Mn to Ca ratios) and are interested in the influence of combined stressors on the TE incorporation.

2 Material and Methods

2.1 Sites description and sampling conditions

Foraminifera specimens were harvested alive from their natural environment in Gullmar fjord (Sweden) from two sites on the 20th of September 2022. The first site was the GF50 oxic station (average water depth: 50 m) (Figure 1: blue diamond) located within the mouth of the fjord (58°17'N, 11°31'E) which hosts typical foraminifera species from fjord environments (Choquel et al., 2021). The site was reached using boat R/V Alice and sediments were collected using a GEMAX twin barrel corer and a box corer. Six undisturbed sediment cores, two core tops (3cm), and two mud box tops were retrieved and kept for the experiment. The hydrographic parameters (temperature, salinity, oxygen, and fluorescence) were recorded with a CTD multiparametric probe, highlighting the oxic station hydrography. On the sampling date, the bottom water temperature was 9 ˚C, salinity was 34,2 psu and oxygen was $[O_2]$ ~4,1 ml/L (Supplementary information (SI) 5; CTB profile).

The second sampling site is an intertidal mudflat located in the harbor of town Fiskebäckskil (58°14'N, 11°27'E) and subjected to tidal changes (Figure 1: red triangle). The mudflat was sampled at low tide where the sediment surface was scraped off with a spoon. On the day of the sampling, the water temperature was 11 ˚C and the salinity 27 psu.

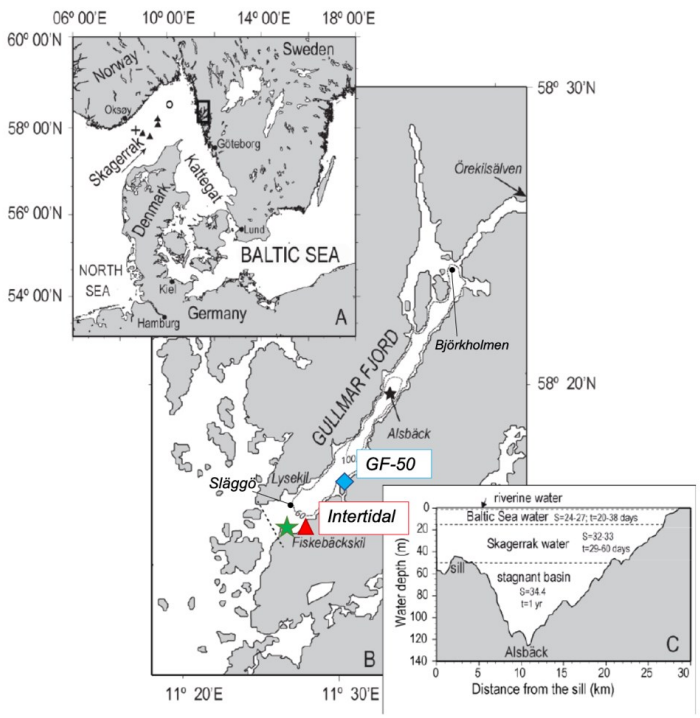

Fig. 1. A. Geographic location of Gullmar fjord. B. Map of Gullmar fjord and its studied station; blue diamond: GF50 oxic station (50 m water depth); Red triangle: Intertidal station; Green star: Kristineberg Centre for Marine Research and Innovation; dark circles: monitoring stations Släggö (65 m water depth), Björkholmen (70 m water depth) and Alsbäck (117m). C. Hydrographic and topographic parameters of the fjord. (Modified from Arneborg et al., 2004)

Sampling sites	Selected species	Total number of picked specimens	Introduction date	Authors
GF 50	*Bulimina marginata*	~1260	12/10/2022	Orbigny, 1826
	Nonionellina labradorica	~420	12/10/2022	Dawson, 1860
	Nonionella sp. T1	~1400	12/10/2022	Deldicq, 2019
Intertidal	*Ammonia confertitesta* (T6)	~742	12/10/2022	Hayward, 2021
		~730	28/10/2022	
	Quinqueloculina	~647	12/10/2022	Orbigny, 1826;
		~1200	28/10/2022	

Table. 1. Harvested species, their sampling sites, number of specimens, introduction date and authors.

2.2 Foraminiferal sampling and labeling

2.2.1 Species of interest for culturing experiments

The sediment cores were transported to the Kristineberg Centre where the first 6cm were sliced over a 2cm interval. All samples (GF50 and intertidal) were gently sieved over nested set intervals of 100-150 mm and 125-250 mm with filtered deep-sea water to dispose of macrofauna and organic pellets. Those sieving sizes were chosen to keep juvenile specimens that would be more likely to grow chambers during the experimental period. The remaining matter was kept in filtered seawater of ~9 ˚C to avoid harsh water conditions changes. Live and dead foraminifera were separated under a light stereomicroscope and live ones were identified through the cytoplasmic coloring common in all live foraminiferal species (e.g., Hallock & others, 1986; Goldstein & Corliss, 1994; Hohenegger & others, 1999). A total of five different species were collected for the experiment from the mudflat and GF50 sites and are presented in Table 1. Our study will focus on the intertidal species *Ammonia confertitesta* (T6) (Hayward et al., 2021) of which a total of 1472 specimens were picked and distributed between 16 aquariums as presented in Table 2. Before insertion, specimens were put in petri dishes alongside silica, to provide a substrate. The petri dishes were then covered with a planktonic net (90 µm) and sealed with rubber bands. A small hole was pierced to allow weekly feeding with a micropipette of the algal mixture of *Dunaliella tertiolecta* and *Isochrysis galbana* (following Wilson-Finelli, 1998). The numbers of foraminifera allowed the settlement of duplicates (except for the Hypoxic normal pH and Hypoxic low pH aquariums, see Figure 4: "experimental set-up"). The experiment lasted around two and a half months. The first foraminifera were introduced on the 12th of October 2022 and a second batch was added on the 28th of October 2022. The experiment ended on the 24th of November 2022 allowing an experimental period of 43 days (1st batch) and 28 days (2nd batch) (Table 1).

2.2.2 Calcein and CellTracker Blue labelling

Prior to the experiment, specimens were incubated (ca. 2-3weeks) in a 10 mgL-1 solution of calcein (Bis [N, N-bis(carboxymethyl)aminomethyl]-fluorescein) used to fluorescently label newly formed chambers, following the protocol of Bernhard et al. (2004). Briefly, chambers that calcified during the calcein incubation period experience fluorescence under epifluorescence microscopy (470 nm excitation) as opposed to pre-existing calcite and post-calcein calcite (non-fluorescent) (Figure 2). The newly formed chambers were verified under an epifluorescence microscope (LEICA MZFL) using the filter ebq 100 and treated with the software ZEN 3.1 (blue edition). This method serves as a "starting point" for the experiment and thus allows the identification of chambers that calcified during the experimental period.

After the experiment, live foraminifera were labeled using the CellTracker Blue (CTB, 4-chloromethyl-6,8-difluoro-7-hydroxycoumarin) fluorogenic probe. Samples were incubated for ca. 24h in CTB and ambient seawater (M = 246,59 g/mil; m=5 mg; 1 µmol final concentration) at *in situ* water temperature (Bernhard et al., 2006). CellTracker Blue (371/464 nm excitation) was used to avoid a fluorescent conflict with the calcein tag as opposed to the usually used CellTracker Green labeling method (e.g., Bernhard et al., 2004). After incubation, the labeled specimens were fixed with 96 % ethanol, stored in tubes, and transported to Lund University (Sweden) where they were stored in micropaleontological cells under a light stereomicroscope. CTB-label was verified at the BIAF laboratory in Angers (France) under an epifluorescence stereomicroscope equipped for fluorescein detection (Olympus SZX13) using a DAPI filter. Live specimens (blue cytoplasm to half blue cytoplasm) from dead specimens (less than half blue and no fluorescence) (Figure 3) were sorted and only specimens considered alive at the end of the experiment were kept for geochemical analyses.

At the end of the experiment, percentages for Survival, Presence, Calcification, and Growth were determined using the following expressions:

Survival percentage = (Number of alive specimens at the end of the experiment*100)/ (number of specimens at the start of the experiment)

Presence percentage = (Number of specimens found at the end of experiment * 100)/ (number of specimens at the start of the experiment)

Calcification percentage = (Number of specimens that presented 1 or more newly formed chambers * 100)/ (number of specimens at the start of the experiment)

Growth percentage (e.g., 1-2chambers) = (Number of specimens that calcified 1-2 chambers*100)/ (Total number of specimens that were alive + calcified at the end of the experiment)

2.3 Experimental set-up and culturing at the Kristineberg Centre for Marine Research and Innovation

Two thermoregulated rooms were used at the Kristineberg Centre for Marine Research and Innovation. The experimental setup is summarized in Figure 4. In each room, we set up aquariums in which water temperatures naturally adjusted to the surrounding air temperature. The first room was designated as the "cold room" and was adjusted to the average *in situ* bottom water temperature in the fjord (~9 ˚C). The second room, named the "warm room", was adjusted to *in situ* temperature +5 ˚C (~14 ˚C). Aquariums in each room display, control (normal pH 8, oxic), medium pH (pH 7.6, oxic), and low pH (pH 7.4, oxic), reached through CO_2 and air bubbling. Furthermore, we investigated hypoxic high-pH (pH 8.0, $[O_2] < 63$ µmol L^{-1}) reached through nitrogen bubbling, and combined effects of hypoxic + low-pH (pH 7.4, $[O_2] < 63$ µmol L^{-1}), reached through nitrogen and CO_2 bubbling. The investigated pH and temperature values were corrected to adjust to the seasonal variations recorded in the fjord (Average

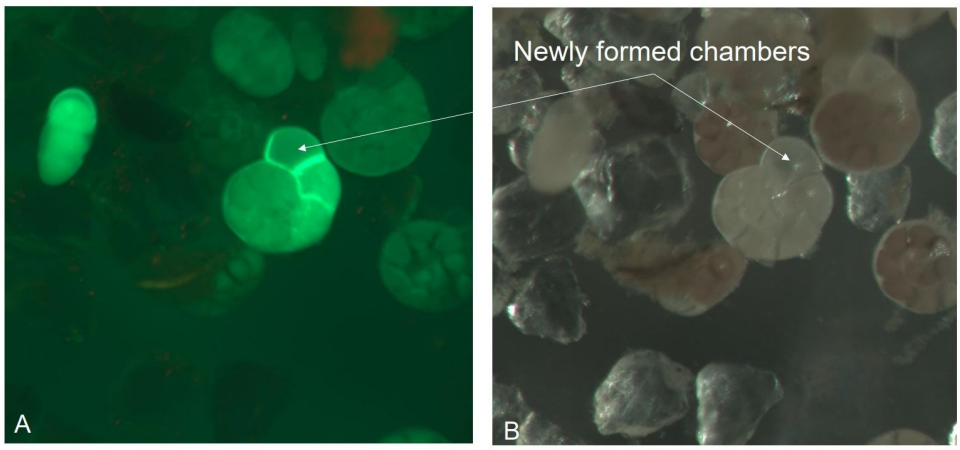

Fig. 2. A. New chambers on *Ammonia confertitesta* after calcein incubation, made visible under an epifluorescence microscope. B. Normal light photo of the same specimens.

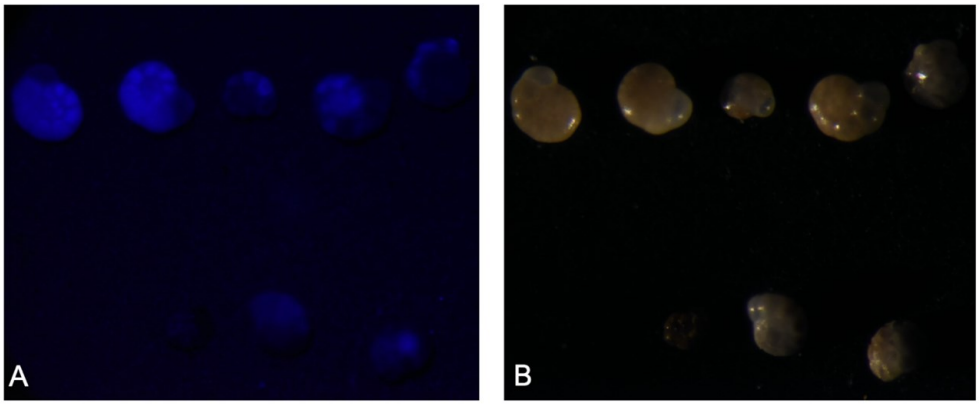

Fig. 3. A. *Ammonia confertitesta* under epifluorescence stereomicroscope made visible by CellTracker Blue fluorescent probe when alive. B. Normal live photo of the same specimen. Dead specimens in the lower part show almost no blue fluorescence of their cytoplasm.

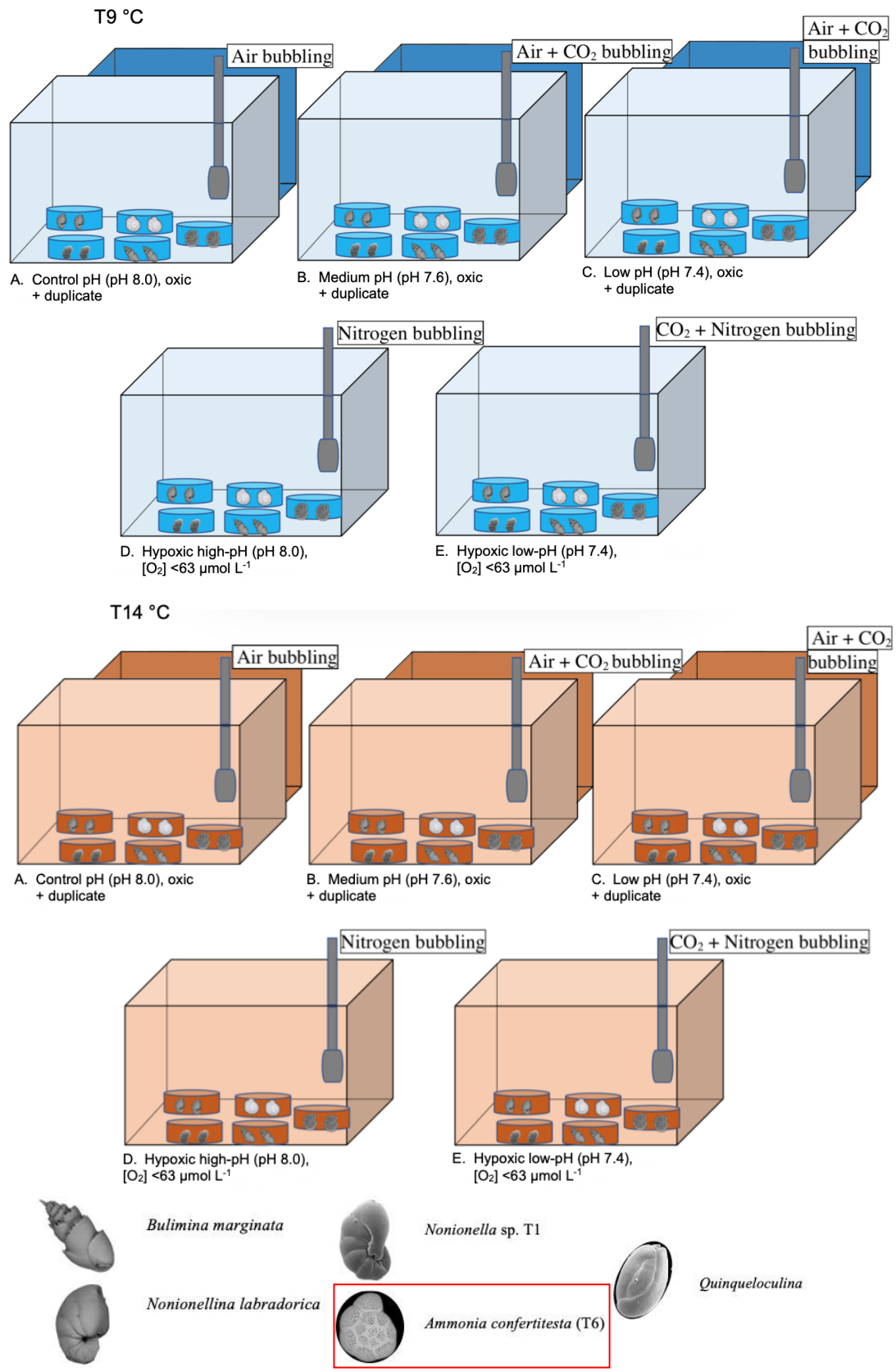

Fig. 4. **Upper panel** "Cold Room" T9 ˚C displaying aquariums A. Control pH, oxic + duplicate; B. Medium pH, oxic + duplicate; C. Low pH, oxic + duplicate; D. Hypoxic high pH [O_2] <63 mmol, no duplicate; E. Hypoxic low pH, [O_2] < 63 mmol L^{-1}, no duplicate. **Lower pannel** "Warm Room" T14 ˚C displaying aquariums A. Control pH, oxic + duplicate; B. Medium pH, oxic + duplicate; C. Low pH, oxic + duplicate; D. Hypoxic high pH, [O_2] < 63 mmol L^{-1}, no duplicate; E. Hypoxic low pH, [O_2] <63mmol L^{-1}, no duplicate. Foraminiferal species introduced in the aquariums are summarized below the figure and in Table 1. The rest of the study focuses on *Ammonia confertitesta* (T6) highlighted in red.

pHT: 8.04 pH units (February) to 8.17 pH units (March), monthly pH variation: from 0.34 (January) to 0.89 (March) pH units; Average temperature: 3.1 ˚C (March) to 15.6 ˚C (September), monthly variation of ca. 3.0 ˚C) (Dorey et al., 2013). Thus, to account for the *in situ* variations experienced by foraminifera in their natural environment, we opted to explore different pH levels that would exhibit a significant deviation from the existing variations found in-situ. Duplicate aquariums were conducted for the control, the medium, and the low pH conditions in both temperatures (Figure 3: darker boxes). The duplicate digits will be indicated next to the aquarium's name in the manuscript as follows: (-1) indicating the first aquarium and (-2) indicating the duplicate for the first aquarium. Water chemistry was stabilized during a 2-week pre-test phase to optimize the geochemistry and checked regularly during the experiment (pH, $[O_2]$, salinity, total alkalinity) except for the hypoxic-low pH warm and cold aquariums. To limit evaporation and the influence of atmospheric CO_2 in low pH conditions as well as oxygen contamination of the hypoxic aquariums, tanks were covered with plastic films. Measurements for pH units were obtained through the NBS method (SI analytics, pH standard for freshwater). To allow comparison with salty water (pH total-scale) a correction of minus 0.11 (pH total-scale = pH NBS - 0.11; Dorey et al., 2013) was applied to all measurements. All water parameters for pH NBS, pH total scale, salinity, water temperature (T˚), and Total Alkalinity ($TA = HCO_3^- + CO_3^{2-}$) are transcribed in Annex 1 and were transferred to the software Rstudio (version 2022.12.0 + 353) with the seacarb library to deduce pCO_2, DIC and, Omega calcite (Ωc).

2.4 Foraminiferal geochemical analyses

2.4.1 Cleaning procedures

Foraminifera with newly formed chambers (i.e., chambers formed after the calcein-labeled ones) and alive (i.e., CTB-label) at the end of the experiment were selected from the aquariums for geochemical analyses. Laser ablation (LA-ICP-MS) analyses on newly formed chambers were carried out at the Department of Geology, Lund University (Sweden). The cleaning procedure by Brinkman et al. 2022 and references therein were adopted for the experiment. Selected specimens were put in glass vials half filled with NaOCl (5 %) and placed under a vacuum for ca. 1.5 hours. The bleaching process removed organic material and cytoplasm which is required for laser ablation analysis. Samples were then centrifuged at low speed (500tour/minutes) for ca. 2 hours at room temperature. Followed by a quintuple rinse with Milli-Q (Milli-Q Integral, EMD Millipore Corporation, Billerica, MA, USA) and dried at room temperature for 2 days. Foraminifera were then aligned on a double-face tape for the laser ablation.

2.4.2 Analytical procedures

LA-MS-ICP analyses were conducted with a Bruker Aurora Elite (quadrupole) and a 193nm Cetac Analyte G2 excimer laser installed with a two-volume HelEx2 sample cell. The abundance of isotope masses ^{27}Al, ^{43}Ca, ^{55}Mn, ^{26}Mg, ^{66}Zn, ^{238}U ^{138}Ba and ^{137}Ba were acquired at 5Hz (i.e., laser shots per second) and used to calculate elemental concentrations. Laser ablation was conducted in manual mode at an energy density of 1 Jcm^{-2}. Primary standard NIST610 and secondary standards, NIST612, MACS- 3 (MicroAnalytical Carbonate Standard, United States Geological Survey, 2012; Jochum et al., 2012), and JCt-1 and JCp-1 (AIST Japan calcium carbonate pellets), were run at the beginning and end of each session. Standards NIST610, MACS-3, and JCp-1 were additionally run after every 10 sample spots, and elemental baseline levels analysis was measured for at least 30 s before each spot. All operating parameters are summarized in SI 1. Calcium was used as an internal standard because its concentration is constant at 40wt% in all foraminiferal tests and allows comparisons with trace elements to Ca ratios from wet-chemistry studies (Dissard et al., 2010a). Therefore, the final (*n*), penultimate (*n1*), antepenultimate (*n2*) and (*n3)* were ablated from outer to inner shell. Because of miscellaneous chamber sizes, a small spot size (40x50 µm) was chosen, kept constant during individual sessions, and applied to all samples and standards (SI1). Geochemical (LA-ICP-MS) analyses were conducted on 42 *A. confertitesta* (T6) (Calcein + CTB label) specimens on a total of 60 newly formed chambers (Table 2). Laser ablation was performed on the last four chambers (a total of 189 ablation profiles). Only the profiles conducted on the chambers that calcified during the experimental period and which were above LOD (Limit of Detection = baseline signal + 3.3 x s; s= standard deviation of background signal) were considered for the results (Total number of ablation profiles for Mg/Ca: 57; Mn/Ca: 56; Ba/Ca: 59; Sr/Ca: 60).

2.4.3 Benthic foraminifera Data processing

After LA-MS-ICP analysis, the raw counts were converted to elemental concentration in ppm using the software package Igor Pro 6.37 with Iolite v3.5 (Paton et al., 2011). The software displays a signal for elemental baselines, standards, and sample spots for each trace element profile. The signal integration profiles were manually determined based on the ^{43}Ca constant counts. Enriched signals of ^{55}Mn, ^{27}Al, or ^{66}Zn at the beginning or end of intervals (respectively corresponding to the outer and inner wall of the shell) were excluded to disregard secondary coating and/or contamination. Trace element ratios (TE/Ca) were calculated based on the average calcium concentration used for the ablation method and converted to mmol/mol. The calculation was based on the assumption of TEs being bound as carbonates (with an assumed 40wt% Ca in a $CaCO_3$ matrix) and normalized to calcium. A total of 189 ablation profiles were performed on chambers *n, n1, n2,* and *n3* of *A. confertitesta* (T6). After data reduction, we applied a 95% confidence limit to remove outliers, excluded ablation signals with possi-

ble contamination (i.e., Al/Ca > 0.4 mmol/mol^{-1} Wit et al., 2010; Mn/Ca>100 µm /mol^{-1}) and profiles where the element of interest is lower than the limit of detection (LOD). Our ablation profiles resulted in extremely low Al counts, indicating no Aluminum contamination.

2.4.4 Statistical analyses

To compare the stability and the differences in the water parameters between duplicates and experimental conditions, the data for normality (Shapiro-Wilk's test) was tested. Because a normal distribution was not observed for all water parameters, a pairwise comparison with the Kruskal Wallis test (i.e., a non-parametric test) was performed. The significant level for all tests was p-value < 0.05. A PERMANOVA test was performed for the comparison of TE/Ca ratios in regard to independent water parameters (water temperature, pH, and [O_2]) and combined (pH*T, pH*[O_2]). These tests were performed using software R (version 2022.12.0).

Furthermore, partitioning coefficients (D) for trace elements (TE) Mg, Mn, Ba, and Sr, representing the elemental distribution, were calculated for each set of experimental conditions according to the following expression:

$$DTE = (TE/Ca)_{calcite} / (TE/Ca)_{seawater}$$

The partition coefficient is a measure of how strongly foraminifers fractionate against or remove a certain element while precipitating the calcium carbonate to build their test. (DTE = 1: element incorporation at the same ratio as calcium in seawater; DTE < 1: element fractionate against; DTE > 1: more elements are incorporated compared to relative abundance seawater [Ca^{2+}]) (Mewes et al., 2015). Boyle (1981) states that if partition coefficient behavior demonstrates control over trace element chemistry, then trace elements can be used as proxies for ocean/water chemistry.

3 Results

3.1 Stability of the experiment

All aquarium's water parameters (pH, salinity, water temperature) were recorded regularly and were plotted over the experimental period in Figure 5. Total alkalinity was measured twice a week and represented by points in Figure 5a. DIC, Omega calcite (Ωc), and pCO_2 average values are presented in SI3. In the cold room, the water temperature of all aquariums combined, stabilized around 8.8 ± 0.7 ˚C, salinity 34 ± 1.2 psu, and alkalinity 2392.5 ± 21 µmol kg-1 SW (SI3). pH values in Control pH stabilized at 7.95 ± 0.04, Medium pH at 7.59 ± 0.02, and Low pH at 7.40 ± 0.02. The Hypoxic control-pH aquarium stabilized around pH 7.90 ± 0.05 and [O_2] = 52.06 ± 11.70 µmol L^{-1} and the Hypoxic low-pH stabilized around pH 7.44 ± 0.16 and [O_2] = 42 ± 8.5 µmol L^{-1} (see SI3). In the warm room, the water temperature of all aquariums combined, stabilized at 13.7 ± 0.9 ˚C, salinity at 34 ± 1.2 psu, and alkalinity at 2391.2 ± 22 µmol kg^{-1} SW (SI3). pH values at Control pH stabilized at 7.98 ± 0.04, Medium pH at 7.60 ± 0.02, and Low pH at 7.40 ± 0.02. The Hypoxic control-pH aquarium stabilized around pH 7.89 ± 0.03 and [O_2] = 54.87 ± 6.36 µmol L^{-1} and the Hypoxic low-pH stabilized around pH 7.43 ±

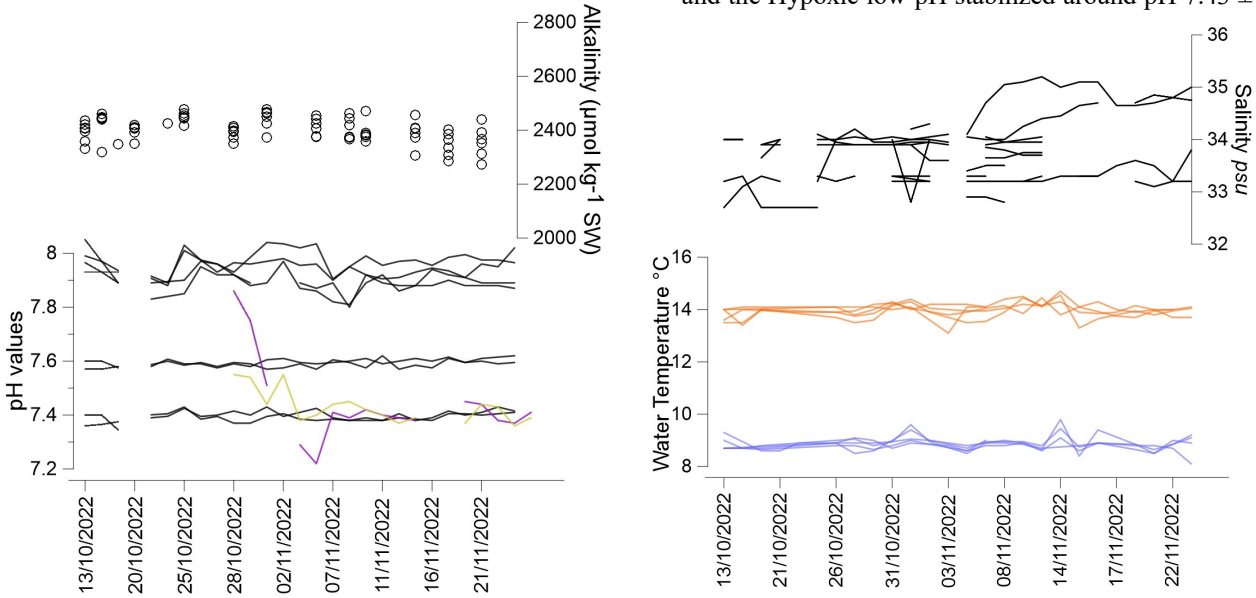

Fig. 4. Water parameters stability over the experimental period from October to November 2022. Left uppermost panel (a): alkalinity. Left lowermost panel (b): pH values for control conditions, pH7.6 and pH 7.4. Yellow and purple lines are the hypoxic low-pH aquariums that display the large variation. Right uppermost panel (c): Salinity (psu). Right lowermost panel (d): Water temperature (°C), oranges lines are aquariums from the T14 ˚C room, blue line from the T9 ˚C room.

0.06 and $[O_2]$ = 45.7 ± 5.5 µmol L^{-1}. (SI3). The experimental conditions were stable in each aquarium because no statistical differences (Shapiro-Wilk's test) were found for water temperature (p-values > 0.05), salinity (p-values > 0.05), and alkalinity (p-values > 0.05). However, the hypoxic aquariums at both temperatures displayed lower salinity. This can be attributed to the fact that these aquariums were established later compared to the previous ones or had their water replaced once per week with seawater from the fjord, which experiences a gradual decline in salinity during the winter season. Regarding the pH measurements, we found no statistical difference (p-value > 0.05) between the duplicate aquariums for Control pH cold, Medium pH cold, Low pH cold, and Control pH warm, Medium pH warm, and Low pH warm. A statistical difference was found between conditions for pairwise comparison (Kruskal Wallis test) between Controls against Medium pH (p-values < 0.05), Controls against Low pH (p-values < 0.05), and Medium pH against Low pH (p-values < 0.05). The Hypoxic-low pH warm and cold aquariums (Figure 5b: purple and yellow lines) pH-values only presented a statistical difference with Controls-pH (p-values < 0.05), but not Medium-pH and Low-pH aquariums. The difficulty of managing the coupled gas bubbling of Nitrogen (for hypoxia) and pCO_2 (for low-pH) explains the large variations at the start of the experiment (Figure 5b, purple and yellow lines).

3.2 Survival, presence, and calcification percentages

A total of 372 *A. confertitesta* (T6) specimens survived the experiment, all conditions combined, which is an overall 25 % survival percentage (start: 1472 specimens; Table 2).

Percentages for survival, presence, and calcification are presented in Figure 6. We found more than 40 % of the specimens for most conditions (indicated by presence percentages) at the end of the experiment (Figure 6). The lowest presence percentages were observed

Conditions	Number of forams start of experiment	Live forams end of experiment	Number of Calcified specimens	Kept specimens for LA_ICP-MS	Number of calcified chambers (LA-ICP-MS)
Control cold (1)	53	13	3	2	3
Control cold (2)	53	6	0		
pH 7.6 cold (1)	106	38	16	7	11
pH 7.6 cold (2)	106	17	1		
pH 7.4 cold (1)	106	16	9	10	10
pH 7.4 cold (2)	106	51	24		
hypoxic 8 cold	106	43	6	3	4
hypoxic 7 cold	100	34	2	1	1
Control warm (1)	53	5	2	2	4
Control warm (2)	53	8	3		
pH 7.6 warm (1)	106	32	17	10	17
pH 7.6 warm (2)	106	24	22		
pH 7.4 warm (1)	106	21	7	5	6
pH 7.4 warm (2)	106	16	5		
hypoxic 8 warm	106	47	11	2	4
hypoxic 7 warm	100	18	0	0	0
Total	1472	389	128	42	60

Table. 2. Harvested Distribution of the specimens per conditions, number of specimens that survived at the end of the experiment, number of specimens that calcified and specimens kept for further Laser ablation analysis.

for Low pH-1 cold (35 %) and Hypoxic low pH warm (42 %). Contrarywise, the highest presence percentages were observed for Low pH-2 cold (i.e., 85 %) as well as for both Hypoxic high-pH cold and warm (respectively 91 % and 83 %). Presence percentages serve as an informative indicator of potential foraminiferal loss during the experimental period through the complete dissolution of their tests. Subsequently, a low presence percentage indicates a high number of specimens that completely decalcified. At least 20 % of the specimens survived in most conditions. Survival percentages (Figure 6, green) were the highest for Low pH-2 cold (48 %) and Hypoxic high-pH warm (i.e., 59 %). Conversely, the lowest survival percentages were recorded for Control-2 cold and Control-1 warm (respectively 11 % and 9 %) (Figure 6). We considered calcification percentages as specimens that calcified at least one chamber in the

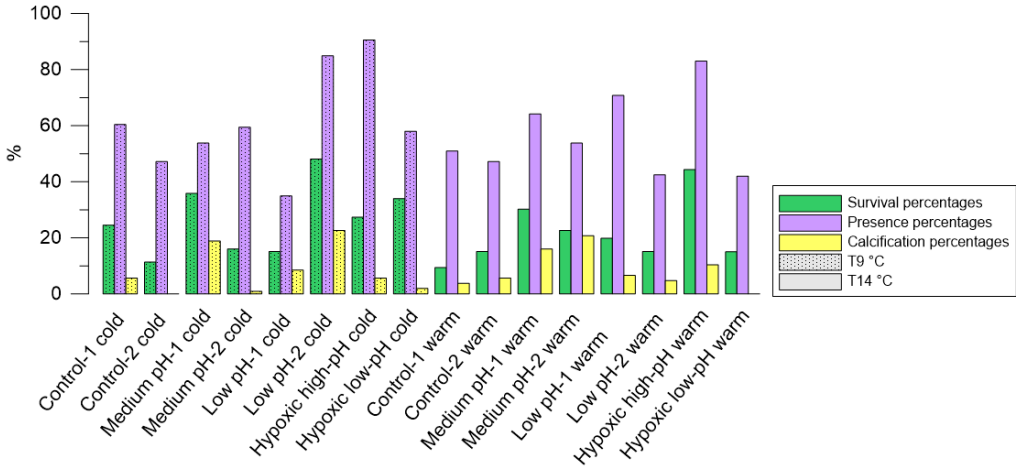

Fig. 6. Survival (green), Presence (purple) and Calcification (yellow) percentages at the end of the experiment per conditions. The duplicate is indicated in brackets.

experimentally assessed conditions (Figure 6, yellow bar). Foraminifera added new chambers in almost all conditions except for Control-2 cold and Hypoxic low-pH warm, which is the most severe combination of stressors. The highest calcification percentages were recorded for Low pH-2 cold (24 %) and Medium pH-2 warm (22 %) while the lowest calcification percentages occurred in Low pH-2 cold (1 %) and Hypoxic low-pH cold (2 %) (Figure 6). Meaning from one duplicate to another, survival, presence, and calcification percentages vary by sometimes a factor of 2. Finally, we did not observe any reproduction or juvenile individuals.

Growth percentages were investigated and presented in Figure 7 only considering alive and calcified specimens at the end of the experiment (Table 2: Total number of calcified Specimens). Due to a limited number of foraminifera, specimens from each condition and their respective duplicate were regrouped for this section, which was possible because of stable water parameters between duplicates (i.e., section 3.1 Stability of the experiment). Here are described the percentages of specimens that grew 1-2 chambers against the ones that grew 3-4 chambers, normalized to 100 %. At T9 ˚C, chambers that grew in Medium pH and Low pH conditions showed a higher percentage of specimens that grew 3-4 new chambers compared to the Control and both Hypoxic conditions. However, at T14 ˚C there was a higher percentage of specimens that calcified 3-4 chambers in Control and Hypoxic high-pH aquariums with the latter displaying the highest growth percentage (57% of 3-4 newly formed chambers). The lowest growth percentages are recorded for Control cold and Hypoxic low-pH cold conditions (Figure 7). However, it is important to note that in the Hypoxic low-pH conditions, only a single surviving specimen remained at the end of the

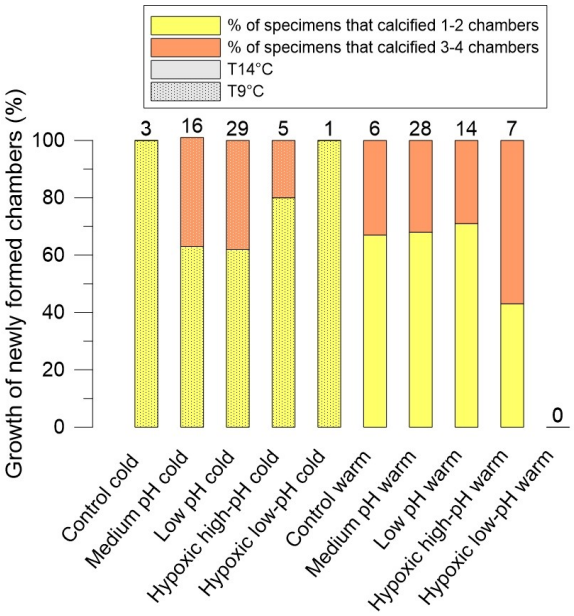

Fig. 7. Growth percentages, only considering alive and calcified specimens, number of data point indicated above the bar charts, temperature indicated by pattern. Condition and their duplicate are regrouped. conditions. The duplicate is indicated in brackets.

experimental period. This limited number of specimens diminishes the representativeness of the results in this particular condition. There was no specimen considered for the most severe combination of stressors (Hypoxic low pH warm), as no calcification was observed for this condition. A summary of the most interesting results is presented in SI6.

3.3 Foraminifera TE/Ca relationship

3.3.1 Intraspecific variability in TE/Ca ratios between chamber stages

Due to the absence of reproduction, the ontogenetic effects based on chamber stages were evaluated. To do so, the TE to Ca ratios were considered (for elements Mg, Mn, Sr, and Ba) of successive chambers from single specimens (Barras et al., 2018). Figure 8 presents the box plots of TE/Ca ratios (Mg/Ca, Mn/Ca, Ba/Ca, and Sr/Ca) for all experimental conditions and duplicates regrouped. We observed variability for elements Mg, Mn, and Ba (Figure 8 a, b, c) but no significant differences between chamber stages for the ratios Mg/Ca (p-value > 0.05), Mn/Ca (p-value > 0.05), Ba/Ca (p-value > 0.05) and Sr/Ca (p-value > 0.05). This suggested the absence of ontogenetic effects for all ratios.

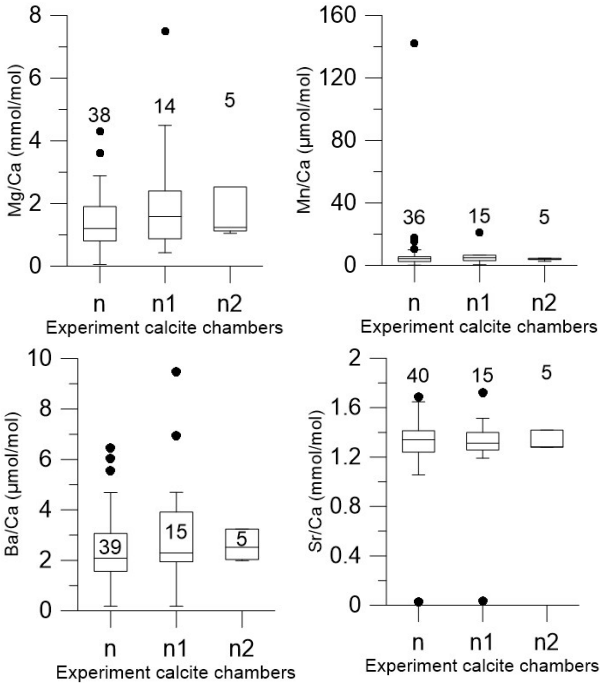

Fig. 8. Box and whisker plot of *A. confertitesta* (T6) ontogenetic effect for (a): Mg/Ca (mmol/mol), (b): Mn/Ca (µmol/mol), (c): Ba/Ca (µmol/mol), (d): Sr/Ca (mmol/mol). Outliers are indicated by dark dots and the number of data points is indicated above the box plots. Considering the final (n), penultimate (n1), and antepenultimate (n2) chambers of specimens which calcified under the experimentally assessed conditions.

3.3.2 Foraminiferal TE/Ca relationship to ambient water parameters

Here is described the TE/Ca variability in regard to water temperature and pH parameters and are presented in Figure 9. The average values at T9 °C were 1.62 ± 1.07 mmol/mol for Mg/Ca, 5.17 ± 3.91 µmol/mol for Mn/Ca, 2.82 ± 1.98 µmol/mol for Ba/Ca and 1.22 ± 0.35 mmol/mol for Sr/Ca. At T14 ˚C the average values were 1.63 ± 1.38 mmol/mol, 4.02 ± 3.83 µmol/mol for Mn/Ca, 2.46 ± 1.34 µmol/mol for Ba/Ca, and 1.34 ± 0.27 mmol/mol for Sr/Ca.

However, for almost all ratios (Mg/Ca, Mn/Ca, and Ba/Ca) foraminifera from the Low pH conditions displayed the highest variability at both temperatures. At T9 °C and Low pH, Mg/Ca, Mn/Ca, and Ba/Ca ranged between 0.70 and 4.30 mmol/mol; 1.67 and 15.39 µmol/mol; 1.28 and 6.46 µmol/mol respectively (Figure 8a, b, c; SI4). One odd Mn/Ca (Hypoxic low-pH cold) value was deleted from the calculations, indicated in orange in SI4. At T14 ˚C and Low pH, Mg/Ca, Mn/Ca, and Ba/Ca ranged between 0.80 and 7.50 mmol/mol; 4.12 and 21.16 µmol/mol; 1.80 and 6.92 respectively (Figure 8a, b, c; SI4). At this temperature, the highest values from all three ratios corresponded to the same laser ablation profile (i.e., the same chamber from the same foraminifera). Only Sr/Ca showed a general uniformity in its ratios with values ranging between 1.06 and 1.38 mmol/mol except for three very low data points, one at Medium pH warm (0.033 mmol/mol) and two at Hypoxic high-pH cold (0.03 and 0.024 mmol/mol) (Figure 9c, SI4). Lower values were observed for foraminifera growing in oxygen-depleted environments at T9 ˚C for Mg/Ca and Mn/Ca (ranging from 0.054 to 1.77 mmol/mol and from 0.12 to 4.03 µmol/mol respectively) compared to their average values at that temperature (respectively 1.62 mmol/mol and 5.17 µmol/mol) (Figure 9a, b). Finally, the Ba/Ca values for the foraminifera in cold oxygen-depleted conditions presented a high variability ranging between 0.17 and 9.48 µmol/mol (Figure 8c, SI4), compared to the other ratios but no statistical differences were found regarding oxygen (p-values > 0.05). A statistical test was performed for comparison of TE/Ca ratios regarding all independent water parameters (water temperature, pH, and $[O_2]$) as well as combined (pH*T, pH*$[O_2]$) and found no significant differences for trace elements ratios Mg/Ca (p-values > 0.05), Mn/Ca (p-values > 0.05), Ba/Ca (p-values > 0.05). Only a statistical significance was found for Sr/Ca in oxygen-depleted conditions (p-value = 0.042; SI2) but no other water parameters (p-values > 0.05). A summary of the most interesting results is presented in SI6.

3.3.3 Partitioning coefficient

Partition coefficient behavior has been recognized to govern the trace element chemistry of the foraminiferal test (Boyle, 1981) and is closely linked to seawater chemistry. Average values for each ratio, all aquaria combined were Dba = 0.56 ± 0.34;

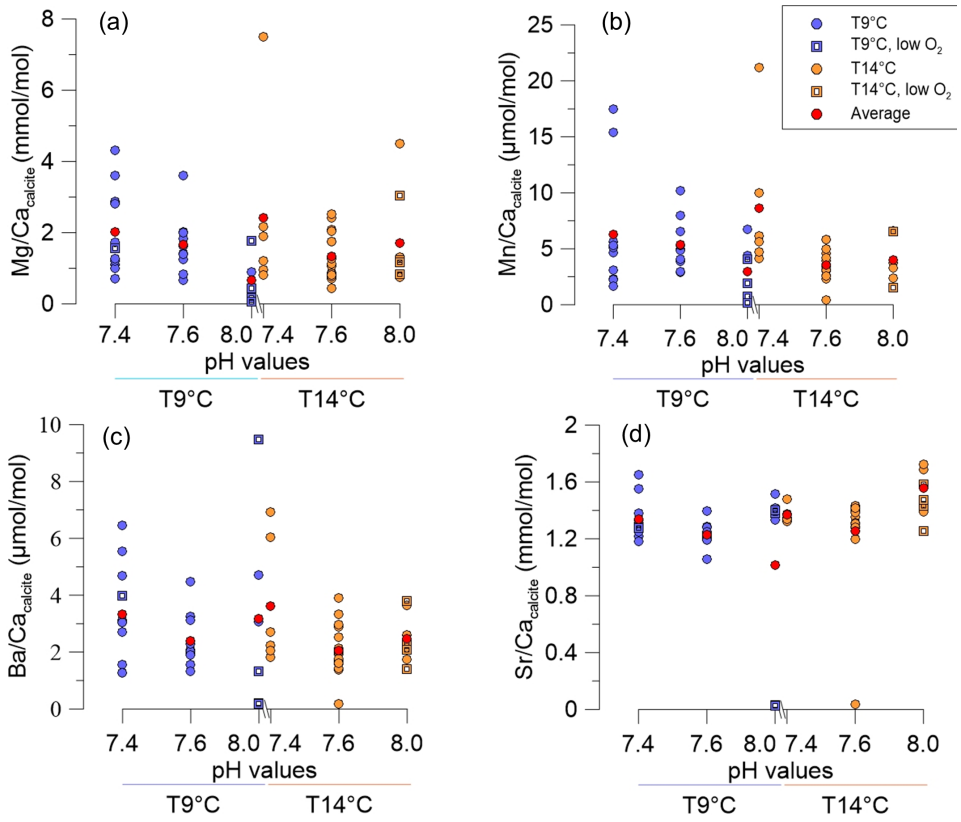

Fig. 9. Scatter plot of TE/Ca ratios against temperature and pH for (a): Mg/Ca (mmol/mol), (b): Mn/Ca (µmol/mol), (c): Ba/Ca (µmol/mol), (d): Sr/Ca (mmol/mol). Low oxygen conditions are indicated with a square shape and mean values with red dots.

DMn = 2.63 ± 1.89; DMg = 0.00028 ± 0.0002; DSr = 0.171 ± 0.041. Almost all partition coefficients are D < 1 (except for Mn/Ca) indicating that elements are fractionated against their relative abundance with respect to [Ca^{2+}]. DMg > 1, indicates that it fractionates relatively more than its abundance in seawater. All the TE partitioning coefficient values are presented in SI4. Statistical analyses showed no significant differences between the partition coefficients and specific water parameters for DMg (p-value > 0.05), DMn (p-value > 0.05), Dba (p-value > 0.05), and DSr (p-value > 0.05).

4 Discussion

4.1 Experimental set-up

Culturing experiments of microorganisms is challenging to achieve due to the difficulty of maintaining stable water conditions throughout the entire experimental period. To our knowledge, previous studies on culturing foraminifera have used pseudo-duplicates, meaning different petri dishes with the same species in one aquarium (e.g., Mojtahid et al., 2023). This study however investigated the use of true duplicates, meaning petri dishes with the same species in different aquariums that displayed the same water parameters. This involved the management of more aquariums, and ensuring their stability can be challenging. The number of investigated variables (i.e., pH, temperature, [O_2]), and specimens (total of 1472 specimens) made the experiment time-consuming but offered many comparable data. Additionally, our targeted pH and O_2 levels were reached through the injection of gas mixtures, and their pressure was adapted every day to reach the targeted values, which is also a challenging task. Thus, many parameters can affect foraminiferal culture (e.g., temperature, salinity, or carbonate chemistry) that our experiment successfully managed to control. Each condition and duplicate displayed statistically stable water parameters throughout the entire experimental period. The targeted pH levels were also managed properly, indicated by the pairwise comparison, which showed significant differences between each targeted pH value. However, the combination of stressors (Hypoxic low-pH) was more difficult to manage resulting in large variability of the measurements at the start of the experiment. The observed variations were thus due to the difficulty of managing the combination of gas bubbling and hermetic coverage. Overall, we are confident that our experimental setup was well-managed and produced coherent results.

4.2 Foraminiferal response

This study was conducted on the species *Ammonia confertitesta* (T6) which is part of the morpho-group *Ammonia tepida* and usually occurs in intertidal mudflats (Hayward et al., 2021). We assumed that studies on *Ammonia* sp. or *Ammonia tepida* are comparable with our investigated species. *Ammonia* is a genus well studied in culturing experiments (e.g., Geslin et al., 2014; Dissard et al., 2010a, b; Mojtahid et al., 2023) and offers a large comparable database. *Ammonia confertitesta* (T6) specimens survived in all the experimental conditions. It was previously shown that shallow-water or paralic species (i.e., *Ammonia* (T6)) display strong adaptative characteristics to laboratory cultures (e.g., Raitzsch et al., 2010; Dueñas-Bohórquez et al., 2011b; van Dijk et al., 2019; Geerken et al., 2022; Mojtehid et al., 2023). This is due to their in-situ exposure to stressful and variable conditions such as salinity, temperature, or even pollution in anthropogenically exposed environments (Bradshaw, 1961, Murray et al., 2006, Pascal et al., 2008, Geslin et al., 2014). Specimens cultured in Controls aquariums, which were designed to reproduce the fjord's in-situ water parameters (control-pH and oxic), were expected to display higher survival percentages. Conversely, the highest survival was recorded for specimens cultured in low pH, warm or oxygen-depleted conditions. Presence percentages are a possible indicator of complete test dissolution during the experiment were also higher for foraminifera growing in stressful conditions (low pH and oxygen-depleted) and lower for control conditions. Finally, *A. confertitesta* (T6) calcified new chambers in almost all the experimental conditions and presented the highest calcification percentages for the low and medium-pH aquariums. This is in line with previous studies showing that *Ammonia tepida* can calcify and add newly formed chambers under laboratory conditions (e.g., Bradshaw 1957, 1961; Goldstein & Moodley 1993; Stouff et al., 1999; de Nooijer et al., 2009). Only the most severe combination of stressors (i.e., warm, hypoxic, low pH) presented no calcification as well as low presence percentages. Thus, the study confirms the adaptive nature of *A. confertitesta* in withstanding challenging conditions, as evidenced by the specimens' ability to both calcify and survive when exposed to one or two stressors. However, their inability to thrive under the combined triple stressor situation (T14 ˚C, low pH, and low oxygen) suggests that a tolerance threshold may have been reached in this specific scenario.

Conversely, we observed that the survival rate for *A. confertitesta* (T6) varied by a factor of two between duplicates from the same environmental conditions, although water parameters showed stability throughout the entire experimental period. This denotes that foraminiferal responses vary extensively between aquariums and their duplicates and suggests that survival, calcification, and presence percentages are not only dependent on environmental conditions but also internal (e.g., physiological, metabolism) or confounding factors (e.g., nutrient availability, contamination). Confounding factors can be genetic variability, nutrient availability, or contamination from bacteria or algae and are not to be dismissed (Boyd & Hutchins, 2012; Boyd et al., 2018). They can be minimized with an improved experimental setup. In this study, additional parameters (DIC, Ωc, pCO_2)

were calculated using a software, whereas previous studies' experimental setup involved the daily measurement of those parameters (Mojtahid et al., 2023) (except Ωc deduced). This would allow greater control of the aquarium's carbon chemistry or potential confounding factors. Furthermore, Mojtahid et al. (2023) noticed the formation of microenvironments when using planktonic nets which is also a possible scenario in this study. These could favor potential bacteria or algae contamination and make the management of nutrient availability challenging. Comparing these results is challenging because to our knowledge previous culturing studies never performed duplicate aquariums.

Furthermore, we investigated the growth percentages by regrouping foraminifera from each condition with their corresponding duplicate and considering them as originating from the same aquarium. Results showed that growth did not seem negatively impacted by the stressors and presented the highest growth percentages in low oxygen + warm conditions. However, deriving a conclusion from these results is challenging, as we showed that foraminiferal response varies between each condition and its corresponding duplicate. This also highlights questions about the accuracy of previous foraminiferal studies and the use of pseudo-replicates. Further perspectives could involve the use of triplicates, a common method in biological studies.

4.3 Environmental effects

To understand the effects of warming only the control aquariums (Control-pH and oxic) results were considered in order to avoid the combined influence of other stressors. No warming-related negative effects regarding survival or presence percentages was observed. In terms of calcification, both controls displayed calcification (around 20 % of specimens that calcified), however in warm aquariums specimens calcified more chambers than in cold ones, indicated by a higher growth percentage. This is in line with previous findings by Dissard et al. (2010a, b) on *Ammonia tepida*, which obtained calcification in warm environments. They however denoted an overall decrease in shell weight, a feature that wasn't investigated in this study but offers future perspective in low-pH experimental studies.

Studies on ocean acidification (OA) generally exhibit a negative response of *A. tepida* and *A. confertitesta* through the decrease in growth percentage or trough mortality (Dissard et al., 2010a; Haynert et al., 2011; Prazeres et al., 2015; Guamán-Guevara et al., 2019; Oron et al., 2020). Thus, we expected a negative foraminiferal response of *A. confertitesta* (T6) in low-pH environments in terms of growth and survival. Furthermore, the impact of acidification and lowered pH on calcifying organisms follows a logarithmic trend. When the calcium carbonate saturation state (Ωc) falls below 1, calcifying organisms are likely to experience dissolution of their tests (Morse and Arvidson, 2002). In our case, this threshold was reached for low-pH conditions at both temperatures (SI3). However, acidification did not seem to have a greater impact on the survival, presence, or calcification percentages than in the control pH level conditions. This was also reported for growth percentages which presented high values at low pH. Additionally, the presence percentages, another possible indicator of dissolution of the test during the experiment, were higher in low pH environments and lower for control conditions. This could either be explained by high foraminiferal loss during the culturing experiment in the other aquariums or that *A. confertitesta* (T6) showed a greater adaptive response to low pH conditions. The latter explanation aligns with studies on *Ammonia* sp. that suggests species robustness in low pH environments because of a strong organismal control over biomineralization during calcification as they reduce their surrounding pH during chamber formation (Glas et al., 2012; Toyofuku et al., 2017; Kawahata et al., 2019; Mojtehid et al., 2023). On the other hand, this could also be due to the settlement micro-environments from using a planktonic net, as previously reported by Mojtehid et al. (2023).

Finally, *Ammonia* sp. has been considered a resistant species in oxygen-depleted conditions because of its occurrence in naturally anoxic environments (Moodley & Hess 1992, Frankel 1975; Buzas 1977; Kitazato 1994; Crosera et al., 2007b). Thus, we expected species robustness to the oxygen-depleted conditions but not for the combination of hypoxia and low pH. Calcification and survival percentages did not seem affected in Hypoxic (normal pH) environments. The highest presence, survival, and calcification percentages all occur for the Hypoxic-high pH warm condition. Geslin et al. (2014) investigated the effects of Hypoxia on survival and growth rate in a culturing experiment, through the observation of additional newly formed chambers. While their results only show a high percentage for 1-2 newly formed chambers, our study shows the highest percentages for 2-3 newly formed chambers at warm temperatures (58%). On the other hand, the combination of stressors (Hypoxic low pH, cold) displayed a very low calcification and growth percentage, and the most severe combination (Hypoxic low pH, warm) presented no calcification probably indicating a negative synergetic effect of low pH, low oxygen concentration and warm temperatures. As mentioned previously this combination of stressors seems to be the most challenging for *A. confertitesta* indicating that we may have reached the species tolerance threshold. However, one of the Control cold aquariums also displays no calcification, even though its duplicate has a high calcification percentage. Since we did not perform duplicates for the Hypoxic low pH (warm and cold) conditions, it is challenging to associate the foraminiferal response to the combination of stressors or to internal effects.

4.4 Trace elements

Trace element incorporation into foraminiferal calcite is known to be largely influenced by ambient environmental parameters present during calcification (Lea., 1999). The involvement of biological effects (growth and metabolic rates) drives intra and inter-specimen substantial variability of the TE incorporations known as ontogenetic effect (Elderfield et al., 2002; Anand & Elderfield, 2005; Hintz et al., 2006a, b; Sadekov et al., 2008; Freitas et al., 2006). However, this study showed an absence of ontogenetic trends in all TE/Ca ratios suggesting no intraspecific variability and making it advantageous for environmental reconstructions. In the following paragraphs, each ratio will be discussed and compared with previous similar studies.

The Mg/Ca values are coherent with previous culturing experiments of *A. tepida* at similar salinity (32-35 psu) and inorganic carbon chemistry (pH ~8.1) which display ranging between 0.5 mmol/mol and 3 mmol/mol (Raitzsch et al., 2010; Dissard et al., 2010a, b; Dueñas-Bohórquez et al., 2011b). This further confirms the accuracy of our experimental study. These studies underline the strong relationship between water temperatures and the incorporation of trace element magnesium (Mg) in inorganically precipitated calcite. Previous research has consistently shown a positive relationship, indicating an increase in Mg incorporation with rising temperatures. (Chilingar, 1962; Katz, 1973; Delaney et al., 1985; Rosenthal et al., 1997; Lea et al., 1999; Lear et al., 2002; Martin et al., 2002). Consequently, we expected that the foraminifera growing in the warm room aquariums would exhibit higher Mg/Ca ratios. Surprisingly, the average values obtained in the cold room (1.62 ± 1.07 mmol/mol) and warm room (1.63 ± 1.38 mmol/mol) were similar, with a slightly higher value observed in the warm room. Even though the highest values of Mg/Ca were observed in the warm environments (i.e., low pH and Medium pH aquariums, see Figure 7), statistical analyses didn't confirm any warming-related significant difference (SI2, p-value = 0.996). We suggest that this study's investigated temperature change (+5 ˚C) may have been insufficient to elicit a significant impact on the Mg/Ca ratios. De facto, De Nooijer et al. (2014) regrouped results from several culturing experiments (i.e., Raitzsch et al., 2010; Dissard et al., 2010a, b; Dueñas-Bohórquez et al., 2011b) and showed that for increasing temperature similar to our study (+5 ˚C) the Mg/Ca would not increase drastically (~0.47 mmol/mol at 10 ˚C to 0.79 mmol/mol at 15 ˚C; Dissard et al., 2010a; 0.88 ± 0.28 mmol/mol at 10 ˚C to 1.08 ± 0.31 mmol/mol at 15 ˚C; Dissard et al., 2010b). This would explain the lack of significant differences observed in our data. We also observed that Dissard et al. (2010a, b) values are slightly lower than ours even though all our parameters are similar (T, pH, salinity, and Ωc) whereas our values fall better into the range of Dueñas -Bohórquez (2011b) (values around 1.63 ± 0.06 mmol/ mol) and Raitzsch (2010) (values around 1.60 ± 0.29 mmol/mol). Conversely, these studies have different salinity (respectively: 35 ± 0.3 and 35.2), temperature (both 18 ˚C), and Ωc (respectively around 4 ± 0.8 and 6.46 ± 0.38) but similar inorganic carbon chemistry. We suggest that these differences in the dimension of the Mg/Ca values are due to confounding factors.

Our studies' Mn/Ca ratios are consistent with studies in natural environments (This study: between 0.12 and 21.16 µmol/mol; Brinkmann et al., 2021 average values: 10.2 ± 4.5 µmol/mol). However, culturing experiments on Mn incorporation displayed values 1/1000 times different (e.g., Barras et al., 2018: 0.13 ± 0.03 and 0.86 ± 0.10 mmol/mol. The Mn/Ca ratio is used in many studies as a proxy for water redox states, considering that benthic foraminifera record the environmental Mn2+ concentration of bottom waters in their test (Groeneveld & Filipsson, 2013; Koho et al., 2015, 2017;). Foraminiferal culturing studies confirmed a positive linear relationship between the dissolved Mn2+ in seawater and the Mn/Cacalcite ratio (species dependent) making it a reliable proxy for bottom water oxygen (Munsel et al., 2010; Barras et al., 2018). Thus, the notable difference in values with Barras et al. (2018) is explained because they manually calibrated the manganese incorporation (higher concentration than in the natural environments) in calcite, which was proportionally incorporated. Their findings showed an increase of 11-25 % for *A. tepida* growing in oxygen-depleted conditions against normal conditions. Petersen et al. (2018) study in natural environments (Lake Grevelingen, Netherlands) demonstrated an increase of twice their mean values for foraminifera growing in oxygen-depleted conditions. Consequently, an increase of around 20 % in the Mn/Ca ratios of foraminifera growing in low oxygen conditions was expected in this study. However, no oxygen-related differences in the Mn/Ca ratios were reported (SI2, p-value = 0.178). This might be explained because the water source originates from a depth of 30 meters, and it is highly probable that the initial Mn content in the water was already low. Furthermore, we didn't examine the water samples' trace elements chemistry during the experiment and are unable to confirm the presence of higher Mn levels in the hypoxic conditions. If the foraminifera grew alongside sediment samples, we could have assessed the potential contribution of Mn leaching from the sediments, which may have yielded different results. We suggest that this is why we didn't find any oxygen -related differences in the Mn/Ca ratio.

The Ba/Ca ratio in biogenic calcium is influenced by the Barium content in ambient water during calcification, which is in turn influenced by terrestrial runoff and river discharge in natural environments (Gattuso & Hansson 2011). Therefore, only in-situ natural events should influence the barium -to-calcium ratio and we did not expect any significant changes for any of the conditions. Statistical analyses showed that the Ba/Ca ratios were not significant in regard to any hydrographic parameters (pH, oxygen, and temperature changes). To our knowledge, the Barium incorporation in culturing experiments hasn't been much studied for *Ammonia* sp. However, in natural environments (Baltic Sea), *Ammonia* sp. (T6) values are around 10 µmol/mol (Groeneveld et al.,

2018) whereas our average value is 2.68 µmol/mol. We suggest that this is due to the growth in an experimentally assessed and nutrient-starved (Ba) environment.

Previous culturing experiments display Sr/Ca values for *Ammonia* sp. around 1.25 and 1.5 mmol/mol (Keul et al., 2013) or 1.16 to 1.73 mmol/mol (Mojtahid et al., 2023) which is the range of our data (this study: 1.34 ± 0.27 mmol/mol). The use of strontium as a proxy is still widely discussed however, Langer (2016) affirmed that there is a correlation between $Sr/Ca_{calcite}$ and $Sr/Ca_{seawater}$ and some studies link the Sr incorporation to increasing [CO_3^{2-}], DIC, [HCO_3^-] or other environmental factors (Dissard et al., 2010, Elderfield et al., 1996, Rosenthal et al., 2006, Mojtahid et al., 2023). We did not expect changes in the Sr/Ca ratios for any of the conditions. Yet, Sr/Ca is the only ratio that showed statistical significance for the oxygen -depleted conditions. Furthermore, Sr/Ca ratio displayed a uniform trend for all conditions which rejoins previous findings that strontium is generally uniform, analytically very robust, and shows high accuracy (e.g., Eggins et al., 2003; Dueñas-Bohórquez et al., 2011a; de Nooijer et al., 2014).

The most interesting results were that for almost all elements a noteworthy large variability of the TE/Ca ratios (Mn, Mg, and Ba) was displayed for foraminifera growing in low pH environments (low pH; warm + cold). When compared to other studies on *Ammonia* sp., this study's Mg/Ca variability at low pH (warm and cold) is larger (e.g., 0.7 to 7.5 mmol/mol in this study; 0.77 ± 0.28 mmol/mol, Dissard et al., 2010a; 1.05 ± 0.10 mmol/mol, Mojtahid et al., 2023). The highest Mg/Ca data point was reported in the combined warm and low pH aquariums (T14 ˚C Low pH). Mn/Ca ratios in the low pH conditions rank between 1.67 and 21.15 µmol/mol and the highest data point was also reported in the warm and low-pH condition. There are no studies on *Ammonia* sp. that investigated the effects of low pH on manganese trace elements incorporation limiting the comparison of our data. Ba/Ca also displays large variability (ranging between 1.27 and 6.92 µmol/mol). To our knowledge, no culturing experiments on *Ammonia* sp. investigated the Ba/Ca ratios, also limiting the comparison. It's interesting to mention that a large variability of the Ba/Ca ratios for foraminifera growing in oxygen-depleted conditions was also observed (ranging from 0.18 to 9.48 µmol/mol). This opens interrogation on the Ba/Ca behavior in low-oxygen conditions. Only Sr/Ca displayed uniform results which is consistent with previous findings that the Sr/Ca ratio is generally analytically robust (de Nooijer et al., 2014). The high variability of Mg/Ca, Mn/Ca, and Ba/Ca suggests a strong physiological influence on the incorporation of TE into the shells and has been previously reported for other species on the Mg/Ca incorporation (Segev et al., 2006). Here we suggest that the high TE/Ca variability observed in low pH environments is due to *A. confertitesta* (T6) struggling to calcify at equilibrium with the ambient TE available. If they had indeed calcified in equilibrium with the ambient seawater, the ratios would have exhibited less variability and shown more uniform results. This hypothesis will be further investigated with additional laser ablation analyses. This study offers new insights into trace elements incorporation behavior into foraminiferal calcite for Mn/Ca, Ba/Ca, and Sr/Ca ratios, rarely investigated in low-pH environments.

4.5 Partition coefficient

The partition coefficients of genus *Ammonia* in culturing experiments previously reported are consistent with this study as exposed in the following paragraph. Dissard et al. (2010a) estimated the partition coefficient of Magnesium DMg for *A. tepida* to be ranging between 9.6 (± 2.7)E^{-5} (at T10 ˚C, high pH) and 14.5 (± 5.3)E^{-5} (at T15 ˚C and low pH) when our study calculated a DMg = 0.00028 ± 0.0002. Munsel et al. (2010) estimated a DMn = 2.4 which comes close to our DMn = 2.63 ± 1.89. On the other hand, Barras et al. (2018) DMn values were consequently lower (between 0.09 and 0.35) for individuals growing in similar salinity 34 and pH 8.1 which was due to manual Mn calibration. Havach et al. (2001) found a DBa = 0.20 ± 0.04 for *Ammonia beccarii*, comparable to our DBa = 0.56 ± 0.34. Finally, Dissard et al. (2010a) also estimated a DSr value for A. tepida between 0.165 (± 0.017) (T10 ˚C, high pH) and 0.175 (±0.019) (T15 ˚C low pH), when our data ranges around DSr = 0.171 ± 0.041. Boyle (1981) states that if partition coefficient behavior demonstrates control (D <1) over trace element chemistry, then the trace elements can be used as proxies for ocean/water chemistry. Therefore Mg, Ba, and Sr are considered advantageous for environmental reconstruction. The partitioning coefficient values being consistent with previous culturing experiments suggests that the trace elements incorporation behavior in specimens from this experiment is coherent. This confirms and adds credibility to our experimental setup which exhibits a consistent foraminiferal response to the given environmental conditions and element availability. However, the statistical test on the partition coefficients revealed that there were no significant differences in the coefficient related to changes in environmental stressors. We suggest that this is due to the lack of values which will be corrected with additional LA-ICP-MS measurements.

5 Conclusions

This study successfully managed to assess a triple-stressor situation on foraminifera in culturing experiments while ensuring stable water parameters. Thus, it offers a viable experimental set-up method for future studies. Foraminifera from the experiment consequently proved to be advantageous for environmental reconstruction due to the absence of ontogenetic trends between chamber stages. *Ammonia confertitesta* (T6) survived and calcified in nearly all conditions

except in the most severe combination of stressors. This may indicate that the resistance threshold of the species was reached. However, the survival percentages varied by a factor of two between each condition and their duplicate maybe indicating an internal response rather than solely being driven by environmental factors. This highlights questioning in the use of duplicates and could be further investigated with the use of triplicates. Considering the TE ratios, the Mg/Ca ratios did not present the expected outcomes, possibly because the investigated temperature gradient was too small. Similarly, the observed Mn/Ca ratios did not yield the expected results, potentially due to very low Mn concentrations in the water. Finally, the large variability of the TE/Ca ratio may suggest that *A. confertitesta* struggles to calcify in equilibrium with the ambient water chemistry at low pH. Because Laser Ablation is a destructive method, half of the selected specimens were saved for complementary study on foraminiferal 3D morphology and will be later analyzed for LA-MS-ICP. In the global context, the study showed that even a well-known resistant foraminifera species is affected by the expected scenarios of the year 2100 in terms of survival, calcification, and trace element incorporation.

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8 Supplementary Information:

LA-ICP-MS operating conditions	
Pulse Repetition Rate	5 Hz
Energy Densitiy	
For samples and carbonate standards	1 J\cm^2
For glass standards	3 J\cm^2
Ablation Spot size	40x50 μm
Measured isotopes	Mg^{26} Al^{27} Mn^{55} Zn^{66} Sr^{88} Ba^{137} Ba^{138} U^{238}
Standard for calibration	US National Institute of Standards and Technology SRM NIST610 with GeoReM (Geological and Environmental Reference Materials, 2021; Jochum et al., 2005) composition values
Secondary Standard	NIST612 MACS-3 (MicroAnalytical Carbonate Standard, Unitate States Geological Survey, 2012; Jochum et al. 2012) JCt-1 and JCp-1 (AIST Japan calcium carbonate pellets)

Supplementary Information 1: Summary of the operating condition of the Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS)

	Mg/Ca		**Mn/Ca**		**Ba/Ca**		**Sr/Ca**	
	R2	p-value	R2	p-value	R2	p-value	R2	p-value
Temperature	0.0001	0.996	0.9138	0.515	0.4599	0.49	1.1182	0.286
pH conditions	2.7609	0.076	2.036	0.179	2.8185	0.074	2.1203	0.136
Oxygen conditions	0.3513	0.527	0.7342	0.178	0.1059	0.72	5.8818	<u>0.042</u>
Temperature:pHconditions	1.2968	0.281	1.8885	0.198	0.4993	0.621	2.8246	0.083
Temperature:Oxy	0.1246	0.658	0.285	0.198	0.0936	0.734	2.4357	0.167
pHconditions:Oxy	0.0008	0.971	2.2569	0.079	1.149	0.283	3.9281	0.099

Supplementary Information 2: R2 and p-value of each TE/Ca ratios (Mg/CA, Mn/Ca, Ba/Ca and Sr/Ca) comparison with water parameters (Temperature, pH conditions and Oxygen conditions) and combined parameters (Temperature:pHconditions, Temperature:Oxy, pH conditions:Oxy.). Only significant p-value (Sr/Ca; Oxygen conditions) is underlined.

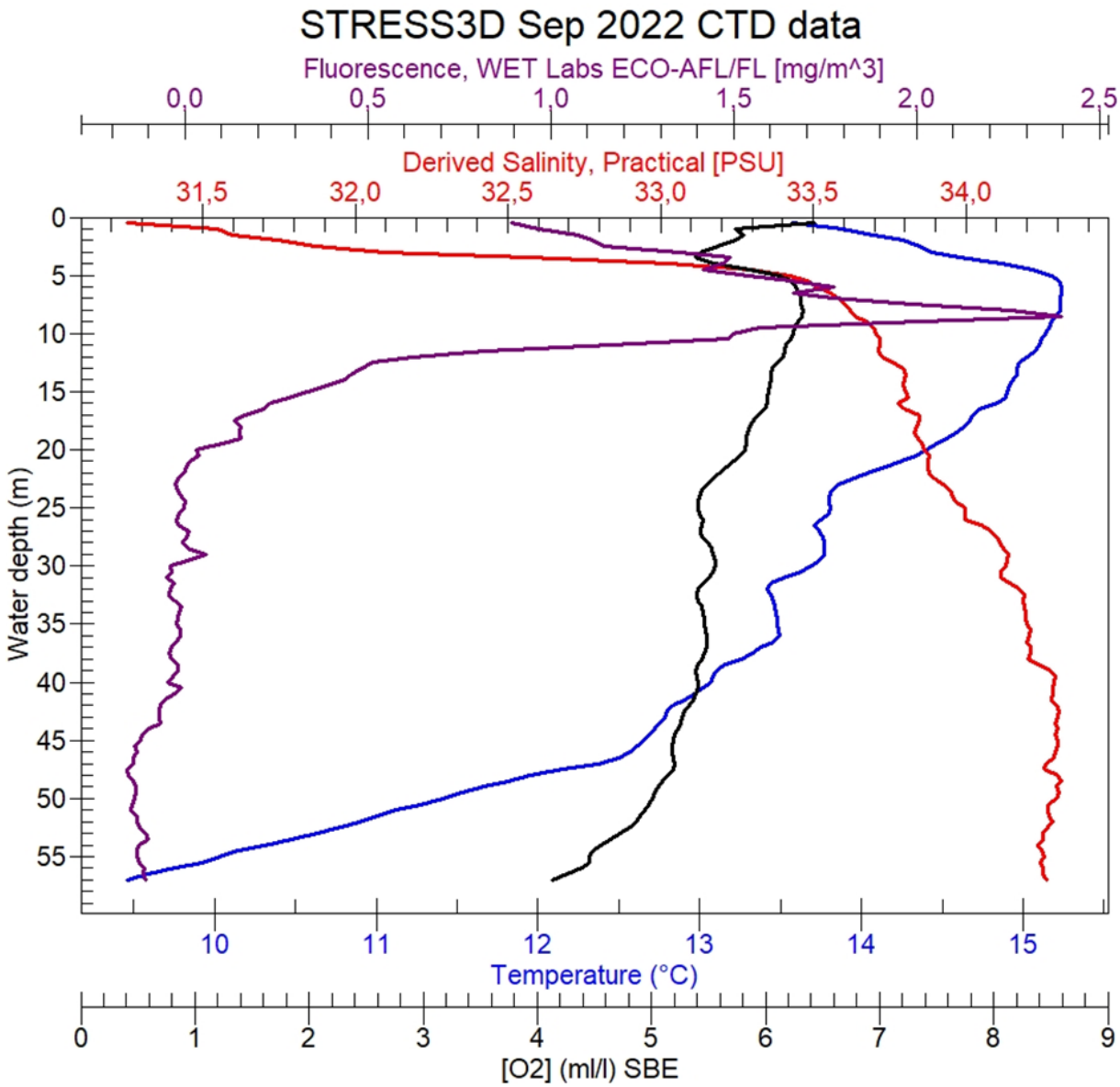
	9°C							
	Control-1	Control-2	Medium pH-1	Medium pH-2	Low pH-1	Low pH-2	Hypoxic-high pH	Hypoxic-low pH
pH "nominal"	8	8	7.6	7.6	7.4	7.4	8	7.4
pH (total scale) "measured"	7.94	7.95	7.59	7.59	7.39	7.40	7.90	7.44
SD pH (total scale) "measured"	0.03	0.04	0.02	0.02	0.02	0.02	0.05	0.16
Water temperature (°C)	9.0	8.9	8.9	8.9	8.8	8.8	8.8	8.9
SD Water temperature (°C)	0.42	0.30	0.19	0.18	0.16	0.16	0.26	0.21
Salinity	34.3	34.4	33.9	33.9	33.9	33.9	33.3	33.0
SD Salinity	0.39	0.36	0.05	0.03	0.13	0.25	0.21	0.47
TA (µmol kg^{-1} SW)	2407.1	2410.1	2406.5	2412.3	2389.2	2383.2	2349.8	2381.9
SD TA (µmol kg^{-1} SW)	32.6	59.6	56.5	52.8	51.6	65.9	73.5	39.4
pCO_2 (µatm)	535.9	535.3	1324.0	1334.5	2137.1	2073.8	614.2	1949.3
SD pCO_2 (µatm)	34.1	38.6	62.5	57.8	142.9	148.9	66.7	508.1
DIC (µmol kg^{-1} SW)	2269.3	2272.3	2389.3	2399.4	2440.0	2430.2	2240.7	2417.6
SD DIC (µmol kg^{-1} SW)	32.3	57.2	57.8	53.2	57.5	69.6	74.9	64.4
$[CO_3^{2-}]$ (µmol kg^{-1} SW)	110.2	109.9	50.5	50.2	31.9	32.5	93.3	36.7
SD $[CO_3^{2-}]$ (µmol kg^{-1} SW)	6.3	7.0	1.9	2.1	1.4	2.0	8.6	13.8
$[HCO_3^-]$ (µmol kg^{-1} SW)	2124.9	2137.7	2278.5	2121.58	2310.3	2302.6	2123.8	2291.4
SD $[HCO_3^-]$ (µmol kg^{-1} SW)	31.9	54.4	55.2	598.5	52.5	65.1	74.8	54.5
Omega calcite (Ωc)	2.6	2.6	1.2	1.2	0.8	0.8	2.2	0.9
SD Omega calcite (Ωc)	0.2	0.2	0.1	0.1	0.03	0.1	0.2	0.3
$[O_2]$ (µmol L^{-1})							52.1	42.0
SD $[O_2]$ (µmol L^{-1})							11.7	8.5

	14°C							
	Control-1	Control-2	Medium pH-1	Medium pH-2	Low pH-1	Low pH-2	Hypoxic-high pH	Hypoxic-low pH
pH "nominal"	8	8	7.6	7.6	7.4	7.4	8	7.4
pH (total scale) "measured"	7.97	7.98	7.60	7.59	7.40	7.40	7.88	7.43
SD pH (total scale) "measured"	0.04	0.04	0.02	0.01	0.02	0.02	0.08	0.06
Water temperature (°C)	13.9	13.9	13.9	13.9	14.0	14.0	14.1	14.2
SD Water temperature (°C)	0.30	0.30	0.26	0.37	0.21	0.23	0.21	0.24
Salinity	34.7	34.6	33.8	33.9	34.1	33.8	33.4	33.3
SD Salinity	0.42	0.50	0.16	0.28	0.26	0.20	0.24	0.20
TA (µmol kg^{-1} SW)	2421.4	2402.1	2407.8	2388.7	2382.5	2402.3	2355.6	2368.8
SD TA (µmol kg^{-1} SW)	46.2	46.8	58.7	41.9	64.2	70.5	50.8	46.2
pCO_2 (µatm)	498.5	487.2	1315.4	1317.4	2098.8	2131.9	616.6	1940.2
SD pCO_2 (µatm)	50.9	52.7	58.7	48.3	95.9	158.5	64.9	336.1
DIC (µmol kg^{-1} SW)	2234.3	2209.3	2368.5	2350.6	2404.7	2426.4	2214.2	2379.7
SD DIC (µmol kg^{-1} SW)	43.2	45.8	48.5	43.2	64.3	69.6	46.9	24.9
$[CO_3^{2-}]$ (µmol kg^{-1} SW)	141.9	142.3	62.2	61.4	40.4	40.4	113.5	43.9
SD $[CO_3^{2-}]$ (µmol kg^{-1} SW)	11.7	13.4	2.3	1.7	2.1	3.2	9.5	8.8
$[HCO_3^-]$ (µmol kg^{-1} SW)	2072.9	2052.3	2255.1	2237.9	2283.1	2303.3	2076.8	2379.7
SD $[HCO_3^-]$ (µmol kg^{-1} SW)	43.1	37.9	46.2	41.1	61.4	66.4	44.7	24.9
Omega calcite (Ωc)	3.4	3.4	1.5	1.5	0.97	0.97	2.7	1.1
SD Omega calcite (Ωc)	0.3	0.3	0.1	0.04	0.05	0.1	0.2	0.2
$[O_2]$ (µmol L^{-1})							54.9	45.7
SD $[O_2]$ (µmol L^{-1})							6.4	5.5

Supplementary Information 3: Average values (black) and standard deviation (grey) for all water parameters ($pH_{totalscale}$, Water temperature, Salinity, TA, pCO_2, DIC, $[CO_3^{2-}]$, $[HCO_3^-]$, Omega calcite, $[O_2]$) in all conditions and duplicates.

	Conditions	Analysed chamber	Mg/Ca calcite (mmol/mol)	Mg/Ca seawater (mmol/mol)	DMg	Mn/Ca calcite (μmol/mol)	Mn/Ca seawater (μmol/mol)	DMg	Ba/Ca calcite (μmol/mol)	Ba/Ca seawater (μmol/mol)	Dba	Sr/Ca calcite (mmol/mol)	Sr/Ca seawater (mmol/mol)	DSr
T9°C	Control	n	0.894561407	5662.815855	0.000157971	LOD	LOD	LOD	LOD	LOD	LOD	1.33334136	7.504210781	1.78E-01
		n	LOD	LOD	LOD	4.413555	2.082031624	2.119831048	3.064357337	4.69473548	0.652722044	1.417961653	7.504210781	1.89E-01
		n1	LOD	LOD	LOD	6.711522	2.082031624	3.223544734	4.69868125	4.69473548	1.000840467	1.514017119	7.504210781	2.02E-01
	Medium pH 7.6	n	1.624226702	5594.488624	0.000290326	2.899815	2.045925634	1.417361022	2.086681425	4.864965929	0.428920049	1.392804268	7.434525784	1.87E-01
		n	LOD	LOD	LOD	4.978928	2.045925634	2.433582131	1.561363024	4.864965929	0.320940177	1.215559062	7.434525784	1.64E-01
		n	2.00348776	5594.488624	0.000358118	7.969932	2.045925634	3.895514254	4.479798583	4.864965929	0.920828357	1.209841475	7.434525784	1.63E-01
		n	0.667829253	5594.488624	0.000119373	5.270733	2.045925634	2.576209656	1.313296002	4.864965929	0.269949681	1.055466617	7.434525784	1.42E-01
		n	1.822102037	5594.488624	0.000325696	5.307209	2.045925634	2.594038096	2.013720536	4.864965929	0.413922845	1.192688713	7.434525784	1.60E-01
		n	1.402853672	5594.488624	0.000250756	4.085274	2.045925634	1.996785339	1.904279202	4.864965929	0.391427038	1.239572929	7.434525784	1.67E-01
		n	3.602980045	5594.488624	0.000644023	10.21319	2.045925634	4.991963346	3.115429959	4.864965929	0.640380633	1.248721068	7.434525784	1.68E-01
		n1	1.416045361	5594.488624	0.000250756	4.842144	2.045925634	2.366725479	2.393117158	4.864965929	0.491908308	1.190973436	7.434525784	1.60E-01
		n1	0.82448056	5594.488624	0.000147374	2.972767	2.045925634	1.453017903	1.940759647	4.864965929	0.39892564	1.210984992	7.434525784	1.63E-01
		n1	2.024099774	5594.488624	0.000361802	6.547382	2.045925634	3.200205074	2.280757389	4.864965929	0.468812613	1.278452522	7.434525784	1.72E-01
		n2	1.236720839	5594.488624	0.000221061	3.848182	2.045925634	1.880900475	3.23946347	4.864965929	0.66587588	1.28417011	7.434525784	1.73E-01
	Low pH 7.4	n	0.704930878	5651.055267	0.000124743	2.334442	2.075151535	1.124950358	1.276815557	4.775958419	0.267342268	1.25672569	7.488012807	1.68E-01
		n	3.611224851	5651.055267	0.000639035	15.39273	2.075151535	7.417641423	5.545027562	4.775958419	1.161029279	1.334484878	7.488012807	1.78E-01
		n	4.307910924	5651.055267	0.00076232	4.668885	2.075151535	2.249900716	4.684089072	4.775958419	0.980764207	1.549466161	7.488012807	2.07E-01
		n	1.096559144	5651.055267	0.000194045	2.243253	2.075151535	1.081006985	1.568659113	4.775958419	0.328449072	1.217846097	7.488012807	1.63E-01
		n	1.731409175	5651.055267	0.000306387	5.106593	2.075151535	2.460828908	2.706848981	4.775958419	0.566765609	1.310471011	7.488012807	1.75E-01
		n	0.997621477	5651.055267	0.000176537	1.677881	2.075151535	0.80855807	3.04246907	4.775958419	0.637038434	1.647808662	7.488012807	2.20E-01
		n	1.20786402	5651.055267	0.000213741	3.063956	2.075151535	1.476497345	1.276815557	4.775958419	0.267342268	1.183540573	7.488012807	1.58E-01
		n	2.881559556	5651.055267	0.000509915	5.653728	2.075151535	2.724489148	3.115429959	4.775958419	0.652315135	1.248721068	7.488012807	1.67E-01
		n	1.273822465	5651.055267	0.000225413	5.325447	2.075151535	2.566293004	3.049765159	4.775958419	0.638566104	1.381369094	7.488012807	1.84E-01
		n	2.819723514	5651.055267	0.000498973	17.4536	2.075151535	8.410761661	6.464334763	4.775958419	1.353515713	1.33334136	7.488012807	1.78E-01
	Hypoxic-high	n	0.44150934	5708.236337	7.7346E-05	1.896735	2.406368748	0.788214401	1.313296002	5.17634612	0.25371101	1.377938541	7.625640566	1.81E-01
		n	0.156651306	5708.236337	2.7443E-05	0.711275	2.406368748	0.2955804	0.211586578	5.17634612	0.040875663	0.030074509	7.625640566	3.94E-03
		n	0.054003477	5708.236337	9.46062E-06	0.127665	2.406368748	0.053052892	0.179483787	5.17634612	0.034673838	0.024345487	7.625640566	3.19E-03
		n1	1.772633203	5708.236337	0.00031054	4.030561	2.406368748	0.053052892	9.484915566	5.17634612	1.832357293	1.399665373	7.625640566	1.84E-01
	Hypoxic-low pH	n	1.550023452	5713.928268	0.000271271	141.8903	2.059320171	68.90153989	3.990960627	4.875656996	0.818548276	1.273878452	7.593756561	1.68E-01
T14°C	Control	n	0.76676692	5722.310612	0.000134193	2.389156	1.747325386	1.367321723	2.152346225	4.746292183	0.453479504	1.685544739	7.61474726	2.21E-01
		n	0.754399712	5722.310612	0.000131835	3.264572	1.747325386	1.868325103	1.729173069	4.746292183	0.364320822	1.389373716	7.61474726	1.82E-01
		n1	4.49341905	5577.126636	0.000786398	6.602095	1.747325386	3.778400487	3.633452271	4.746292183	0.765534891	1.722137297	7.61474726	2.26E-01
		n2	1.315046492	5577.126636	0.00022981	3.738756	1.747325386	2.139701934	2.597407647	4.746292183	0.547249842	1.41910517	7.61474726	1.86E-01
	Medium pH	n	0.840970171	5577.126636	0.000150789	3.629329	1.51492797	2.395710283	1.692692624	4.663533933	0.362963505	1.353924675	7.383683191	1.83E-01
		n	1.747898786	5577.126636	0.000156333	3.428712	1.51492797	2.263284086	2.896547292	4.663533933	0.621105654	1.400808891	7.383683191	1.90E-01
		n	0.701220716	5577.126636	0.000188265	2.334442	1.51492797	1.540959378	1.583251291	4.663533933	0.339496037	1.389373716	7.383683191	1.88E-01
		n	0.849214976	5577.126636	0.000313405	3.410475	1.51492797	2.251245341	1.371664713	4.663533933	0.294125599	1.278452522	7.383683191	1.73E-01
		n	2.073568607	5577.126636	0.000125732	3.082194	1.51492797	2.034547929	2.969508181	4.663533933	0.636750632	1.430540345	7.383683191	1.94E-01
		n	0.758522115	5577.126636	0.000152267	2.535059	1.51492797	1.673385574	1.415441246	4.663533933	0.303512586	1.197262782	7.383683191	1.62E-01
		n	Missing Chamber	Missing Chamber	Missing Chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber
		n	0.803868546	5577.126636	0.000240228	LOD	LOD	LOD	1.772949602	4.663533933	0.380172982	1.430540345	7.383683191	1.94E-01
		n	1.265577659	5577.126636	0.000430932	4.942452	1.51492797	3.262499933	1.597843469	4.663533933	0.342625033	1.253295138	7.383683191	1.70E-01
		n	2.028222177	5577.126636	0.000201791	5.79963	1.51492797	3.828320954	3.319720448	4.663533933	0.71184653	1.413387583	7.383683191	1.91E-01
		n1	0.87188819	5577.126636	0.000371799	3.939372	1.51492797	2.60036895	1.678100446	4.663533933	0.35983451	1.313329805	7.383683191	1.78E-01
		n1	1.33978091	5577.126636	0.000313405	3.02748	1.51492797	1.998431693	1.911575291	4.663533933	0.409898442	1.287600662	7.383683191	1.74E-01
		n1	2.40336083	5577.126636	0.000453107	5.817868	1.51492797	3.8403597	3.910703649	4.663533933	0.838570857	1.305896941	7.383683191	1.77E-01
		n1	1.74789879	5577.126636	0.000136006	3.136907	1.51492797	2.070664164	2.137754047	4.663533933	0.458397875	1.385943164	7.383683191	1.88E-01
		n1	0.42872989	5577.126636	7.68729E-05	0.441356	1.51492797	0.291337632	0.180213396	4.663533933	0.03864097	0.033276358	7.383683191	4.51E-03
		n2	1.049975993	5577.126636	0.000144137	4.614171	1.51492797	3.04580252	2.029771931	4.744202779	0.430610787	1.27959604	7.383683191	1.73E-01
		n2	1.125415964	5743.937644	0.000226923	2.598891	1.51492797	1.715521182	1.991832269	4.663533933	0.427107918	1.282454833	7.383683191	1.74E-01
		n2	2.527032915	5743.937644	0.000363668	4.194701	1.51492797	2.768911382	2.51715067	4.663533933	0.539751765	1.278452522	7.383683191	1.73E-01
	Low pH 7.4	n	2.160139066	5743.937644	0.000376073	4.12175	1.924564468	2.141653367	2.225307114	4.744202779	0.469058178	1.34706357	7.583034133	1.78E-01
		n	0.952275046	5743.937644	0.000165788	4.723598	1.924564468	2.454372664	1.809430047	4.744202779	0.381398125	1.345920052	7.583034133	1.77E-01
		n	1.90042769	5743.937644	0.000140453	9.976094	1.924564468	5.183559256	6.026569429	4.744202779	1.270301821	1.375651507	7.583034133	1.81E-01
		n	1.195496811	5743.937644	0.000330858	5.599014	1.924564468	2.909237096	2.706848981	4.744202779	0.570559292	1.480855113	7.583034133	1.95E-01
		n	Missing Chamber	Missing Chamber	Missing Chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber	Missing chamber
		n1	0.806754228	5743.937644	0.000140453	6.146149	1.924564468	3.193527366	2.042904891	4.663533933	0.435243307	1.319619151	7.583034133	1.74E-01
		n1	7.502773092	5743.937644	0.001306207	21.15588	1.924564468	10.99255711	6.923988364	4.744202779	1.459462988	1.339058948	7.583034133	1.77E-01
	Hypoxic-high pH	n	0.820358157	5705.537367	0.000143783	LOD	LOD	LOD	1.393552979	5.423905369	0.256927967	1.433970897	7.645210504	1.88E-01
		n	1.162517589	5705.537367	0.00053178	LOD	LOD	LOD	2.079385336	5.423905369	0.383374192	1.584915202	7.645210504	2.07E-01
		n1	3.034088459	5705.537367	0.00021459	6.565619	2.023515401	3.244659972	3.801262315	5.423905369	0.700834926	1.25672569	7.645210504	1.64E-01
		n1	1.224353631	5705.537367	0.000203753	1.550216	2.023515401	0.766100271	2.290971914	5.423905369	0.422384197	1.475137526	7.645210504	1.93E-01
Total data points			57			56			59			60		

Supplementary Information 4: Laser ablation data point, water chemistry and corresponding partition coefficient for Trace elements to Ca ratios of Mg, Mn, Ba and Sr.



Supplementary Information 5: CTD profile of the GF50 oxic station displaying Temperature (˚C), Salinity (psu), and Fluorescence (mg/m^3)

Foraminiferal behavior

Conditions		Presence	Survival	Calcification	Growth
T9 °C	Control	Medium	Low	Low	Very Low
	Medium pH 7.6	Medium	Medium	Low	Medium
	Low pH 7.4	High	High	Medium	Medim
	Hypoxic high-pH	High	Medium	Low	Low
	Hypoxic low-pH	Medium	Medium	Low	Very Low
T14 °C	Control	Medium	Low	Low	Medium
	Medium pH 7.6	Medium	Medium	Medium	Medium
	Low pH 7.4	Medium	Medium	Low	Medium
	Hypoxic high-pH	High	High	Low	High
	Hypoxic low-pH	Medium	Medium	None	None

Trace Elements

Conditions		Mg/Ca	Mn/Ca	Ba/Ca	Sr/Ca
T9 °C	Control	-	-	-	-
	Medium pH 7.6	-	-	-	-
	Low pH 7.4	-	-	-	-
	Hypoxic high-pH	-	-	-	+
	Hypoxic low-pH	-	-	-	+
T14 °C	Control	-	-	-	-
	Medium pH 7.6	-	-	-	-
	Low pH 7.4	-	-	-	-
	Hypoxic high-pH	-	-	-	+
	Hypoxic low-pH	-	-	-	+

Significant change	+
No significant change	-

Supplementary Information 6: Summary of the most interesting results.

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