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Interpreting environmental signals from the coralline sponge *Astrosclera willeyana*

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Abstract

Coralline sponges (sclerosponges) have been proposed as a new source for paleo subsurface temperature reconstructions by utilizing methods developed for reef-building corals. However unlike corals, coralline sponges do not have density variations making age determination difficult. In this study we examined multiple elemental rations (B, Mg, Sr, Ba, U) in the coralline sponge *Astrosclera willeyana*. We also measured skeletal density profiles along the outer "living" edge of the sponges and this data indicates significant thickening of skeletal material over intervals of 2-3 mm or 2-3 years. This suggests that any skeletal recovered environmental record from *Astrosclera willeyana* is an integration of signals over a 2-3 year period. Sponge Sr/Ca seemed to hold the most promise as a recorder of water temperature and we compared Sr/Ca from 2 sponges in the Great Barrier Reef and one from Truk in Micronesia to their respective sea surface temperature record. The correlations were not that strong ($\sim r = -0.5$) but they were significant. It appears that the signal smoothing due to thickening or perhaps even some biologic control on Sr skeletal partitioning limits the use of Sr/Ca as an indicator of water temperature in *Astrosclera willeyana*.

Keywords: Sr/Ca ratios, paleoceanography, sclerosponge, *Astrosclera willeyana*, ocean temperature, calibration.

Introduction

In order to increase our understanding of the dynamic processes resulting in climate change, proxy records of environmental variables are needed. We currently use hermatypic reef-building corals to provide records of surface water temperature (δ^{18}O, Sr/Ca), salinity (δ^{18}O), runoff (Ba/Ca) and ocean circulation (Δ^{14}C) e.g. (Cole et al., 1993; Emiliani et al., 1978; Guilderson et al., 1998; McCulloch et al., 2003; McCulloch et al., 1994). This is accomplished by measuring isotopic and elemental ratios incorporated into the coral skeleton while it grows. To explore thermocline and deeper water variability, techniques historically applied to reef building corals are being applied to coralline sponges (Fallon et al., 2003a; Fallon et al., 1999a; Haase-Schramm et al., 2003; Lazareth et al., 2000; Rosenheim et al., 2004; Swart et al., 2002).

Coralline sponges are slow growing (0.15 to 1.2 mm yr^{-1}), long lived and their calcareous skeletons can provide proxy records of salinity and water temperature over the 100 to 1000 year time range. Their compressed record (slow growth) make them ideal for a high-resolution trace element analytical technique such as laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Coralline sponges are also found at depths ranging from 10-185 m, therefore providing unique information on the history of the upper water column. Their skeleton is extremely dense providing more resistance to diagenesis than corals. They can be used to augment and in some cases replace records

obtained from coral skeletons, and have the advantage that they are in isotopic equilibrium with the surrounding seawater for carbon and oxygen (Böhm et al., 1996; Druffel and Benavides, 1986). Here we evaluate the variations of trace elements (specifically Sr/Ca) in the coralline sponge *Astrosclera willeyana* as a potential proxy for sea surface temperature (SST).

The coralline demosponge *Astrosclera willeyana* has been observed to depths of 185m (Hartman, 1980). In shallower areas (~10m) they occupy reef caves and overhangs (Wörheide, 1998). Their shape is pyriform-half spherical (mushroom) and they are mostly bright orange in color. They are found widely distributed throughout the Indo-Pacific and are the most abundant coralline sponge in this area (Reitner et al., 1996). They have a in/exhalent water system that extends to the basal skeleton throughout the tissue layer. The living tissue can be several mm's thick encompassing 3 major zones: ectosome, choanosome and zone of epitaxial backfill (ZEB) (Wörheide, 1998). In the ectosome (100-300 μm thick) aragonite crystal formation begins, ultimately leading to the formation of aragonite spherulites (Wörheide, 1998). In the top section of the choanosome the spherulites fuse together to begin forming the basal skeleton but space is still available for tissue and bacteria (Wörheide, 1998). As the soft tissue slowly moves upward in the ZEB, the remaining vacant space is filled by epitaxially growing skeleton. This secondary infilling may make up 50% or more of the basal skeleton (Wörheide, 1998). It is crucial to understand the calcification process of coralline sponges, which imply that at any given position below the top of the basal skeleton the material constitutes a time average equivalent to the time/distance from the outer tissue surface to

the beginning of the basal skeleton (Böhm et al., 1996; Druffel and Benavides, 1986; Wörheide, 1998).

Methods

Instrumental

All coralline sponges were identified to be *Astrosclera willeyana* (Lister, 1900). The concentration of the elements (B, Mg, Ca, Sr, Ba, U) was determined by LA-ICP-MS. The sample processing and analytical methods are described in detail in Fallon et al. (1999b). In summary, the sponges are cut into 5-mm thick slices and a transect from the center of the sponge was sub-sampled into 20x45 mm rectangles to fit into the sample chamber. A slit was used to reduce the laser image to a 20x100 μm rectangle on the sample. This small size was originally chosen because the growth rate was thought to be on the order of 0.2 mm yr^{-1} (Wörheide, 1998). The laser was pulsed at 5Hz using a 50-mJ power setting (Fallon et al., 1999b). The data was collected in time-resolved mode with the samples being bracketed by 60-s scans on a pressed powder coral standard and 60-s of "instrumental" background (Fallon et al., 1999b). The isotopes (^{11}B, ^{25}Mg, ^{84}Sr, ^{138}Ba, ^{238}U) were background subtracted, ratioed to ^{43}Ca and then standardized to the coal pressed powder standard as per Fallon et al. (1999b). The overall analytical uncertainty of this LA-ICP-MS technique is 3.8% for B/Ca, 4.2% for Mg/Ca, 1.6% for Sr/Ca, 4.2% for Ba/Ca and 3.9% for U/Ca (Fallon et al., 2003b).

Locations

Coralline sponges have been analyzed from three locations from the Southwest Pacific. These sites are: Otta Island (Truk), Caroline Islands, and from Ribbon Reef #10 and Myrmidon Reef on the Great Barrier Reef (Figure 1).

Density Measurements

The density of the coralline sponges was measured on the gamma densitometer at the Australian Institute of Marine Science using the methods of Chalker *et al*. (1985) and Chalker and Barnes (1990). For the sponge analyses, the beam diameter was masked with a 1mm diameter (round) lead castle. This was the smallest size currently available. Multiple tracks were analyzed on each sample.

Results and Discussion

Skeletal Thickening

It was apparent by visual examination that away from the living edge of the sponge the density variations were very small (if any) and did not correspond to any environmental or annual patterns. The density scans on the sponge slabs showed an increase in density away from the outer "living" edge until approximately 5mm from that edge when the density approached that of solid aragonite (2.93 g cm^{-3}). The density tracks from the Ribbon Reef sponge are shown alongside a SEM image of the sponge (Figure 2). The outer ~ 2 mm has a similar density of ~1 g cm^{-3}. At approximately 3 mm from the outer edge the density increases until it reaches ~ 2.9 g cm^{-3} at 4-5 mm from the outer edge (Figure 2). All sponges analyzed in this study exhibited this pattern.

These density profiles suggest that thickening of aragonite occurs throughout the "living" tissue layer. This observation was confirmed by staining experiments in which

the ZEB near the base of the "living" layer was shown to be a site of high calcification (Wörheide, 1998; Wörheide et al., 1997). The calcification appears to occur in two main stages, the outer 2 mm grows and extends while building the framework. This is accompanied by thickening of the ZEB until near solid aragonite is formed at the base of the "living" tissue layer (Figure 2). Therefore the trace elements are being incorporated into the $CaCO_3$ skeleton over an extended period in essentially side-by-side locations. This results in a smoothing of environmental signals over the entire "living" tissue layer, 5 mm in this case. Potentially if the smoothing was equal over the entire 5 mm then a smoothing function of ~5 years would be occurring. More probable, it may be that ~ 1/3 of the skeletal material is deposited initially (t = 0) with the remaining 2/3 deposited over the bottom 2-3 mm "tissue" layer (Figure 2). Thus *Astrosclera* smoothes any incorporated signal preserved in its skeleton. If this smoothing function is consistent (year-by-year) then the recovered paleo-proxy record would be reliable, albeit smoothed. If the smoothing is not consistent then small-scale amplitude variations would not be robust throughout the lifetime of the sponge resulting in a misinterpretation of the included signals. A similar type of smoothing has been postulated for *Porites* corals (Barnes et al., 1995; Taylor et al., 1993; Taylor et al., 1995). In contrast to *Porites*, the coralline sponge *Astrosclera willeyana* clearly exhibits prolonged density thickening resulting in smoothing of the incorporated signals.

Trace elements in Astrosclera willeyana

The boron, magnesium and barium in *Astrosclera willeyana* are 2-5 times lower than average *Porites* corals with concentrations of 20, 200 and 4 ppm respectively. The

strontium and uranium concentration are 1-2.5 times higher than *Porites* corals with concentrations of ~9000 and ~10 ppm respectively. The trace element analyses (0.1 mm resolution) are shown for the Truk sponge in Figure 3. The elements are all correlated with the exception of U/Ca, which is mostly uncorrelated between the elements (Figure 3, Table 1). The other samples show similar relationships although not all elements are always correlated (Table 1). One significant difference between trace elements in corals and *Astrosclera willeyana* is that Mg/Ca is positively correlated to the other elements whereas in corals it is negatively correlated (Figure 3, Table 1). In corals, Mg/Ca has a postitive relationship to temperature, while the other elemental ratios (Sr/Ca, B/Ca and U/Ca) all have negative relationships to temperature e.g.(Beck et al., 1992; Fallon et al., 2003b; Mitsuguchi et al., 1996). This is due to the thermodynamic relationship between these elements and their substitution into the calcium carbonate skeleton. This type of positive relationship between Sr/Ca and Mg/Ca has been seen in records from the mussel *Pinna nobilis*, however this shell is calcite and not aragonite like *Astrosclera willeyana* and their relationship is not necessarily applicable to this sponge (Richardson et al., 2004).

Direct substitution or adsorption of elements into carbonate skeletons should remain in near equilibrium with the surrounding seawater to be useful as a proxy, as in the case of *Porites* corals that incorporate these elements in near equilibrium. In *Porites* corals the distribution coefficient for Sr/Ca:Seawater is ~1.05, whereas the GBR *Astrosclera* has a coefficient of 1.26. Otherwise, the incorporation mechanism needs to be consistent to provide steady elemental incorporation or it is of little use to the development of proxy records. In the case of *Astrosclera*, the elemental concentrations

suggest that there may be some type of biological control on the partitioning of these trace elements into the sponge skeleton. If that is the case then using them as proxy recorders of climate will be difficult.

Astrosclera Dating

One of the difficulties with using coralline sponges is translating distance to time. In corals, annual growth bands and trace element cycles permit the generation of time series data relatively easily. Coralline sponges do not exhibit annual growth bands nor do they have very clear annual cycles. One way to overcome this problem is by isotopic dating. Various dating methods ^{14}C, ^{210}Pb or U-series make it possible to obtain an age for the oldest parts and subsets of the sponge. This enables the determination of an average growth rate. Using these methods and direct staining of skeleton provides average growth rates that range from 0.1 –0.3 mm yr^{-1} (Benavides and Druffel, 1986; Dunstan and Sacco, 1982; Willenz and Pomponi, 1996; Wörheide, 1998). Direct staining and ^{14}C from another sponge collected at Ribbon Reef #10 suggested a growth rate of 0.23 mm yr^{-1} (Wörheide, 1998). However, recent results suggest that the growth rate of Astrosclera is closer to 1mm yr^{-1} (Fallon and Guilderson, submitted). Using multiple measurements of ^{14}C from each sponge in this study compared to independently dated coral ^{14}C "bomb" curve records they determined the average growth rate of the Ribbon Reef sponge to be 1.0 ± 0.3 mm yr^{-1}. The Myrmidon Reef sponge has an average growth rate of 1.2 ± 0.3 mm yr^{-1} and the Truk sponge has an average growth rate of 1.2 ± 0.1 mm yr^{-1} (Fallon and Guilderson, submitted). But more importantly the growth rate can vary by a factor of two suggesting that single linear extension growth rates are not valid

(Fallon and Guilderson, submitted). Using the time series developed by the "bomb" radiocarbon method we can examine the variations of Sr/Ca related to seawater temperatures at these locations.

Sr/Ca in Astrosclera as an Environmental Proxy

Many reef building corals show strong relationships between Sr/Ca and temperature e.g.(Beck et al., 1992; McCulloch et al., 1994; Shen et al., 1996). We are using this premise to examine the *Astrosclera* sponge Sr/Ca variations and relationship to water temperature. Unfortunately due to the fact that secondary skeletal thickening smoothes the recoverable record of Sr/Ca (SST) this is a difficult task. To finalize our sponge time series and to compare the sponge Sr/Ca to water temperature we used the radiocarbon time series as a starting point. This time series was then resampled to a monthly resolved time series and smoothed with a 5 point least square filter to remove high frequency variations (Paillard et al., 1996). We then smoothed the monthly sea surface temperature record with a 17-point filter to dampen the seasonal cycle and account for the sponge skeletal thickening (1-2 years). Similar to coral proxy studies, we then matched each of the seasonal maximum Sr/Ca to the winter SST minimum and then "fine-tuned" the time series with ~5-7 summer SST points. This provides a reasonable fit between the sponge Sr/Ca and SST records. This type of peak matching accounts for variations in annual growth rate even better than the multipoint radiocarbon "bomb" method.

The Sr/Ca and SST comparisons for all three sites are shown in Figure 4. Visual examination suggests that during some years the relationship between Sr/Ca and SST is

robust while other years summers or winters are missing (Figure 4). Nonetheless we can attempt to calibrate the Sr/Ca proxy in *Astrosclera* sponges. Figure 5 shows the sponge Sr/Ca vs. SST from the three locations. The correlation coefficients are –0.46, -0.49 and –0.54 for the Truk, Ribbon Reef and Myrmidon Reef sponge respectively (Figure 5). These relationships are not very strong but they are significant (P<0.0001). The calibration equations are shown in Table 2. These calibrations all lie above the inorganic aragonite Sr/Ca-SST line of Kinsman and Holland (1969) and significantly above that of the reef building coral *Porites* (labeled GBR coral). These three sponges also have a higher Sr/Ca ratio than the *Ceratoporella* sponges reported by Rosenheim et al. (2004). The Sr/Ca-SST slopes between the two GBR sponges are similar with the Ribbon sample being slightly shallower at $-1.2e^{-4}$ mol/mol/°C vs. $-1.7e^{-4}$ mol/mol/°C for the Myrmidon sponge (Figure 5, Table 2). The Truk sponge however has a significantly steeper slope of $4.7e^{-4}$ mol/mol/°C (Figure 5, Table 2). The slope of the temperature calibrations are very sensitive to the amplitude of the SST and at this site the seasonal SST amplitude is only ~2°C compared to the 5°C seasonal amplitude of the GBR sponges. The only other relationships for Sr/Ca-SST in coralline sponges suggest a slope of $-0.11e^{-4}$ mol/mol/°C from a *Ceratoporella* sponge in the Caribbean (Haase-Schramm et al., 2003; Rosenheim et al., 2004). The two GBR sponge temperature equations have similar slopes to the *Ceratoporella* sponge but the Truk sample is significantly different.

The variability of the Sr/Ca-SST relationship and the many seasonal misfits between Sr/Ca and SST (Figure 4) suggest that either thickening of skeletal material is highly variable, a distinct possibility especially after looking at the SEM image (Figure 2) or the sponge can exert significant control over Sr partitioning into the $CaCO_3$ skeleton.

This data suggests that there is a temperature component to the *Astrosclera* Sr/Ca signal, although it is not the dominant component of the signal (SST explains only 20-25% of the Sr/Ca variance, Table 2). At this point we are unable to discern between these two influences suggesting that *Astrosclera willeyana* is not necessarily going to provide high quality water temperature reconstructions from Sr/Ca like those shown by *Ceratoporella* sponges (Haase-Schramm et al., 2003; Rosenheim et al., 2004).

Summary

Multiple elements B, Mg, Sr, Ba, U were measured in the coralline sponge *Astrosclera willeyana* from three locations around the Southwest Pacific. The concentration of these elements vary from those of reef building corals suggesting that the sponge may have some control on the incorporation of these elements into the skeleton. The positive relationship between Mg/Ca and Sr/Ca, not seen in reef building corals, may also be indicative of a biologic control on elemental incorporation. Density measurements near the outer surface of the sponges indicate that thickening and addition of $CaCO_3$ occurs over distances of 2-3mm. The initial $CaCO_3$ deposition appears to not be thickened until approximately 2-3 mm from the outside "living" edge. This suggests that the sponges are smoothing the included trace element signal, maybe as much as 2-3 years. Overall, *Astrosclera willeyana* coralline sponges appear to show some promise that they will be useful for providing water temperature. However problems such as dating, constant growth rates, signal smoothing (is it constant?) and whether the sponge has a direct influence over Sr/Ca partitioning need to be addressed. At this point it appears that the Sr/Ca record in *Astrosclera willeyana* is not robust enough to use as a proxy for water temperature.

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Table 1A. Correlation Coefficients (0.1 mm resolution) Otta Island p < 0.001.

	B/Ca	Mg/Ca	Sr/Ca	Ba/Ca
B/Ca				
Mg/Ca	0.44			
Sr/Ca	0.60	0.65		
Ba/Ca	0.40	0.71	0.68	
U/Ca	N.A.	0.21	N.A.	0.31

Correlation Coefficients (0.1 mm resolution) Myrmidon Reef p < 0.001.

B	B/Ca	Mg/Ca	Sr/Ca	Ba/Ca
B/Ca				
Mg/Ca	N.A.			
Sr/Ca	0.26	N.A.		
Ba/Ca	N.A.	N.A.	0.58	
U/Ca	N.A.	N.A.	N.A.	0.14

Correlation Coefficients (0.1 mm resolution) Ribbon Reef p < 0.001.

	B/Ca	Mg/Ca	Sr/Ca	Ba/Ca
B/Ca				
Mg/Ca	0.72			
Sr/Ca	N.A.	N.A.		
Ba/Ca	0.2	N.A.	0.5	
U/Ca	0.17	0.5	0.15	0.37

Table 2. Sr/Ca Calibrations

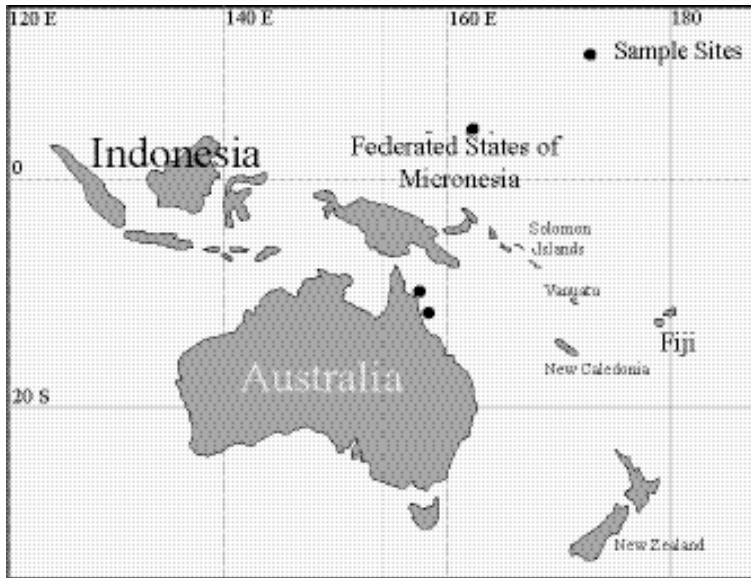| Location	Sr/Ca = a-b*SST
Truk	Sr/Ca = $2.44e^{-2}(\pm2.1e^{-3})$ – $4.7e^{-4}(\pm7.3e^{-5})$*SST r = -0.46
Ribbon Reef	Sr/Ca = $1.42e^{-2}(\pm2.7e^{-3})$ – $1.2e^{-4}(\pm1.1e^{-5})$*SST r = -0.49
Truk	Sr/Ca = $1.49e^{-2}(\pm3.1e^{-3})$ – $1.7e^{-4}(\pm1.2e^{-5})$*SST r = -0.54
Rosenheim et al., 2004	Sr/Ca = $12.75e^{-2}(\pm2.19e^{-3})$ – $1.11e^{-4}(\pm5e^{-5})$*SST

Figure 1. Map showing the 4 *Astrosclera willeyana* sample locations, Ribbon Reef and

Myrmidon Reef from the Great Barrier Reef and Truk from the Caroline Islands in the
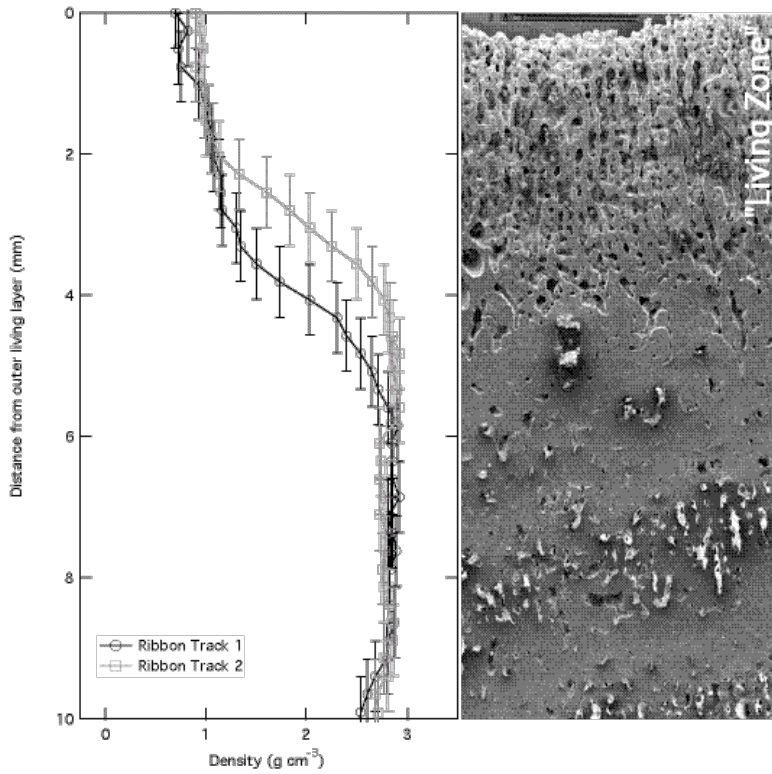
Federated States of Micronesia.

Figure 2. Density of Ribbon Reef *Astrosclera willeyana* sponge measured by the densitometer at the Australian Institute of Marine Sciences (Chalker and Barnes, 1990). Also shown is a SEM image of the Ribbon Reef sponge, note lower density skeleton in living tissue zone.
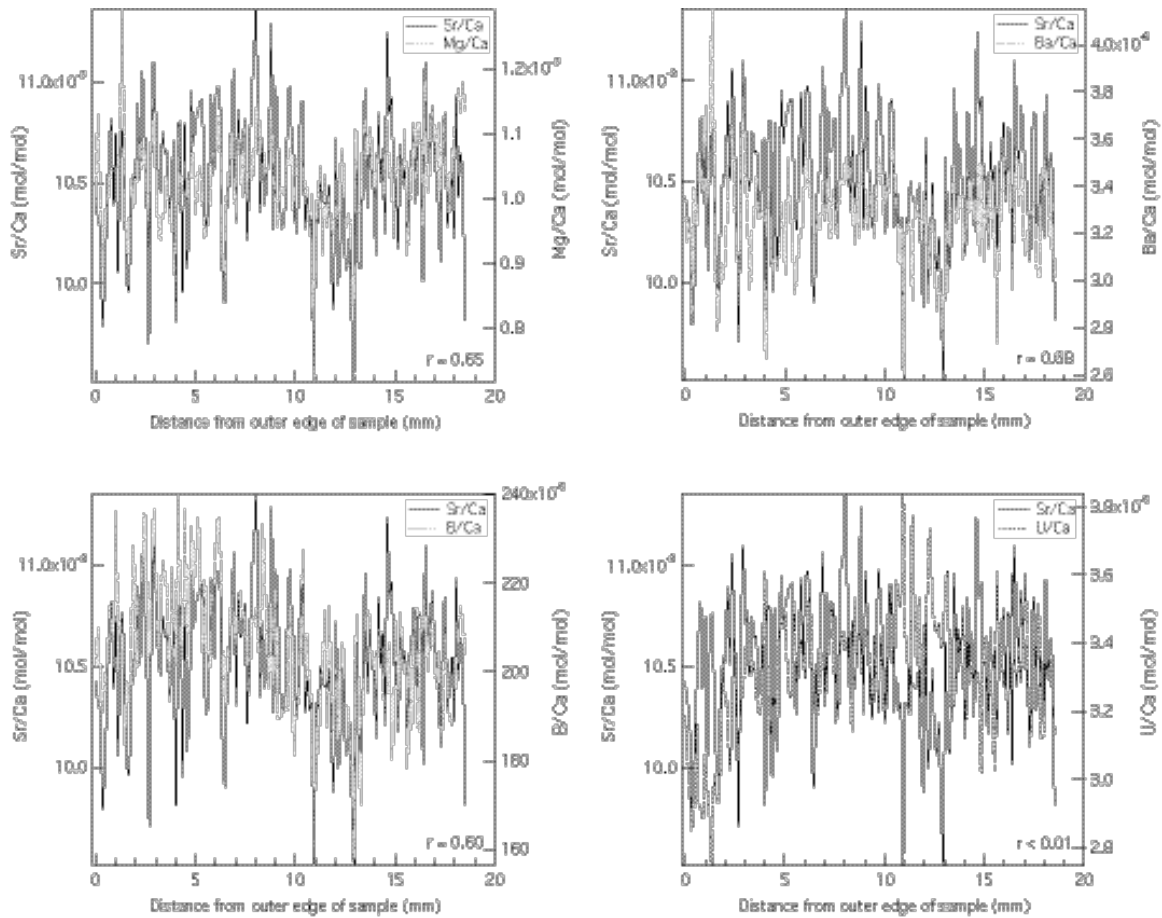
Figure 3. A) Sr/Ca and Mg/Ca vs. distance from the outer edge of the Truk sponge

sample, correlation coefficient shown in bottom corner. B) Sr/Ca and Ba/Ca vs. distance

from the outer edge of the Truk sponge sample, correlation coefficient shown in bottom

corner. C) Sr/Ca and B/Ca vs. distance from the outer edge of the Truk sponge sample,

correlation coefficient shown in bottom corner. D) Sr/Ca and U/Ca vs. distance from the

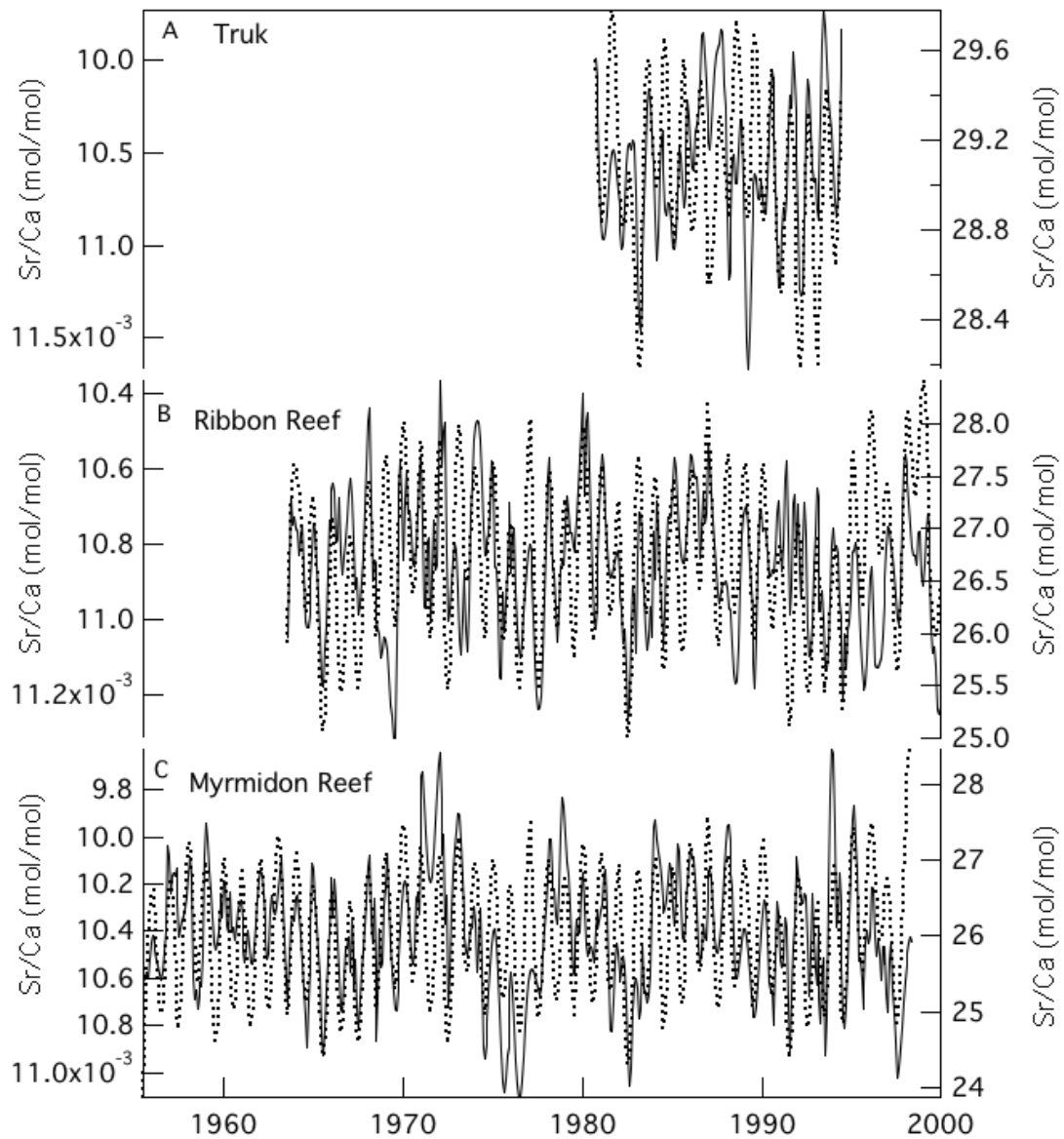outer edge of the Truk sponge sample, correlation coefficient shown in bottom corner.

Figure 4. A) Truk sponge Sr/Ca and SST vs. time using the marker point method, sponge

Sr/Ca captures the cooling associated with the 1982/83 El Niño. B) Ribbon Reef Sr/Ca

and SST vs. time using the marker point method. C) Myrmidon Reef sponge Sr/Ca and

SST vs. time using the marker point method, both GBR sponges also capture the 1982/83
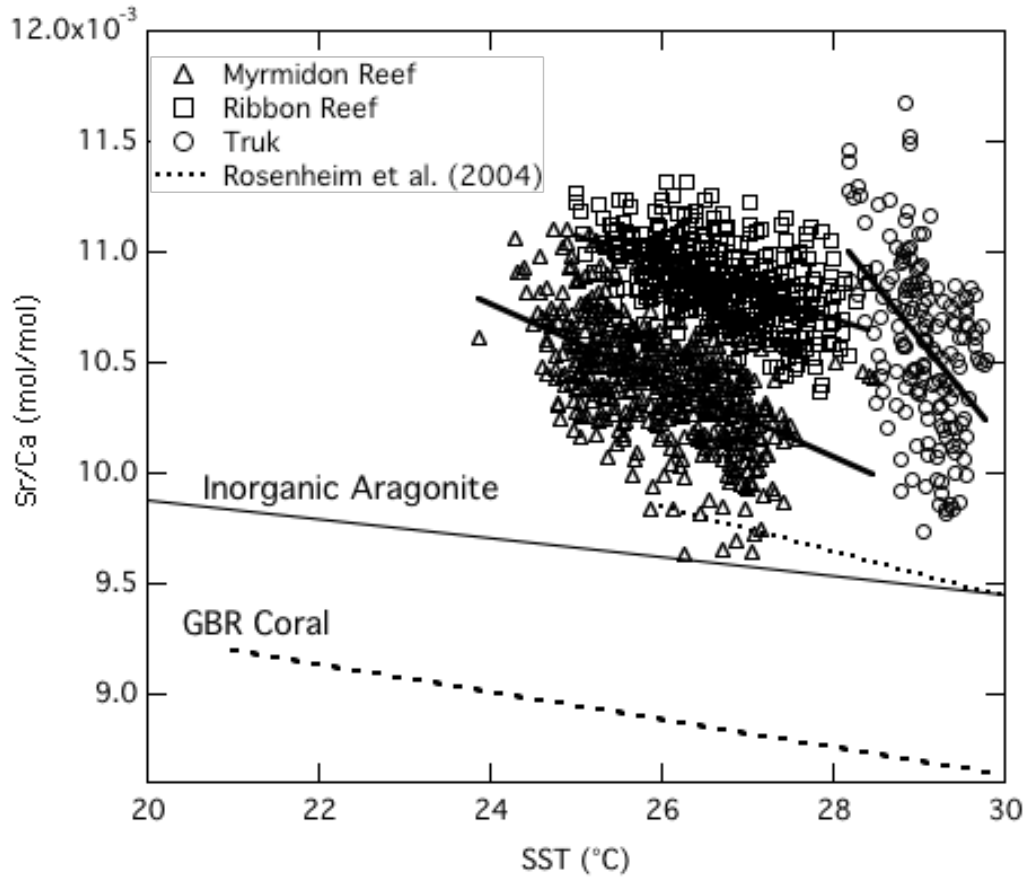
El Niño cooling.

Figure 5. *Astrosclera willeyana* sponge Sr/Ca vs. SST calibrations, also shown are

inorganic aragonite calibration (Kinsman and Holland, 1969), calibration of *Porites* coral

(Fallon et al., 2003b), and the coralline sponge *Ceratoporella nicholsoni* (Rosenheim et

al., 2004).