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Comparison of climate signals obtained from encrusting and free-living rhodolith coralline algae

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ABSTRACT

Coralline algae have been used for sclerochronological studies throughout the last decade. These studies have focused on two different growth morphologies of the photosynthetic coralline algae: massive crusts forming small buildups on hard substrate, and free-living branching algal nodules, known as rhodoliths. The latter are generally found on soft-substrate, where they are frequently overturned by water movement and bottom feeding organisms, leaving one side of the rhodolith partially buried in the sediment at any given time. Here we test whether either of these growth morphologies is more suitable for proxy reconstructions by comparing Mg/Ca ratios – a temperature proxy – in multiple replicates of rhodoliths of *Lithothamnion glaciale* and in rhodoliths as well as encrusting specimens of *Clathromorphum compactum*. With both species being widespread throughout the Temperate and Arctic regions, we have chosen two North Atlantic localities at Nuuk Fjord, Greenland (Subarctic), and off the southeastern coast of Newfoundland, Canada (Temperate), for this study. Two to three Mg/Ca ratio transects spanning 18 years of growth were analysed on multiple specimens with encrusting morphologies and along different sides of rhodoliths using laser ablation inductively coupled mass spectrometry and compared to remotely sensed sea surface temperature (SST) data. The length of the common time span used for comparison was limited by growth interruptions in rhodoliths. Furthermore, our comparison is based on the assumption that rhodolith growth increments are annual – an assumption that has recently been challenged by mesocosm studies. Monthly Mg/Ca values from multiple transects within each individual were compared and in samples from Nuuk fjord significant correlations were found in 4 of 4 encrusting *C. compactum*, 4 of 4 *C. compactum* rhodoliths, and 2 of 3 *L. glaciale* rhodoliths. In Newfoundland significant correlations were found in 6 of 6 encrusting *C. compactum* comparisons (average: $r = 0.61$, $p < 0.001$), and in 6 of 6 *L. glaciale* rhodolith comparisons (average: $r = 0.43$, $p < 0.001$) for monthly resolved time series. The monthly Mg/Ca ratios ($n = 216$) from each morphology were compared with instrumental Reynolds SST yielding the following correlations: encrusting *C. compactum* ($r = 0.64$, $p < 0.001$), *C. compactum* rhodolith ($r = 0.62$, $p < 0.001$) and *L. glaciale* ($r = 0.58$, $p < 0.001$). In Newfoundland both morphologies indicate a similar strength in recording SST: encrusting *C. compactum* ($r = 0.85$, $p < 0.001$) and rhodolith-forming *L. glaciale* ($r = 0.84$, $p < 0.001$). In summary, Mg/Ca ratios derived from both coralline algal growth forms can yield SST information, however, massive encrusting forms generally yield higher correlations to SST than transects measured on individual rhodoliths, which only allowed for the generation of short uninterrupted time series due to frequent growth irregularities.

1. Introduction

Accurate instrumental sea surface temperature (SST) data only extends back to the 1850's and only in a select few places (Rayner et al., 2003), while in more remote locations data exist only for the last few decades. This leaves a significant gap in our knowledge of past climate, especially in poorly studied regions such as the Subarctic and Arctic. In these regions proxy data are required to provide extended time series of

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Abbreviations: SST, sea surface temperature; MODIS, Moderate Resolution Imaging Spectroradiometer; LA-ICP-MS, laser ablation inductively coupled mass spectrometry

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past climate. A better understanding of past climate decreases the uncertainty of projections of future climate through models. Typically, annual and subannual resolution environmental proxy data from high-latitude terrestrial settings have come from tree rings, lake sediments and ice cores that can provide information about temperatures and rainfall over centuries and millennia (Fritts and Swetnam, 1989). In temperate to subarctic oceans bivalve shells have been used to reconstruct environmental conditions including surface temperatures (e.g. Butler et al., 2010; Reynolds et al., 2013; Schöne et al., 2005), and coralline algae from subarctic and arctic settings have served as a proxy for temperature as well as a variety of environmental variables such as light, glacial runoff, nutrients, freshwater and sea ice variability (Burdett et al., 2012; Chan et al., 2017; Halfar et al., 2013; Hetzinger et al., 2013; Kamenos et al., 2012). Extratropical climate reconstructions from the annual-increment forming photosynthetic coralline algae have focused on two different growth morphologies and genera: massive crusts of *Clathromorphum compactum* and *Clathromorphum nereostratum* forming buildups as thick as 50 cm on hard substrate (Adey et al., 2013; Chenelot et al., 2011), and free-living branching algal nodules, so called rhodoliths, of the species *Lithothamnion glaciale* (Kamenos et al., 2013).

While *C. compactum* commonly occurs as encrusting small buildups that have a hemispherical shape with a smooth surface (Adey, 1965), it has recently also been found in the form of free-living massive (i.e. non-branching) rhodolith nodules (Jørgensbye and Halfar, 2016). Individual specimens of encrusting *C. compactum* can have lifespans of up to 650 years with maximum annual growth rates of 400 μm/year (Halfar et al., 2013). Annual growth rates do not exhibit a decline with increasing specimen age (ontogenetic decline) allowing the use of annual growth as a paleoclimate proxy without requiring the statistical removal of ontogenetic trends (Halfar et al., 2008). Removal of ontogenetic trends has been shown to obscure long-term climate variability (Schöne et al., 2005). *C. compactum* is widely-distributed throughout the Arctic and Subarctic, with often dense coverage on rocky substrate at water depths ranging from 5 to 30 m and has been sampled as far north as 79.5° (J. Halfar, pers. obs.).

L. glaciale exhibits a branching morphology and can grow attached or unattached (Fig. 1). *L. glaciale* lives in the mid to lower photic zone and occasionally in tide pools and the upper photic zone (Adey, 1970). Although its growth is not inhibited at high light levels, branches are too fragile to withstand heavy wave action (Adey, 1970). Compared to other species of sub-arctic coralline algae *L. glaciale* is relatively fast growing, up to ~12 μm/day in optimal conditions (Adey, 1970). As a result it is the most abundant coralline species in the North Atlantic (Adey, 1970).

Rhodolith-forming morphologies of *L. glaciale* and *C. compactum* are generally found on soft-substrate, where they are overturned by water movement and bottom feeding organisms, leaving one side of the rhodolith partially buried in the sediment at any given time (Marrack, 1999). Rhodolith turning frequency can also be correlated with water depth, since rhodoliths are turned by waves, rather than tidal currents, so shallow rhodoliths are more frequently moved (Steller and Foster, 1995). Depending on the environmental setting it is possible that rhodoliths are not moved on a regular schedule and that the side facing the seafloor, which is often partially buried in sandy sediment, may cease growing if it remains buried for too long (Freiwald and Henrich, 1994).

In this study, we evaluate the climate archiving potential of both genera by comparing Mg/Ca ratio-based time series from samples collected at two North Atlantic localities: (1) Massive growing *C. compactum* rhodoliths and encrusting samples, as well as *L. glaciale* rhodoliths from Nuuk, Greenland, and (2) encrusting *C. compactum* and *L. glaciale* rhodoliths from Bay Bulls, Newfoundland (Fig. 2). At both localities we will statistically test for inter- and intra-specimen time-series similarities, as well as compare algal Mg/Ca ratios with local instrumental temperature time series.

2. Methods

2.1. Sampling

Coralline algae were live collected in the Nuuk fjord in Greenland (64°10N, − 51°60W; 12 m depth) by dredge (rhodoliths) or by divers (encrusting morphologies) in summer 2013. Rhodoliths and encrusting coralline algae were also collected near Saint John's, Newfoundland (47°18N, 52°47W; 9 m depth) by divers in summer 2008 (Table 1). Live collection of *C. compactum* was determined by the presence of an undamaged meristem (sub-surface growth plate) and an epithallial crust (cover cells), which is extremely fragile and is easily dislodged after death. In addition, live collection of branched *L. glaciale* rhodoliths was confirmed by the presence of pink pigmentation on all branches. Encrusting samples were selected based on maximum thickness, while the most spherical rhodolith samples were chosen. *C. compactum* rhodoliths selected for this project all contained a pebble nucleus, *L. glaciale* did not have nuclei (see Fig. 1). From the Greenland collection 4 of 13 encrusting *C. compactum* samples, 5 of 14 *C. compactum* rhodoliths, and 3 of 3 *L. glaciale* rhodoliths were analysed. From the Newfoundland collection 4 of 14 encrusting *C. compactum* samples, and 4 of 7 *L. glaciale* rhodoliths were analysed.

2.2. Sample preparation

Due to the fragility of the fine branches (average branch thickness 3 mm), *L. glaciale* samples were embedded in resin prior to preparation. All samples were thick sectioned and polished to 1 μm. The software geo.TS (Olympus Soft Imaging Systems) was utilized with an automated sampling stage on a reflected light microscope to produce two-dimensional maps of the polished samples (for details see Hetzinger et al., 2009). These high-resolution composite images were used to count growth increments, and to select the most promising long-lived individuals in terms of regularity of growth increments and length of a continuous record for geochemical analysis.

2.3. Analysis

Mg/Ca ratios of coralline algae were measured with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) along line profiles. Data obtained with this method formed the basis for generating annual resolution age models. Mg/Ca ratios have previously been used as a paleotemperature proxy in coralline algae (e.g. Hetzinger et al., 2011; Kamenos et al., 2009; Williams et al., 2014). Each sample underwent a pre-ablation step to remove surface contaminants, and line transects were programmed to avoid unconformities and conceptacles. A New Wave NWR 213 laser ablation system coupled with an Agilent 8800 Quadrupole ICP-MS in the Earth Sciences department at Gothenburg University was used to measure ^{24}Mg, and ^{43}Ca. For these measurements laser energy was approximately 6 J/cm^2, helium and nitrogen were carrier gases. The laser spot used was a 50 μm^2 square and traveling speed of the sampling stage was set at 10 μm/s with a 10 Hz pulse rate. The internal standard was ^{43}Ca, using calcium concentrations measured by ICP-OES (Hetzinger et al., 2009). The external standard was NIST SRM 610 glass (US National Institute of Standard and Technology Standard Reference Material). Periodic measurements of NIST SRM 610 were taken to quantify instrumental drift. GLITTER 4.4.4 (Macquarie University, Sydney) was used for data reduction.

Two to three LA-ICP-MS transects were analysed on each sample along the direction of growth from young to old to generate an at least 18 year long time series (Greenland: 2012–1994, Newfoundland: 2008–1990). These years were established by assigning the year of live collection to the most recent band and counting back. Eighteen years was the longest common time span that could be analysed in all samples without a detectable unconformity (irregularity or interruption in