

Metals and metalloids in corals from the Western Indian Ocean

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Abstract

Coral reefs are one of the most species diverse biomes on earth. One of the many dangers that coral reefs face because of anthropogenic activities is the accumulation of metals and metalloids in skeleton and tissues of the colonies. No knowledge exists on the state of metal and metalloid contamination in corals from the Western Indian Ocean (WIO). Fragments of four soft- and five hard coral genera were collected from five sites in the WIO. Sodwana and Aliwal Shoal constituted the coastal sampling localities from South Africa. Three Mauritian outer-islands in the Mascarene basin– Agalega, Rodrigues, and St Brandon’s Atoll– were the selected oceanic sampling sites. A total of 81 coral fragments were collected and analysed for 31 metallic elements using ICP-MS analysis. The corals collected from South Africa contained a higher concentration of most of the metals that were analysed compared with the Mascarene Island samples. Corals without symbiotic algae could only be collected from the South African reefs, and contained the highest concentration of metalloids. Soft corals exhibited a different accumulation pattern of metals than hard corals. Alkaline earth metals, Fe, and U predominated in the hard corals. Soft corals contained a higher concentration of most of the post-transitional metals that were analysed. *Sinularia* is the coral with the most elements of the highest concentration. *Pocillopora* from SBR had very high concentrations of Fe and Cr present, possibly due to several shallow shipwrecks in the atoll. Most of the elements tested had lower concentrations in the WIO than in certain regions of the Great Barrier Reef and the Red Sea. Iron was consistently higher in all corals collected during this study than in corals from other studies. Some metals, such as Cu, Ni, and Cd inhibit fertilization success of corals. The reported decline of *Sinularia* cover in Sodwana during the last decade may be attributable to very high concentrations of Ni found. As ocean temperature rises and ocean acidification increases, metals can become more bioavailable to corals. Conservation efforts and legislation need to address these factors in order to effectively promote the conservation of coral reefs.

Keywords

Coral reef; Ecotoxicology; Hard corals; Metallic elements; Mineralogy; Soft corals

Chapter 1: Introduction

1.1 General Introduction

The oceans are the most prominent feature of planet Earth. They cover more than 70% of the Earth's surface at $361 \times 10^6 \text{ km}^2$ (Weast, 1980). They connect and surround the continents and are home to billions of creatures. The world-renowned oceanographer and National Geographic Explorer in Residence, Sylvia Earle, summarised humanity's dependency on the ocean "No blue, no green." (Mission Blue, 2013).

The health of the ocean is under threat from anthropogenic activities including, but not limited to overfishing, plastic pollution, acidification, sea level rise, and ocean temperature increase caused by human-induced global warming (Gray, 1997; Barnett *et al.*, 2005; Bouwman *et al.*, 2016). This situation is further intensified by industrial processes that result in the anthropogenic release of metals and metalloids into, amongst others, the marine environment. Exposure and uptake of these substances by organisms may lead to acute toxicity (when the organism has a high concentration of the contaminant in its system) or long-term, chronic toxicity (Li *et al.*, 2016). It may also result in biomagnification— an increase in concentration of a contaminant from one trophic level to the next (Newman, 2010). Consumption of fish with high levels of metals is known to affect adversely human health (Castro-González & Méndez-Armenta, 2008).

Chemical analysis is part of the field of toxicology. From this, the field of ecotoxicology developed— combining chemical analyses and toxicology with ecology to gain a more holistic view of contamination in the environment (Chapman, 2002). A brief overview of ecotoxicological terminology is needed. The term "bioaccumulation" is often used carelessly, disregarding of context. Bioaccumulation is the sum of biomagnification and bioconcentration of contaminants in an organism. The term "biomagnification" pertains to contaminants that have increased in concentration through the food web, from one organism to the next as predation occurs. Contaminants that enter an organism through water are referred to as "bioconcentrated". (Newman, 2010). The uptake of metallic elements by corals present a conundrum to the common

understanding of bioaccumulation. In this study, contaminants taken up by corals will be referred to as “accumulated”, for simplicity sake. A more detailed discussion of bioaccumulation pertaining to corals will be addressed in Section 4.3, based on the results of this study.

Investigating metals in marine animal tissue is not a novel science. Metals have been reported the presence of vanadium in the blood of sea cucumbers, and cobalt and nickel in mussels and lobsters as early as 1951 (Carson, 1964). One of the earliest studies conducted on metals in corals was conducted in 1964 (Harriss & Almy Jr., 1964). Several other studies have identified metals in the tissue of high-trophic marine animals such as sharks, dolphins, seals, and sport fish (Wagemann & Muir, 1984; Marcovecchio *et al.*, 1991; Dural *et al.*, 2007; Mull *et al.*, 2012). The presence of contaminants in tissue of these species begs the question: Where do these contaminants come from? They can certainly not spontaneously appear in high trophic level organisms. Therefore, it is important to research contamination levels in organisms in the lower trophic levels of the marine food web. If contaminants are detected low in the food web, they can be expected to biomagnify through trophic transfer to organisms higher in the food web (Chang & Reinfelder, 2000).

The need to study the accumulation of metals and metalloids in corals from the Western Indian Ocean (WIO; generally understood to stretch southwards from Somalia to the Southern Ocean) stems from a knowledge *lacunae* on this topic. There have been several reports on metals in corals from other locations (e.g. Harriss & Almy Jr, 1964; Fallon *et al.*, 2002; David, 2003; Mohammed & Dar, 2009; Sabdono, 2009; Chen *et al.*, 2010; Berry *et al.*, 2013), but none from the WIO.

The coral reef biome boasts the greatest and most concentrated biodiversity on earth. Even though it covers only 1% of the seafloor, A quarter of all marine species can be found in this biome (Coral Reef Alliance, 2017). Beyond its ecological value, coral reefs are the livelihood and primary food source of millions of people from over 100 countries (White *et al.*, 2000). It is therefore paramount to conserve these ecosystems (UNEP, 2016).

Corals were chosen as a study taxon because of four key features:

- Their relatively low-trophic level in the marine food web. However, this is a generalised statement, which will be expanded on later.
- Corals have measurable concentrations of metals in tissues and skeleton (e.g. Richmond, 1993; Mitchelmore *et al.*, 2007). A company in Korea even use coral skeletons as a cost effective method to remove metals from aqueous solutions (Ahmad *et al.*, 2010). Corals may accumulate metals into their skeleton through substituting calcium with metals in the crystal lattice of their skeleton (Ferrier-Pagès *et al.*, 2005), via trapped matter within skeletal cavities, feeding, and or uptake of organic matter from coral tissue (Ali *et al.*, 2011; Corrège, 2006).
- Because corals are sessile benthic suspension feeders (Gili & Coma, 1998), they will only accumulate contaminants that are present in the area where they are situated— as opposed to fish that might encounter pollution at one site but migrate to another.
- Corals also have the ability to recover from physical damage (Chadwick & Loya, 1990). (Because of this, the colonies from which samples were collected for this study will not be permanently affected.)

Chapter One is aimed at contextualizing the study by providing an overview on the biology of corals and the ecology of coral reefs. The Indian Ocean will be discussed, with particular emphasis on the Western Indian Ocean. The definition of metals and metalloids that will be used throughout the study will also be presented in Chapter One. Lastly, the hypotheses of the study will be presented. Chapter Two provides an exposition of the materials and methods, and provides information regarding the chosen study sites, target corals, field collection, laboratory analysis, and statistical analysis. Results obtained will be presented in Chapter Three and their implications discussed in Chapter Four. Chapter Five is dedicated to summarising the conclusions and Chapter Six is devoted to presenting recommendations to streamline similar studies in the future.

1.2 Coral biology

This section is intended to provide a brief overview of corals. The phylum Cnidaria will be discussed to provide context as to where corals fit into the Domain Eukarya. The morphology of corals will be explored to provide a framework within which to assess metallic elements. Some of the aspects of their morphology tend to lean into the field of geology and it is discussed below that interesting perspectives can be acquired by also looking at these organisms from a geological perspective. The vital relationship between corals and the symbiotic algae that live within the living cells of coral polyps will also be discussed.

1.2.1 Cnidarians

Corals (along with other cnidarians) hold a special place on the evolutionary phylogeny as being the most basic (and possibly first) eumetazoa— true animals (Kardong, 2008), after sponges (Figure 1). The first Scleractinian corals appeared in the fossil record during the Middle Triassic (Stanley Jr., 2003; Park *et al.*, 2012). These organisms are relatively easy to follow through the fossil record due to their robust skeletons (Romano & Palumbi, 1996). Through molecular studies, the divergence between hard and soft corals has been determined to the Mesozoic Period (Park *et al.*, 2012).

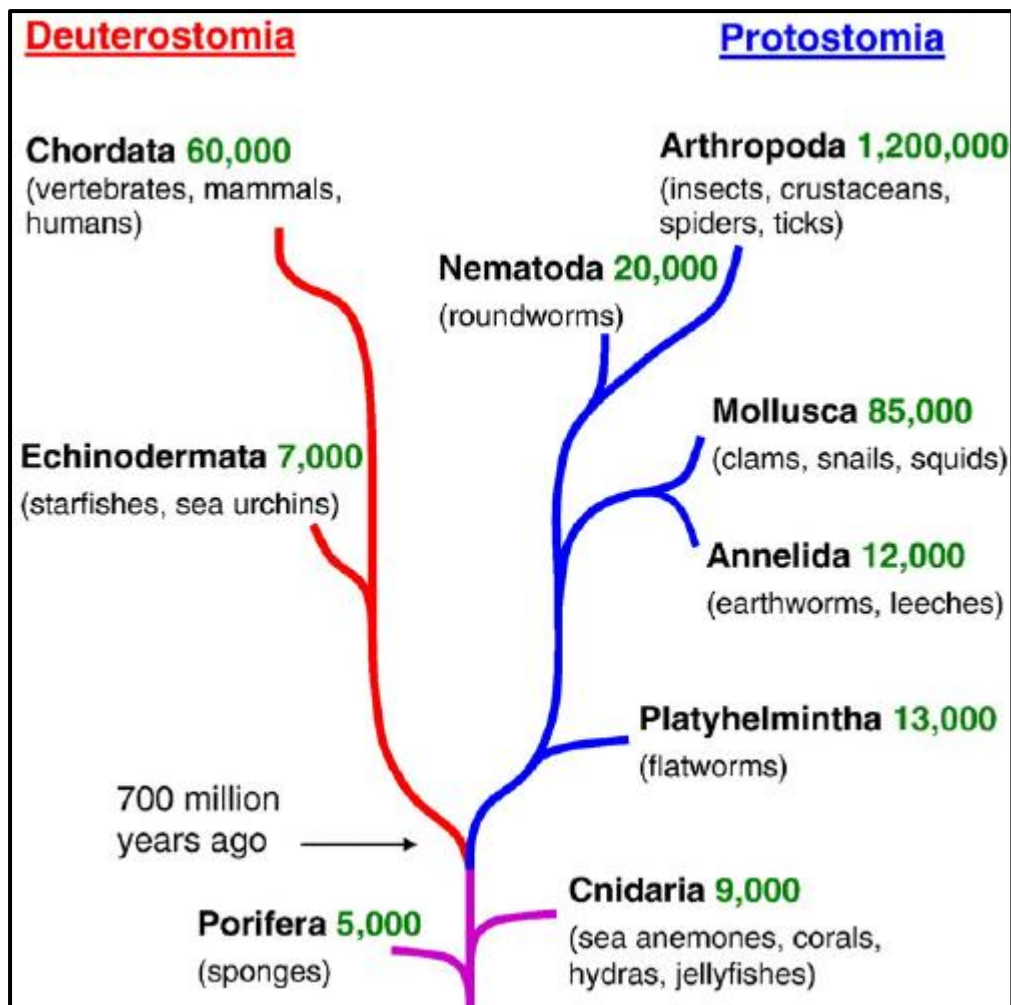


Figure 1. A simplified phylogeny of animal evolution (Grimmelikhuijzen & Hauser, 2012).

There are four classes in the phylum Cnidaria:

- Hydrozoa (Portuguese man-o'-war, fire corals)
- Scyphozoa (Jellyfish)
- Cubozoa (Box jellies)
- Anthozoa (Corals and anemones).

My study will focus on the class Anthozoa. There are two subclasses under Anthozoa—Octacorallia and Hexacorallia. Octacorallia has eight-fold symmetry, and contains the order Alcyonaria— the leather and soft corals, as well as the pipe organ corals. Hexacorallia has six-fold symmetry. The order Scleractinia— hard corals resorts under this subclass (Erhard & Knop, 2005).

1.2.2 Coral morphology

Coral colonies are composed of thousands of individual polyps (Sheppard *et al.*, 2009; Sorokin, 1995). Each polyp is little more than a stomach topped with a mouth (Erhardt & Knop, 2005; KSLOF, 2017a). Polyps in a colony are asexual replicates of one original polyp. In essence, all the polyps in a colony are clones of each other and consequently they are genetically identical (Gritzner, 2009). The skeleton of an individual polyp is called a corallite, with a basal plate in the centre. Septa radiate inward from the edges of the corallite to the centre; this is a useful feature to identify coral taxa. The outer edge of a polyp is defined by a wall-like edge enclosing the septa (KSLOF, 2017a).

Each polyp is connected to the adjacent polyps through the coenosarc—the tissue that connects colonial polyps. Food can be distributed throughout the entire colony through this organ (KSLOF, 2017a).

Polyps capture plankton and other micro-organisms with their tentacles containing nematocysts, similar to jellyfish. Food items extracted from the gut of a stony coral by Porter in 1974 (cited by Sorokin, 1995) included a wide range of zooplankton species, nematodes, small jellyfish, and fish faeces. Porter noted that plant material was rejected by the polyp (Sorokin, 1995).

Cnidarians do not possess a digestive tract. Instead, the stomach is directly attached to the opening that serves as both the mouth and anus (Levine & Miller, 1994).

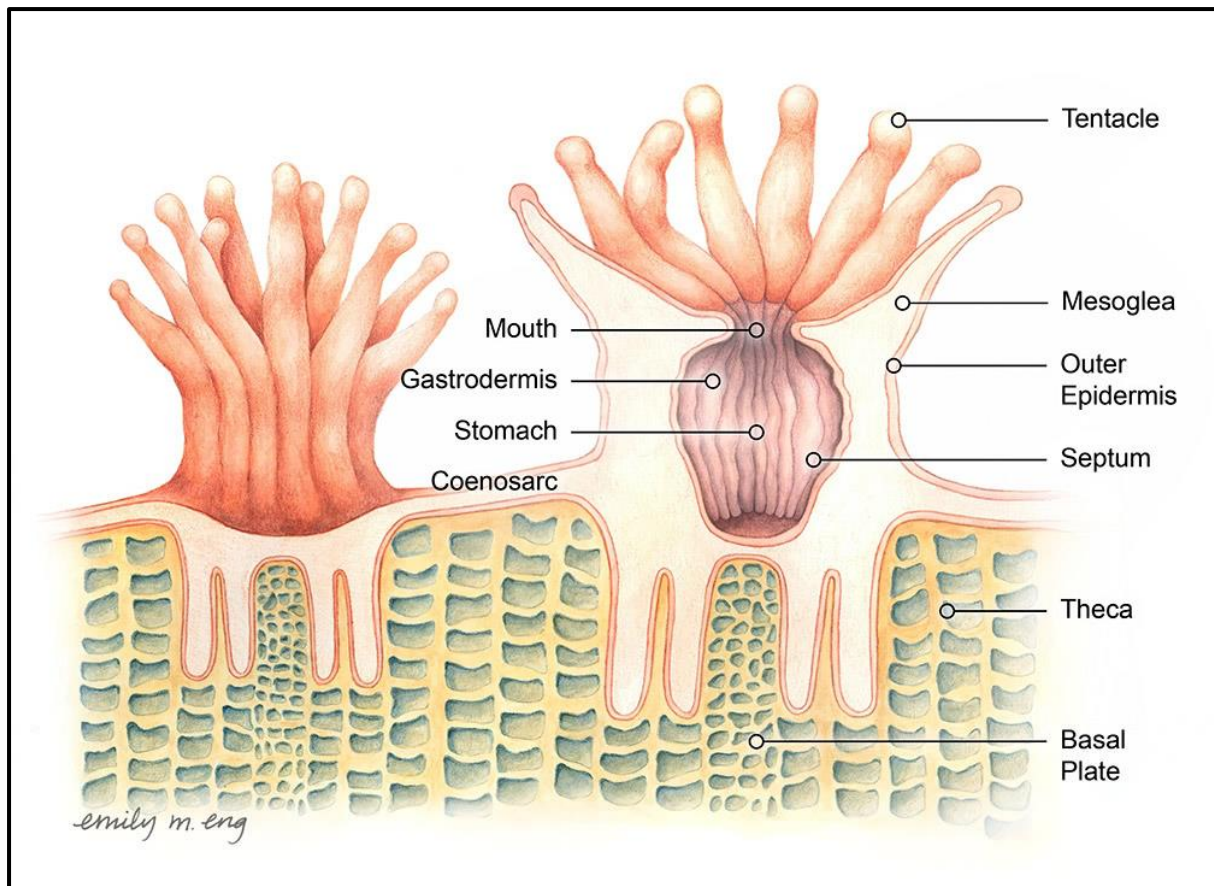


Figure 2. Cross section of a scleractinian coral polyp (Coral Reef Alliance, 2017)

Scleractinian colonies (hard corals) are mainly composed of aragonite (CaCO_3). Soft coral colonies do not have a hard skeleton, but maintain their shape by hydrostatic pressure in mesentery chambers. Mesentery chambers are muscles that extend from partitioning chambers that stretch from the body wall to the foot of the base of the coral. In addition to hydraulic pressure of water in the partitioning chambers, the muscle fibres of the mesenteries can contract to straighten the polyp (Erhard & Knop, 2005). This is an important feature because soft corals can occur at great depth, and the external water pressure is then greater than the internal hydraulic pressure of the polyp. The spicules of soft corals, called sclerites, are calcite (CaCO_3) (Rahman & Oomori, 2008). It is interesting to note that aragonite has the same chemical composition as calcite, but with a different crystallographic build. This subtle difference has to do with the number of oxygen atoms bound to the calcium (Klein & Dutrow, 2007). CaCO_3 is a structural derivative (analogue) of NaCl . Because they share the same basic structure, elemental exchange can take place. In this case, Cl is replaced by the triangular CO_3 compound. Na is replaced by Ca. It is important to note that the

term “derivative” is here used in a crystallographic, or mathematic context. It pertains to the shape of the compound, not the origin thereof. In specific circumstances, Ca can be exchanged by other elements to form other carbonate minerals. These carbonate minerals often have a metal ion in the place of calcium (Klein & Dutrow, 2007). The calcite group of minerals can include magnesite (MgCO_3), siderite (FeCO_3), rhodochrosite (MnCO_3) and smithsonite (ZnCO_3). The aragonite group contain the minerals witherite (BaCO_3), strontianite (SrCO_3) and cerussite (PbCO_3) (Klein & Dutrow, 2007). The association of certain minerals to different mineralographic groups will be relevant for the discussion in Section 4.2.

1.2.3 Symbiosis of corals with zooxanthellae

An interesting part of coral biology is the mutualism with the dinoflagellate algal genus, *Symbodium*. The algae that live as intercellular symbionts in the endodermal cells of the corals are known as zooxanthellae (Swart, 2013). It is proposed that this symbiosis began when some of these algae cells avoided being digested by corals. Because they proved beneficial to the coral’s growth and additional nutrition, the corals did not digest or expel the cells (Erhard & Knop, 2005). This process was promoted through natural selection. The corals and zooxanthellae exchange metabolites to conserve nutrients. In addition, the algae provide oxygen and photosynthates to the coral that the algae produce during photosynthesis. The zooxanthellae are also responsible for initial photosynthetic carbon fixation and assists in the calcification of colonies (Baker *et al.*, 2008; Richmond, 1993). The additional nutrients received from zooxanthellae enable coral colonies to thrive in nutrient poor environments (Swart, 2013). Soft corals contain less zooxanthellae in their tissue than hard corals. They rely more heavily on suspension feeding and direct nutrient uptake from seawater (Sheppard, 2009).

It has been noted by Douglas (2003) that the symbiosis between coral and *Symbodium* is sub-optimal. The algal cells are not physically integral to the polyp and can be expelled (called bleaching). If expelled however, it is to the disadvantage of the coral colony. Corals and their symbiotic algae generally thrive in temperatures 2°C cooler than temperatures that can trigger a breakdown of the symbiosis— certain genera, such

as *Cyphastrea*, *Turbinaria* and *Galaxea* are more resilient to bleaching than most genera. However, the genera discussed in this dissertation have a relatively narrow temperature range in which they survive (Marshall & Baird, 2000). This is in contrast with other symbiotic relationships that are normally rather tolerant of abiotic factors (Douglas, 2003). The breakdown of the symbiosis typically results in coral bleaching. This process will be discussed in Section 1.3.4.

1.3 Coral reef ecosystem

The term “ecosystem” can be described as the interaction of the biotic and abiotic components in an environment (Levine & Miller, 1994). Coral reefs are strongly affected by abiotic factors such as ocean temperature, water pH, nutrient concentration, and sedimentation (Leal *et al.*, 2016). In the next section, the interactions between the biotic and abiotic components of coral reefs and how the reef is formed will be discussed. Humanity’s dependency on coral reefs will be discussed, and a synopsis of the damage that anthropogenic activity have on coral reefs will be provided.

1.3.1 The importance of coral reefs

Coral reefs play a vital role in the ecology as well as the economy of various developing countries (Brander *et al.*, 2007; White *et al.*, 2000). More than 100 countries have reefs off their coastline. Fish caught from coral reefs contribute approximately 10% of fish consumed by humans, providing sufficient protein to 300 people per 1 km² of reef, per annum (Moberg & Folke, 1999). Reefs are also a magnet for ecotourism activities, particularly SCUBA diving and snorkelling (Hawkins & Roberts, 1993; Abidin & Mohamed, 2014). Tourists visit coral reefs for their aesthetic value and the abundance of animals. The net value of these activities combined with associated activities, such as catering and accommodation may result in tourists spending more than US\$ 100 per day (Brander *et al.*, 2007). This supports the livelihood of thousands of people (White *et al.*, 2000).

Ecologically, coral reefs have been described as the rainforest of the ocean (Erhardt & Knop, 2005) — a comparatively miniscule biome with the largest biodiversity. Knowlton (2001) even remarked that rainforests should be known as the coral reefs of the land. Whilst coral reefs cover less than one percent of the sea floor, they are home to more than 25% of all known marine species (Coral Reef Alliance, 2014; Ko *et al.*, 2014). Of the 34 known animal phyla, 32 are found on coral reefs.

Beyond their direct ecological value, coral reefs play a pivotal role in island creation. Broken coral fragments erode even further to become bioclastic sand and eventually form islands or components of islands. Coral reefs also serve as buffers against wave action that prevents coastal erosion, particularly during tropical cyclones or heavy storms (Richmond, 1993).

1.3.2 Coral reef formation

Reef building corals are known as hermatypic (Erhardt & Knopf, 2005). The limestone (CaCO_3) that constitutes the skeleton of hard corals forms the foundation of all reef systems. Within their endoderm, corals possess calciblastic cells. One school of thought poses that calcification takes place in the space underneath the calciblastic cells through physiochemical processes similar to the growth of abiotic aragonite. The other school of thought states that calcification is mediated through an organic matrix excreted by coral (Roberts *et al.*, 2009). Suffice to say, the process of coral calcification is not yet fully understood. Corals diffuse the Ca ions through their oral layers. The ions are transported to the site of calcification through active membrane transport (Gattuso *et al.*, 1999). The polyp then lifts its organic tissue from the base of the skeleton to deposit the calcite as a new layer through the basal plate, before lowering itself back into position. As each polyp in the colony does this, the colony grows in size (KSLOF, 2017b). As the colony grows, it can enter in competition for space with adjacent colonies (Rees *et al.*, 2005).

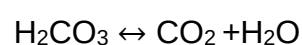
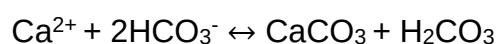
Reef growth is a factor of coral growth minus erosion. A differentiation can be made between biological and physical erosion. Biological erosion occurs because of biological activity, such as burrowing annelids, polychaetes, sponges and other organisms burrowing into either live coral or coralline bedrock (Moberg & Folke, 1999).

Another important bio-eroder is the parrotfish (*Scarus*). These fish scrape algae from coral reef substrate with their parrot-like tooth plates (Branch *et al.*, 2016). The fish will take a bite of a coral colony, but only metabolise the algae within. The calcium skeleton is excreted in the form of very fine bioclastic sand. A shoal of parrotfish can produce tons of sand per year (NOAA, 2010).

Physical erosion is the breakage of coral colonies and reef structure. Natural causes of physical erosion include extreme erosion events such as storms and tsunamis. Wave action and strong current consistently erode the reef at a gentler pace. Dredging of channels, dynamite fishing, and boat anchoring are anthropogenic causes of physical erosion. Fishing gear, such as nets or sinkers being dragged over the reef also causes coral breakages and reef erosion (Sheppard *et al.*, 2009). SCUBA divers are often a source of physical damage. The damage caused by divers is often considered minor in relation to damage caused by highly destructive events such as dredging and dynamite fishing. In the context of a smaller geographical range, such as a particular diving location such as Sodwana, the damage by divers to a reef can be substantial. [Interestingly, it has been found that male divers tend to cause more damage to the reef than women do (Worachananant *et al.*, 2008).]

Whilst corals are the organisms that contribute the most to reef formation, they are not solely responsible for reef growth. Corals are not the only organisms that produce calcium carbonate. Certain macroalgae, calcareous red algae, echinoderms, molluscs and crustaceans, and, zooplankton such as foraminifera, pteropods, and coccolithores (Sheppard *et al.*, 2009) also include calcium into their physiology in various fashions. Together, these organisms are referred to as reef community calcifiers. All these organisms release trace amounts of Ca into the water column.

Endosymbiotic zooxanthellae (as discussed in paragraph 1.2.3) play a major role in coral calcification. The chemical formulae is as follow (Constantz, 1986):



Calcium cations and bicarbonate anions in seawater are processed by the endosymbiotic algae to produce calcium carbonate and carbonic acid. Carbonic acid

is in a pH-dependent equilibrium with CO₂, which zooxanthellae use in photosynthesis, and water.

1.3.3 Distribution of coral reefs

Coral reefs are mostly located in the tropics, between the tropics of Cancer and Capricorn (Sorokin, 1995). These ecosystems mostly occur in warm, shallow, nutrient poor environments (Spalding *et al.*, 2001). This “reef belt” extends from 25°N to 25°S (Erhardt & Knop, 2005), as seen in Figure 3. Reefs such as Sodwana and Aliwal that exceed these latitudes are known as marginal reefs. Coral diversity declines at higher latitudes (Obura, 2012).

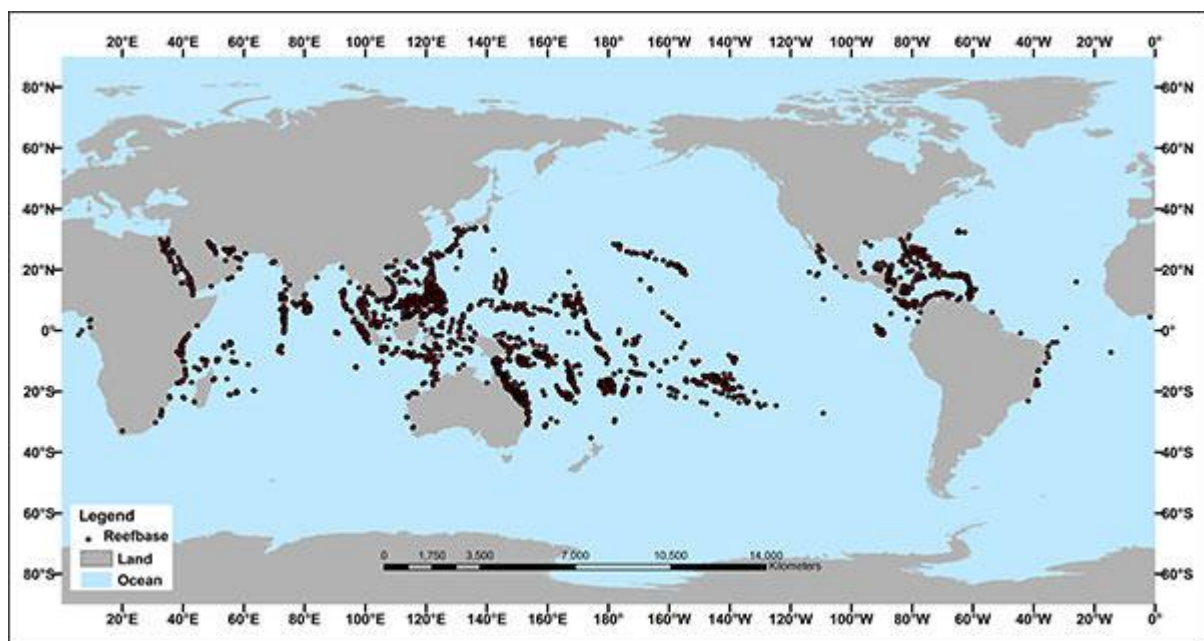


Figure 3. Locations of coral reefs in the world (NOAA, 2017)

1.3.4 Threats to coral reefs

The biggest threat to coral reefs stem from humanity, and particularly overpopulation. Issues of fossil fuels and greenhouse gasses that are generally associated with overpopulation have extensively been discussed (e.g Barnett, 2005; Fernandez *et al.*, 2007; Millero *et al.*, 2009). For this study, it is important to note that greenhouse gasses and their subsequent effect, global warming, pose a huge threat to the ocean, and coral reefs in particular. The ocean acts as a heat sink that traps most of the heat of

global warming. This raises the temperature of the ocean (Buddemeier & Fautin, 1993). The ocean is also a sink for CO₂, released by the burning of fossil fuels. The influx of CO₂ is one of the reasons for the lowering of the pH of seawater and subsequently ocean acidification (Longo & Clark, 2016). At the current rate of ocean acidification, the pH of the ocean will drop from 8.1 to 7.4 within 150 years (Caldeira & Wickett, 2003). If the pH of the ocean decreases as dramatically as predicted, the concentration of hydroxide (OH⁻) and carbonate (CO₃²⁻) ions will decrease proportionally. Calcifying organisms, including corals will experience a reduced growth rate due the limited CO₃²⁻ ions with which to produce CaCO₃ skeletons (Millero *et al.*, 2009).

Another threat to the existence of corals that is associated with global warming is coral bleaching. Bleaching is the stress response where symbiotic algae living inside an organism are expelled by said organism. The process is mostly associated with coral, but can also occur in other organisms living in symbiosis with dinoflagellate algae, such as anemones, sponges, and giant clams (Sheppard *et al.*, 2009). Coral bleaching is the process where coral polyps expel the symbiotic algae cells living in the endodermis. Without the algae in their tissue, the polyps appear translucent, and only the white of the CaCO₃ skeleton is seen. Because the algae provide corals with 95% of their nutritional needs, bleached corals typically starve (Sheppard *et al.*, 2009). The algae provide corals with, amongst other products, oxygen, and nutrients produced through photosynthesis. In the event of elevated sea surface temperatures, O₂ form superoxide radicals (Lesser, 1997). The oxygen is now in a toxic form. The corals sense that their cells are being damaged by the toxic oxygen, and expel the algae cells as a defence mechanism (Baker *et al.*, 2008; Loya *et al.*, 2001). Bleaching can be triggered by several factors: A sudden change in water temperature (heat or cold shock), high solar radiation, prolonged periods of darkness, or high concentrations of certain metals– including copper or cadmium (Douglas, 2003). Branching coral, such as *Acropora* and *Pocillopora* are more susceptible to bleaching than massive forms (Anu *et al.*, 2007). In optimal circumstances, corals can acclimatize to changing conditions by shuffling the genetic population of zooxanthellae living in their tissue. The *Symbiodium* expelled by bleaching can be replaced by recruiting another species or genetic strain of *Symbiodium* with a greater resistance to the reigning abiotic conditions, such as higher seawater temperature (Edmunds & Gates, 2008). It is

important to note that bleaching in and of itself is not permanently detrimental to corals. Bleaching can be compared to the human body experiencing a fever. The damage occurs when the corals cannot recover from a bleaching event. Coral bleaching is an evolutionarily defence mechanism that enables corals to expel damaged zooxanthellae. Metals such as Fe, Cu, and Cd can accumulate in algal cells without accumulating in coral tissue. The expulsion of these metal contaminated algae cells is to the benefit of the coral colony (Marshall, 2002). Baker (2001) explained that bleaching is “an ecological gamble that... sacrifices short-term benefits for long-term advantage”.

Over-exploitation of coral reefs is another consequence associated with overpopulation. Some of the poorest countries with the highest human population growth rates have coral reefs– for example Kenya, Tanzania, India, and Mexico. The coastal residents of these countries are very dependent on coral reefs as a food source. Over-exploitation and poor management pose a severe threat to the reef systems (Sammarco, 1996).

Diseases also pose a threat to coral reefs. Like all animals, corals are susceptible to diseases. Most coral diseases are caused by bacterial pathogens. Some of these pathogens are endemic to a reef, but are triggered by warming ocean temperatures (Celliers & Schleyer, 2002). Other pathogens are introduced through anthropogenic activity, particularly sewage pollution. Both White Band Disease and Black Band Disease were first recorded in the 1970's and wreaked havoc in the Caribbean. *Acropora palmata* cover was reduced by 80–90%. The Indo-Pacific and WIO region, fortunately, has escaped severe impact by coral diseases (Sheppard *et al.*, 2009).

1.4 The Indian Ocean

The Indian Ocean, and specifically the WIO, forms the backdrop against which this study was conducted. It is therefore necessary to provide more information regarding this area although the selection of the study site is motivated in Section 2.1.

The Indian Ocean is the third largest ocean, containing 20% of the seawater on the planet. It is bordered by Australia, Africa, and Asia (Gritzner, 2009). The Indian Ocean

does not experience the same intensity of geological activity as the Pacific and Atlantic Oceans, in terms of earthquakes and volcanoes (Monroe *et al.*, 2007) However, an earthquake originating in Sumatra, Indonesia, caused one of the most destructive tsunamis on December 26, 2004 (Wilkinson *et al.*, 2005). Since tsunamis contribute to physical erosion of coral reefs (see Section 1.3.2), the occurrence of a devastating tsunami in the Indian Ocean it is noteworthy in the context of this study.

Geographically, the WIO extends the entirety of East Africa to areas of Asia (Figure 4). However, the Western Indian Ocean Marine Science Association (WIOMSA), recognises ten member countries: Somalia, Tanzania, Kenya, South Africa, Mozambique, Comores, Seychelles, Réunion (an island of France), Madagascar, and Mauritius. (WIOMSA, 2017). These WIOMSA countries are of concern to this study—particularly South Africa and Mauritius.



Figure 4. The Western Indian Ocean

The flow of the subtropical gyre of the southwestern Indian Ocean is stronger than the southern gyres of either the Pacific or the Atlantic oceans. The South Equatorial current (SEC) is the most prominent current in the Indian Ocean. It flows from east to west at the northern section of the gyre. At the East coast of Africa, the SEC diverges into the Agulhas current that flows south through the Mozambique Channel, and the Somali current to the north. Unlike the Pacific and Atlantic, the Indian Ocean does not have two gyres in the Northern and Southern hemisphere, but rather one trans-equatorial gyre that is subjected to the monsoon conditions in India, moving marginally

north or south, in accordance to the prevailing monsoon conditions. Oceanic eddies are constantly being severed from the SEC, Somali, and Agulhas currents, distributing water from these currents to other locations in the Indian Ocean. The oceanography of the Indian Ocean gives rise to five distinct bioregions in the WIO, each with distinct species diversity (Stramma & Lutjeharms, 1997; Schott & McCreary Jr., 2001; Obura, 2012).

The coast of KwaZulu-Natal, on the east coast of South Africa is subject to regular, but small deep water upwelling events. As previously stated, corals reefs thrive in nutrient poor environments. Additional nutrient input (including trace-metals) through deep water upwelling events is essential for coral nutrition. The upwelling also regulates the water temperature of the reef by supplying an influx of cold deep water. This acts as a buffer against extreme sea surface temperature rise that is detrimental to corals. However, regular, strong up-welling can lower the water temperature or oversaturate the water to the extent that coral growth is inhibited. The upwelling events that occur along the KwaZulu-Natal coast are not strong enough to inhibit coral growth, as is the case in North Africa. It is however, a factor that contributes to the low coral biodiversity (Diaz-Pulido & Garzón-Ferreira, 2002; Riegl & Piller, 2003; Sheppard, *et al.*, 2009).

The Agulhas current is the fast flowing boundary current of the KwaZulu-Natal coast of Southern Africa. The current flows southwards, close to the African shoreline. Fifteenth century sailors voyaged far out to sea when traveling north around Africa to India, but close to shore on their return journey to make use of the current's direction (Gyory *et al.*, 2004). However, an annual reversal of the inland section of the Agulhas current triggers the sardine run. During this time, a thin section of the current alters its course and flows northward. Sediments and other matter (such as contaminants) can be transported northward, due to this littoral drift (Roberts *et al.*, 2010).

The Nairobi Convention was signed in 1985 and came into force in 1996. All WIOMSA countries are signatories of the Nairobi convention to address the accelerating degradation of coastal areas and oceans by means of sustainable management and use of the coastal and marine environment (Bosire *et al.*, 2015). All countries bordering the WIO are third world countries (Kaplan, 2010). Civil unrest and hunger are topics that require greater government concern than coral reef conservation.

1.5 Metals and metalloids

“Heavy metal” pollution has been indicated as the highest priority out of 22 emerging chemical management issues in developing countries (STAP, 2012). The term “heavy metal” was traditionally applied to metals with a specific density of 5 g/cm³ or higher (Newman, 2010). However, some elements are of environmental concern, regardless of its specific gravity. Modern ecotoxicologists tend to avoid the term “heavy metal” (Duffus, 2002) and prefer the terms “metals” or “metalloid”. The term “metallic elements” is used as a collective term when reference is made to both “metals” and “metalloids”. For the sake of brevity, selenium will also be lumped in this term, although it is a non-metal.

Trace metals such as Ni, Cu, and Fe are essential metals when they occur in low concentrations (Bryan, 1971). If concentrations are present beyond natural background levels, the phenomena can be considered contamination. If these chemicals rise to concentrations where they cause adverse effects on biota or the habitat, it can be considered as pollution (Chapman, 1995). An important fact to remember in all toxicological studies is that any substance can be toxic at high concentrations- even water (Farrell & Bower, 2003).

Most elements play a vital role in creating the ocean chemistry that is necessary for all marine life. There are several natural ways in which metallic elements are incorporated into the water column including, but not limited to: erosion of rocks on land, volcanic ejecta, meteorites, and hydrothermal vents (Kastner, 1999). It is because of these elements that ocean salinity is obtained and it is with these elements – particularly calcium – that scleractinian corals build skeletons (Taylor *et al.*, 1994).

Turekian (1968) published a complete analysis of seawater. Table 1 is the concentration of most metals and metalloids in unpolluted seawater. The values have most likely increased since 1968 due to anthropogenic activities, but for the moment, it is the most accurate analysis of the composition of a reference site available. Values are presented in µg/L in Table 1

Table 1. Concentrations of metals in seawater (µg/L).

Element	Concentration	Element	Concentration	Element	Concentration
Mg	1.29 ×10 ⁶	Mo	10	Cu	23
Be	0.0006	Pd	-	Zn	11
B	4.45	Ag	0.28	As	2.6
Al	1	Cd	0.11	Se	0.09
Ti	1	Sb	0.33	V	1.9
Cr	0.2	Ba	2.1	Pb	0.03
Mn	1.9	Pt	-	Bi	0.02
Fe	3.4	Au	0.011	Th	0.0015
Co	0.39	Hg	0.15	U	3.3
Ni	6.6	Tl	-	Sr	8.1

The periodic table of the elements (Figure 5) is divided into different sections based on certain properties of the elements situated in that group.

Alkaline-earth metals are any of the six element that comprises Group 2 of the periodic table of the elements. All alkaline earth metals easily lose electrons, and become cations. They often bind with oxygen to form oxides, are soluble in water and are unaffected by heat (Phillips & Hanusa, 2014). Beryllium (Be), magnesium (Mg), calcium (Ca), strontium (Sr), and barium (Ba) are alkaline earth metals. These are indicated in pink in Figure 5.

Transitional metals that will be examined include titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), molybdenum (Mo), palladium (Pd), silver (Ag), cadmium (Cd), platinum (Pt), gold (Au) and mercury (Hg). The transitional metals occupy most of the periodic table. They have partially filled d sub shell orbits and readily bind with other elements to form cations (IUPAC, 2014). These are indicated in yellow in Figure 5 together with actinides that constitute a sub-category of transitional metals.

Actinides are the 6th group of the periodic table. Actinides are also known as inner transitional metals, or rare earth elements, and are closely associated with the transitional metals. All elements in this grouping are radioactive (LibreTexts, 2016). Uranium (U) and thorium (Th) are actinides that will be discussed in this study.

Aluminum (Al), thallium (Tl), lead (Pb), and bismuth (Bi) are all post-transition metals. Post transitional metals share many properties with transitional metals. However, they tend to be softer with a lower boiling point than transitional metals (LANL, 2016). These are indicated in green in Figure 5.

Metalloids include boron (B), arsenic (As), and antimony (Sb). Selenium (Se) is technically a non-metal, but it will be analysed because it is an element with known toxicological properties (Hamilton, 2004). Metalloids are elements with similar properties to both metals and non-metals. At room temperature, metalloids are not conductors of electricity (as non-metals), but they do conduct electricity when heated (similar to metals) (*Encyclopædia Britannica*, 2016). Metalloids are indicated in orange and Se in blue in Figure 5.

1																											18																					
1 H 1.008		2																									2 He 4.0026																					
3 Li 6.94		4 Be 9.0122												5 B 10.81		6 C 12.011		7 N 14.007		8 O 15.999		9 F 18.998		10 Ne 20.180																								
11 Na 22.990		12 Mg 24.305		3		4		5		6		7		8		9		10		11		12		13 Al 26.982		14 Si 28.085		15 P 30.974		16 S 32.06		17 Cl 35.45		18 Ar 39.948														
19 K 39.098		20 Ca 40.078		21 Sc 44.956		22 Ti 47.867		23 V 50.942		24 Cr 51.996		25 Mn 54.938		26 Fe 55.845		27 Co 58.933		28 Ni 58.693		29 Cu 63.546		30 Zn 65.38		31 Ga 69.723		32 Ge 72.630		33 As 74.922		34 Se 78.97		35 Br 79.904		36 Kr 83.798														
37 Rb 85.468		38 Sr 87.62		39 Y 88.906		40 Zr 91.224		41 Nb 92.906		42 Mo 95.93		43 Tc (98)		44 Ru 101.07		45 Rh 102.91		46 Pd 106.42		47 Ag 107.87		48 Cd 112.41		49 In 114.82		50 Sn 118.71		51 Sb 121.76		52 Te 127.60		53 I 126.90		54 Xe 131.29														
55 Cs 132.91		56 Ba 137.33		57-71 *		72 Hf 178.49		73 Ta 180.95		74 W 183.84		75 Re 186.21		76 Os 190.23		77 Ir 192.22		78 Pt 195.08		79 Au 196.97		80 Hg 200.59		81 Tl 204.38		82 Pb 207.2		83 Bi 208.98		84 Po (209)		85 At (210)		86 Rn (222)														
87 Fr (223)		88 Ra (226)		89-103 #		104 Rf (265)		105 Db (268)		106 Sg (271)		107 Bh (270)		108 Hs (277)		109 Mt (276)		110 Ds (281)		111 Rg (280)		112 Cn (285)		113 Nh (286)		114 Fl (289)		115 Mc (289)		116 Lv (293)		117 Ts (294)		118 Og (294)														
* Lanthanide series																			57 La 138.91		58 Ce 140.12		59 Pr 140.91		60 Nd 144.24		61 Pm (145)		62 Sm 150.36		63 Eu 151.96		64 Gd 157.25		65 Tb 158.93		66 Dy 162.50		67 Ho 164.93		68 Er 167.26		69 Tm 168.93		70 Yb 173.05		71 Lu 174.97	
# Actinide series																			89 Ac (227)		90 Th 232.04		91 Pa 231.04		92 U 238.03		93 Np (237)		94 Pu (244)		95 Am (243)		96 Cm (247)		97 Bk (247)		98 Cf (251)		99 Es (252)		100 Fm (257)		101 Md (258)		102 No (259)		103 Lr (262)	

Figure 5. Periodic table of the elements. Elements discussed are coloured.

1.6 Hypotheses and objectives

The hypotheses of this study are:

1. The corals collected in South Africa will contain a higher concentration of metals and metalloids than those from the Mascarene Basin.

The Mascarene Islands sites I sampled all have relatively low anthropogenic input and relatively small human populations. South Africa has a much larger population and much more anthropogenic activities. The South African reefs are more often visited by SCUBA divers and have more boating activity than the Mascarene sites.

2. Soft corals will accumulate higher concentrations of metals and metalloids than hard corals.

Soft corals are comprised of a thicker organic matrix, and contain less inorganic matter than hard corals. Although still reliant on zooxanthellae for nutrition, soft coral are more dependent on suspension feeding and active predation. If prey items are contaminated with metals and metalloids, soft corals are more likely to bioaccumulate metals and metalloids.

Aim: To investigate metallic elements in corals from the WIO.

Objectives:

- To determine the concentrations of metallic elements in corals from various sites
- To investigate geographic differences in levels and relative contribution patterns
- To investigate differences in metallic elemental concentrations and relative contribution patterns between hard and soft corals
- To evaluate possible pollution sources
- To assess any toxicological implications

Chapter 2: Materials and Methods

In this chapter, I will give an overview of the materials and methods used to gather information to investigate the claims of the formulated hypotheses. I will firstly explain why the particular sites were chosen for collection. Each site will be briefly described with reference to the geology of the region and anthropogenic activities that might affect the area. The second section of the chapter briefly identifies the coral genera that were selected as study taxa. The third section describes the process of collecting the coral. An exposition is then provided of safety measures to protect field staff, and permits acquired to collect and import coral fragments. Finally, a brief discussion will be given on the manner in which the statistical analysis was conducted.

2.1 Study sites

It is impossible to have a perfect reference site with guaranteed absence of any contamination in the ocean. Very limited, if any, studies were conducted on coral reef integrity during the colonial period, and we have no idea what effect those sailors had on the reefs they visited (Turner & Klaus, 2005). The best reference sites would be remote and largely uninhabited islands. In this study, I investigated both coastal and remote island coral reefs in the WIO. Mauritius was identified as a region with low environmental susceptibility to climate change, and a high social adaptive capacity (McClanahan *et al.*, 2009). McClanahan *et al.* (2009) praised Mauritius for creating an environment that promotes self-initiated recoveries and protection of reefs through social involvement. This attitude towards conservation is not limited to the main island, but is also implemented in the outer islands. For this reason, three Mauritian outer-islands in the Mascarene Basin – Rodrigues, Agalega, and St Brandon's Atoll (SBR) – were selected as reference sites for the metallic contamination in corals. The Mascarene Islands are isolated with endemic species, but low biodiversity (Obura, 2012). Corals were not collected from the main island of Mauritius. Mauritius is a

popular tourist destination and the reefs are subject to physical damage and local pollution. Réunion Island was also not sampled for similar reasons.

Corals from South Africa were collected from Sodwana and Aliwal Shoal, both Marine Protection Areas (MPAs) on the KwaZulu-Natal coast. The Agulhas Current that flows close to the South African coast causes a decline in coral diversity, compared to the high coral diversity of the equatorial zone (Obura, 2012).

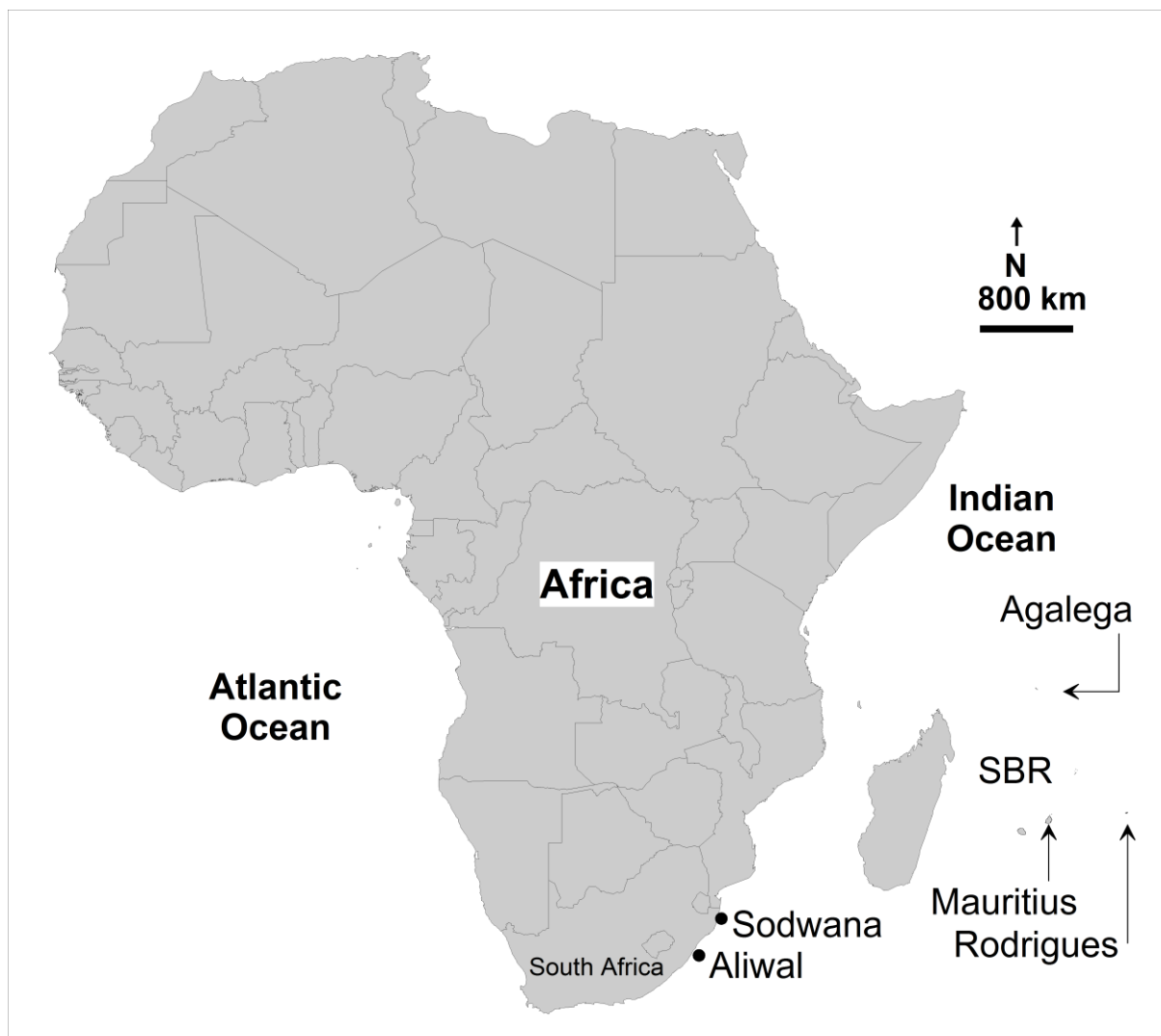


Figure 6. Map of Africa, indicating the sampling localities of this study

2.1.1 Agalega

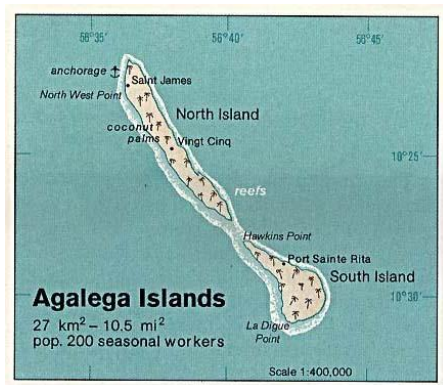


Figure 7. Agalega Island (Island University of Texas Library, 2017)

The island of Agalega is the most northern of the Mauritian outer-islands. Agalega consists of a Northern and Southern island, connected by a shallow lagoon. This lagoon is accessible by a tractor to move between the islands at low tide. It is a very remote island with minimal contact with the industrialised world. A ferry from Mauritius brings supplies and ferries people once every two-three months. Approximately 300 people permanently reside on Agalega. The only economic activity practiced on the island is coconut harvesting and processing. Approximately 2 million whole coconuts as well as oil are exported annually (Statistics Mauritius, 2011).

2.1.2 Rodrigues

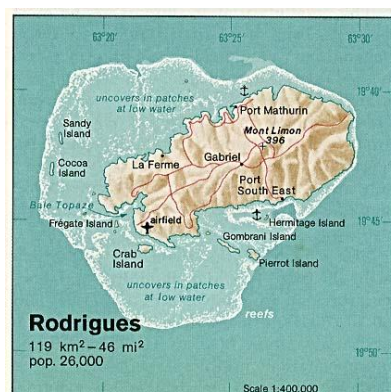


Figure 8. Rodrigues Island (University of Texas Library, 2017)

The island has a lagoon coverage of 200 km² that surrounds the entire island (Turner & Klaus, 2005). The island itself is of volcanic origin, but distinguished from the other Mascarene Islands in that it does not originate from the same volcanic hot spot as Mauritius and Réunion. The underlying geology is layered limestone and basalt. The platform of the characteristic reef flat of Rodrigues is a lava flow from the early Pliocene, on which corals have settled and a reef developed. Rodrigues hosts the best developed coral reef system in the Mascarene basin (Rees *et al.*, 2005). 40 400 people reside on Rodrigues (Statistics Mauritius, 2011). A supply ferry from Mauritius visits the island on a regular basis and the island is served twice daily by medium aircraft. Low levels of DDT, mirex, and brominated flame retardants have been reported in eggs from noddies and terns nesting on the island (Bouwman *et al.*, 2012). This indicates that anthropogenic contaminants are present in low levels in Rodrigues's ecosystem.

2.1.3 St Brandon's Atoll

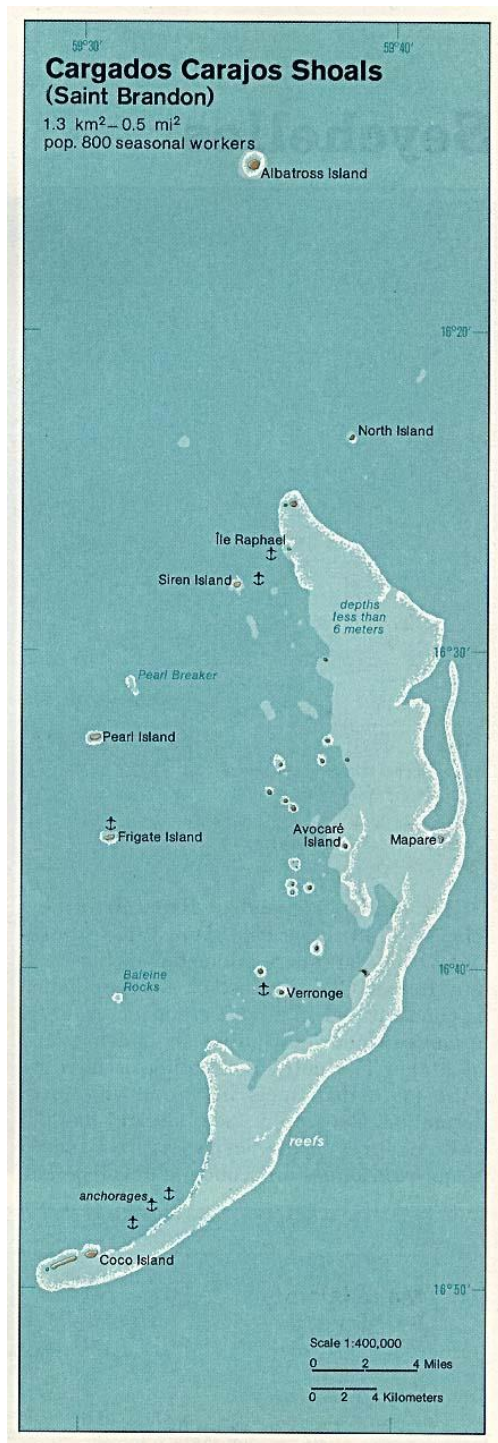


Figure 9. St Brandon's Atoll (University of Texas Library, 2017)

St Brandon's Atoll (SBR), also known as Cargados Carajos, is located approximately 400 km north of Mauritius. The atoll encompasses approximately 200 km² (Quod,

1999). The atoll consists of 19 sandbars and 24 vegetated islands (Evans *et al.*, 2016). Small coral reefs occur as patchy segments amongst the sandbars, instead of the fringing reefs, as seen at Rodrigues and Agalega. Charles Darwin (although he did not visit SBR) could not fit the atoll into any conventional reef categorization, due to the vast expense and variable environments of the atoll (Darwin, 1910). The atoll is estimated to be approximately 5000 years old (Turner & Klaus, 2005).

St Brandon's does not have any permanent residents, but in 2014, there was a temporary population of 41—mainly composed of fishermen, coast guard and weather station personnel (Bouwman *et al.*, 2016). Raphael Fishing Co. is the main stakeholder in most of the St Brandon's islands. It is currently lobbied that SBR should be declared a bird and turtle conservation area. Over a million individuals of seven breeding bird species reside on the atoll. It is also an important nesting site for green- and hawksbill sea turtles (Evans *et al.*, 2016). Several shipwrecks can be found along the edge of the atoll. Wave action, currents, and grinding of the wrecks on the reef may hasten the degradation of the wrecks, and release smaller particles from the wreck into the environment. The most publicized of these wrecks was a yacht participating in the Volvo Ocean race that ran aground in 2014 (Bouwman *et al.*, 2016).

2.1.4 Aliwal

Aliwal Shoal is located 4 km from the Green Point light house, approximately 40 km South of Durban in KwaZulu-Natal, South Africa (between 30°15.50'S; 30°49.70'E and 30°16.20'S; 30°49.20'E). The reef is not a typical limestone formation, but rather a submerged sand dune- or aeolianite- submerged $\pm 30\,000$ years ago (Schleyer *et al.*, 2006). Today, the reef system is a marine protected area (MPA) comprised of two restricted zones and a controlled area where fishing and SCUBA diving is permitted with applicable authorisations (Olbers *et al.*, 2009). It is a world-renowned congregation area for spotted ragged tooth sharks, *Carcharias taurus* (Van Tienhoven *et al.*, 2007).

Aliwal Shoal is located near the largest SAPPI/Saiccor paper plant. In 1955, the factory released the first effluent into the ocean. The result was that residents of Umkumaas complained of unaesthetically foam washing up on the beaches of the surrounding

properties (Figure 10). A 6.5 km long pipeline was constructed in 1963 as a way to remove effluent in such a manner not to cause a nuisance to the local community (Stone, 2002).

Saiccor dissolves pulp using acid sulfates, with Mg and Ca as basis. Each base is used in a different context to produce the best quality product. All effluent is eliminated through the submarine pipeline into the ocean. The released effluent primarily consists of lignin and lignosulphate; along with hemicelluloses, resin acid, tannins, and sugars (Fathima, 2003).



Figure 10. Foam on the beach, 1963, caused by effluent emitted by Saiccor, prior to the construction of the effluent pipeline (Stone, 2002)

2.1.5 Sodwana

Sodwana is a popular recreational SCUBA diving destination in the north of South Africa, near the Mozambique border. Sodwana is a high latitude, marginal coral reef (Schleyer *et al.*, 2008), meaning its location is outside of what is considered typical for coral reefs. Because Sodwana is one of the most southern reefs, at 28°30'S, there is little coral biodiversity compared with areas such as the Great Barrier Reef (Sheppard *et al.*, 2009).

High latitude reefs, such as Sodwana, are not as susceptible to bleaching events as reefs along the equator. The relatively deep water, turbidity of the environment and the Agulhas Current normally acts as a buffer to extreme temperature fluctuations. However, in 2000, the shallow reefs of Sodwana, Two Mile- and Nine Mile reefs, experienced a bleaching event. More than 12% of the live coral on Two Mile reef experienced bleaching (Celliers & Schleyer, 2002). The damage was not permanent, and most of the affected corals have recovered from the bleaching event (Riegl & Piller, 2003).

Sodwana is not close to any large industries, but thousands of SCUBA divers visit the reef throughout the year. Several dive charters own and launch multiple boats (mostly rubber ducks with two-stroke or four-stroke engines) on a daily basis. Physical damage to the reef is highly visible. This damage is primarily caused by unexperienced or reckless divers breaking corals. In 1996, 17 614 boat launches and 118 389 divers were recorded (Schleyer & Tomalin, 2000).

2.2 Permits required

In 2014, permission was obtained from Ezemvelo KZN Wildlife and iSimangaliso Wetland Park to sample corals from Aliwal Shoal and Sodwana, respectively. Permits were obtained from the Department of Environmental Affairs (RES2014/96). Because Scleractinian corals are listed on the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Annex B (CITES, 2016), a CITES permit (No147512) was also acquired.

Corals collected from the Mauritian islands were transported to South Africa (Import permit No. P0075626).

The Department of Health registered NWU Ethics Committee, AnimCare, approved this study. A notification form for the collection of lower invertebrates was completed.

2.3 Selected genera

Nine coral genera were selected for this study, based on different taxonomic orders (hard and soft corals), size, and availability. All the soft corals collected are order Alcyonaria– the leather- and soft corals. Hard corals are order Scleractinia.

Because corals have the ability to recover from physical damage, and even reproduce asexually by broken fragments of the main colony growing on a new location (Chadwick & Loya, 1990), fractions of colonies removed during the sampling process of this study would have little to no lasting impact on the health of the mother colony. General characteristics of the selected coral genera are presented in table 2.

Table 2. General characteristics of collected corals

Genus	Type	Common name	Corallite/polyp size (mm)	Colony Size (mm)	Symbiotic algae
<i>Acropora</i>	Hard	Staghorn coral	< 3	300- 400	Yes
<i>Pocillopora</i>	Hard	Knob-horned coral	< 2	250	Yes
<i>Stylophora</i>	Hard	Tramp coral	< 2	250	Yes
<i>Fungia</i>	Hard	Mushroom coral	70	200	Yes
<i>Dendrophyllia</i>	Hard	Turrent coral	30 (+tentacles)	50	No
<i>Sarcophyton</i>	Soft	Mushroom soft coral	5	200-500	Yes
<i>Sinularia</i>	Soft	Leather coral	1	1000	Yes
<i>Dendronephthya</i>	Soft	Thistle soft coral	2	200	No
<i>Eleutherobia</i>	Soft	Golden soft coral	10 (+tentacles)	12-150	No

(Branch *et al.*, 2016; Erhard & Knop, 2005)

Acropora

Acropora is the most species-diverse coral genus, with approximately 30 species. It is also one of the fastest growing genera of Scleractinia (Erhardt & Knopf, 2005). They are restricted to calm waters due to brittle skeleton. A distinctive characteristic of the genus is a single larger corallite at the tip of each branch (Branch *et al.*, 2016).



Figure 11. *Acropora*

Pocillopora

Pocillopora is a branched genus full of wart like bumps that house corallites (called verrucae). It is also one of the fastest growing hard corals and a recruitment species. The skeletons are often sold in the souvenir trade (Erhardt & Knop, 2005). Colonies can occur from very shallow areas, such as intertidal pools, to 40 m deep water (Branch *et al.*, 2016).



Figure 12. *Pocillopora*, left. *Stylophora*, right

Stylophora

Stylophora is closely related to *Pocillopora*. It is classified within the family Pocilloporidae, but lack the diagnostic wart like structures of the *Pocillopora*. However, it is hard to discern when the polyps are extended. *Stylophora* have been recorded at 80 m depth, which is unusual for a hermatypic coral (Erhardt & Knop, 2005).

Fungia

Fungia polyps are normally very large and solitary, as opposed to most other corals that build skeletons comprising of numerous polyps. Adult *Fungia* are non-sessile and mobile to an extent (Erhardt & Knop, 2005). Small polyps are attached to substrate with a small stalk (*personal observation, 2014*).



Figure 13. *Fungia*, a solitary individual

Dendrophyllia

These coral do not have a symbiotic relationship with zooxanthellae and are not prominent reef building corals. They closely resemble anemones. Large polyps with long golden tentacles are extended at night to catch plankton (Erhardt & Knop, 2005). Often found in caves or beneath overhangs (Branch *et al.*, 2016).



Figure 14. *Dendrophyllia*

Dendronephthya

Dendronephthya are members of the soft coral family Neptheidae. Corals of this family have hydrostatic skeletons- chambers in the stem that are filled with water to lend stability to the organism. *Dendronephthya* colonies are azooxanthellate, but the sclerites are bright shades of red, pink, or purple. Colonies usually grow up to 20 cm, but certain species in the Indo-Pacific can grow to two meters in size (Erhardt & Knop, 2005).



Figure 15. *Dendronephthya*

Sinularia

Sinularia, along with *Sarcophyton* and *Eleutherobia* is a member of the family Alcyoniidae, also known as leather corals. *Sinularia* is a massive encrusting leather coral with finger-like projections that house the polyps. They are normally found on the inner-reefs (Erhard & Knop, 2005). *Sinularia* can grow to a massive size of more than two metres area are a long-lived genus (Fabricius, 1995).

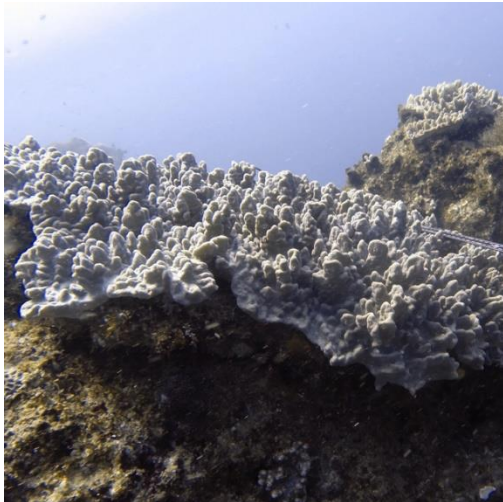


Figure 16. *Sinularia*

Sarcophyton

This is also a soft leather coral. *Sarcophyton* is smaller than *Sinularia*. It is mushroom-shaped, a disc with polyps situated on a pale stem, with a brownish yellow colouration (Erhard & Knop, 2005). *Sarcophyton* tissue is toxic to most corallivorous fish (Sorokin, 1995).



Figure 17. *Sarcophyton*

Eleutherobia

Eleutherobia is one of the smallest leather corals, measuring around 5 cm in length. It is an azooxanthellate coral with small polyps that extend at night to catch plankton (Erhard & Knop, 2005). In 2013, taxonomers established that *Eleutherobia grayi*, which we collected from Aliwal Shoal are placed under the new genus of *Parasphaerasclera* (McFadden & van Ofwegen, 2013). Because most sources still refer to *Eleutherobia*, I will also do so throughout the dissertation. The permits I acquired also acknowledges *Eleutherobia*. I will refer to it as such for the sake of continuity.



Figure 18. *Eleutherobia*

2.4 Field collection

Sampling in South Africa was conducted in June 2014. The Mascarene sites were visited in September and October 2014. However, after the 2014 sampling trip, the corals collected from Rodrigues island were stored on the island itself, awaiting transport to Mauritius (Agalega and St. Brandon's' samples were directly stored on Mauritius, pending export permits to South Africa). During the time when the Rodrigues samples were still stored on the island, a hurricane rendered the island without electricity for approximately ten days. The collected corals perished (and the premises where they were stored rendered uninhabitable due to the stench). A return trip to resample commenced in March 2015.

The same sampling procedure was applied at all sites. A boat transported the divers to the dive site and everyone descended together to the reef. On the reef, colony fragments of the target coral genera were removed and placed in the collection bag lined with a plastic Ziplock bag dedicated to the specific genera. It was found most convenient to remove fragments of hard coral with a side cutter (plier) and soft coral with a diving knife. A picture of the target coral was placed on the collection bag for underwater verification. Ten whole *Fungia* polyps were collected from each of the Mascarene sites, due to their unique lifestyle as a free-living polyp (Chadwick-Furman *et al.*, 2000). Due to the small size of *Eleutherobia*, multiple whole colonies were collected. Several researchers used the average of three colonies as the average to work with (e.g. Akagi *et al.*, 2004; Ali *et al.*, 2011) to reduce the impact the study has on the reef environment.

The benthic cover of an ocean vary significantly between individual islands, across latitudes, and different oceanic regions (Smith *et al.*, 2016). For this reason, not all corals were found on all of the selected sites. Table 3 shows the sites on which the corals were collected. Eighty one coral fragments were analysed.

Table 3. Sites from which certain coral genera were collected

	Sodwana	Aliwal	Rodrigues	Agalega	SBR
<i>Stylophora</i>		X	X	X	X
<i>Pocillopora</i>	X	X	X		X
<i>Acropora</i>	X		X	X	X
<i>Fungia</i>			X	X	X
<i>Dendrophyllia</i>		X			
<i>Dendronephthya</i>	X	X			
<i>Sinularia</i>	X	X	X	X	X
<i>Sarcophyton</i>	X		X	X	
<i>Eleutherobia</i>		X			

2.5 Laboratory analysis

Metals and metalloids can be included into coral skeletons, as well as tissue (Van Dam, 2011). For this reason, it was deemed necessary to use the full coral fragment, instead of analysing the tissue and skeleton separately.

The coral fragments were stored frozen until analysis could commence. Fragments were placed in 50 ml falcon tubes and frozen at -80°C for 24 hours. They were then freeze-dried for 24 hours to remove all moisture. The fragments were ground fine with a granite mortar and pestle and placed back into the same falcon tubes. The internationally standardised 3050B method (EPA, 1996) was used to determine metal and metalloid concentration in the coral. Two gram of ground coral fragments were acid digested by adding hydrogen peroxide and nitric acid. The solution was heated and diluted to 50 ml. The coral solution was then diluted an additional 10% to prevent blockage in the tubing of the machines used for analysis. The digested solutions were analysed for the presence of metals and metalloids using inductively coupled plasma mass spectrometry (ICP-MS) (Agilent 7500c ICP-MS). Analysis was conducted by the EcoRehab Laboratory in Potchefstroom. The laboratory frequently participates in inter-laboratory calibration, and a standard reference material was used (ERM-CE 278 K Sample No 0449 mussel tissue). The results of the percentages standard reference material recovered is shown in Table 4. The unit of expression is milligram per kilogram, dry mass (mg/kg dm).

Table 4. Recovery of standard reference material

Element	Percentage recovered
Cr	83%
Mn	76%
Fe	88%
Cu	76%
Zn	85%
As	91%
Se	83%
Sr	92%
Hg	80%
Pb	100%

2.6 Safety considerations

All divers involved in the study are PADI certified. For safety considerations, no less than three divers at a time participated in the underwater sampling. A diver with a divemaster (DM) qualification was present at all times. The boat was on the surface, following the buoy of the DM and bubbles from the divers bellow. A bottle of emergency oxygen and a defibrillator was at hand at all times. Safety was of primary concern. All team members involved had at least level I First Aid training. All sampling took place during daylight hours. Black tipped reef sharks and nurse sharks actively avoided divers. All divers were knowledgeable about dangerous marine life. The diving equipment was properly washed and dried after each dive.

2.7 Statistical analysis

Mann Whitney tests were conducted in Graphpad Prism 5. Because the data is not normally distributed, it is handled as non-parametric data. Mann Whitney tests and the p-values assumed a Gaussian approximation. Outliers were removed from this

analysis; however, they will be addressed in the discussion. A confidence interval of 95% was used.

Secondly, nonmetric multivariate statistics (NMS) were conducted to compare the metal contents in different corals from different localities. Multivariate analysis was conducted using MjM Software PC-ORD version 6. The data was relativized by PC-ORD in order to present a proportional profile of metallic elements. Sørensen was used as relative measurement of distance. 250 runs of real data was used as random starting configurations. Monte Carlo tests were done with 250 runs of randomised data. A final stress of 10.79 was obtained for a two-dimensional solution, with a final instability of 0, reached after 74 iterations. Most solutions of ecological studies will have a stress value of between 10 and 20. A lower value is more satisfactory, and a value exceeding 20 is cause for concern in terms of accuracy (McCune & Grace, 2002). The final stress of 10.79 obtained for this study is satisfactory, and the data points trustworthy.

CHAPTER 3: RESULTS

3.1 General results

In this chapter, the results obtained through ICP-MS analyses are presented.

Firstly, the quantified results of the means are presented in table form. Seven tables are presented, based on the position of the particular element in the periodic table. The elemental groups examined were; alkaline earth metals, metalloids, post transitional metals, actinides, and transitional metals. The transitional metals are additionally presented as either row four, five, or six of the periodic table. The unit of expression is milligram per kilogram, dry mass (mg/kg dm). The values were calculated as the mean from three samples of coral from each site. Blank spaces indicate no samples.

A complete table, with the mean, median, minimum value (min), maximum value (max), standard deviation from mean (SD), and the coefficient of variation (%CV) given for each element can be found in Appendix 1.

Table 5. Mean concentrations and standard deviation, in brackets, of alkaline earth metals in corals from the WIO (mg/kg dm).

Alkaline earth metals										
Element	Location	<i>Sin</i>	<i>Sarco</i>	<i>Eleu</i>	<i>Dendt</i>	<i>Acro</i>	<i>Fun</i>	<i>Poc</i>	<i>Styl</i>	<i>Dendl</i>
Be	Agalega	0.00099 (0.000066)	0.001 (4.3E-06)			0.00091 (0.000018)	0.000913 (5.9E-06)		0.00103 (8.5E-06)	
		0.00099 (0.000011)	0.00099 (6.5E-06)			0.00092 (0.000033)	0.00092 (0.000012)	0.00098 (0.000014)	0.00101 (0.000021)	
	Rodrigues	0.00103 (4.2E-06)				0.00091 (9.7E-06)	0.00069 (0.00031)	0.00099 (0.000038)	0.00100 (0.000026)	
	SBR	0.00028 (0.00017)	0.00059 (0.000015)		0.00059 (0.000014)	0.00060 (0.000012)		0.00058 (0.000033)		
	Sodwana	0.00019 (0.000013)		0.00056 (0.000022)	0.00059 (0.000019)			0.00056 (0.000028)	0.00051 (0.00004)	0.00054 (0.000013)
	Aliwal									
Mg	Agalega	34000 (3800)	46000 (3500)			1900 (140)	2200 (410)		2600 (430)	
		35000 (5300)	29000 (12000)			1500 (29)	1900 (430)	4630 (690)	3800 (160)	
	Rodrigues	40000 (5400)				1800 (380)	2100 (410)	5300 (970)	3400 (670)	
	SBR	8300 (490)	35000 (620)		34000 (1949)	2000 (150)		5300 (920)		
	Sodwana	8700 (680)		19000 (776)	34000 (1457)			4100 (180)	3400 (140)	2900 (385)
	Aliwal									
Ca	Agalega	330000 (30000)	320000 (16000)			410000 (16000)	500000 (49000)		420000 (40000)	
		270000 (21000)	200000 (65000)			380000 (16000)	450000 (33000)	500000 (68000)	510000 (25000)	
	Rodrigues	360000 (78000)				460000 (80000)	500000 (92000)	470000 (8600)	430000 (18000)	
	SBR	150000 (10000)	270000 (3900)		350000 (16000)	460000 (23000)		430000 (12000)		
	Sodwana	130000 (12000)		150000 (9800)	290000 (13000)			420000 (10000)	410000 (17000)	430000 (18000)
	Aliwal									
Sr	Agalega	2400 (220)	2600 (210)			8000 (350)	9400 (870)		7500 (740)	
		1900 (130)	1400 (600)			7600 (370)	8200 (610)	9500 (1300)	9100 (450)	
	Rodrigues	2400 (480)				9000 (1500)	9100 (1700)	8600 (140)	7600 (300)	
	SBR	2000 (110)	1700 (24)		2100 (89)	8400 (420)		7400 (220)		
	Sodwana	800 (81)		1000 (94)	1800 (79)			6900 (160)	7000 (360)	7100 (325)
	Aliwal									
Ba	Agalega	4.7 (1.7)	4.0 (1.1)			8.1 (1.4)	7.9 (0.81)		6.2 (1.6)	
		3.3 (0.8)	3.8 (3.5)			17 (7.7)	6.7 (0.34)	16 (5.2)	8.6 (0.29)	
	Rodrigues	3.7 (1.6)				27 (3.8)	7.1 (1.6)	11 (2)	7.8 (1.2)	
	SBR	21 (1.7)	4.6 (1.6)		5.8 (0.048)	10 (2.8)		11 (1.2)		
	Sodwana	14 (3.1)		12 (0.76)	4.9 (0.34)			11 (1.2)	11 (0.59)	16 (0.32)
	Aliwal									

All alkaline earth metals had the highest concentrations in corals collected from the Mascarene basin.

Table 6. Mean concentrations and standard deviation, in brackets, of metalloids in corals from the WIO (mg/kg dm).

		Metalloids								
Element	Location	<i>Sin</i>	<i>Sarco</i>	<i>Eleu</i>	<i>Dendt</i>	<i>Acro</i>	<i>Fun</i>	<i>Poc</i>	<i>Styl</i>	<i>Dendl</i>
B	Agalega	25 (6)	33 (4.3)			45 (5.9)	62 (12)		57 (3.8)	
		23 (2.6)	43 (10)			47 (3)	53 (7)	67 (3.6)	66 (6.1)	
	Rodrigues	27 (7)				55 (12)	68 (14)	70 (2.9)	59 (2)	
		10 (2.4)	33 (3.8)		14 (2.9)	61 (6.4)		48 (4.6)		
	Sodwana	0.16 (0.031)		0.11 (0.14)	12 (1.7)			45 (4.6)	39 (3.6)	30 (2.7)
	Aliwal									
As	Agalega	1.1 (0.6)	3.6 (2.7)			0.025 (0.034)	0.0026 (0.00065)		0.0019 (0.00074)	
		1.4 (0.63)	2.1 (1.4)			0.009 (0.01)	0.0022 (0.0015)	0.0017 (0.00058)	0.06 (0.044)	
	Rodrigues	1.6 (0.48)				0.041 (0.057)	0.12 (0.75)	0.0018 (0.00036)	0.066 (0.091)	
		6.5 (0.2)	3.6 (0.05)		2.4 (0.085)	0.3 (0.13)		0.33 (0.062)		
	Sodwana	6.5 (0.24)		27 (1.1)	4.3 (0.19)			0.72 (0.032)	1.6 (0.11)	3.6 (1.1)
	Aliwal									
Sb	Agalega	0.0011 (0.00012)	0.0014 (0.00017)			0.0013 (0.00011)	0.0012 (0.0001)		0.0014 (0.00081)	
		0.00079 (0.00028)	0.0010 (0.00011)			0.0013 (0.00018)	0.0010 (0.00022)	0.0014 (0.00035)	0.0013 (0.0002)	
	Rodrigues	0.0012 (0.00041)				0.0008 (0.0004)	0.0007 (0.00049)	0.0013 (0.00026)	0.0012 (0.00017)	
		0.016 (0.011)	0.00044 (0.00032)		0.022 (0.024)	0.0005 (0.00009)		0.049 (0.069)		
	Sodwana	0.0013 (0.0015)		0.094 (0.1)	0.00062 (0.0001)			0.00018 (0.0001)	0.00028 (0.0002)	0.00067 (0.00041)
	Aliwal									
Se	Agalega	0.0081 (0.002)	0.0089 (0.001)			0.010 (0.0015)	0.010 (0.0016)		0.011 (0.00011)	
		0.0057 (0.0019)	0.0092 (0.001)			0.012 (0.0019)	0.011 (0.0017)	0.0092 (0.012)	0.012 (0.00067)	
	Rodrigues	0.0096 (0.0011)				0.0091 (0.0011)	0.017 (0.01)	0.010 (0.00084)	0.013 (0.00065)	
		1.1 (0.25)	0.31 (0.12)		0.79 (0.11)	0.0023 (0.0003)		0.0028 (0.00049)		
	Sodwana	0.54 (0.13)		3.3 (0.31)	0.97 (0.12)			0.0012 (0.00065)	0.38 (0.12)	0.29 (0.21)
	Aliwal									

With the exception of B, all metalloids had the highest concentration in *Eleutherobia* from Aliwal Shoal. *Pocillopora* had the lowest concentration of metalloids, again with the exception of B. Boron presented itself in the opposite fashion to the other metalloids. *Pocillopora* had the highest concentration, and *Eleutherobia* the lowest.

Table 7. Mean concentrations and standard deviation, in brackets, of post transitional metals in corals from the WIO (mg/kg dm).

Post transition metals										
Element	Location	<i>Sin</i>	<i>Sarco</i>	<i>Eleu</i>	<i>Dendt</i>	<i>Acro</i>	<i>Fun</i>	<i>Poc</i>	<i>Styl</i>	<i>Dendl</i>
Al	Agalega	49 (26)	58 (34)			76 (24)	120 (79)		120 (26)	
		58 (11)	57 (19)			50 (6)	100 (31)	360 (38)	240 (15)	
	Rodrigues	35 (14)				56 (23)	80 (22)	420 (83)	240 (82)	
		270 (41)	71 (13)		83 (2.7)	100 (14)		370 (9.7)		
	Sodwana	440 (36)		80 (18)	80 (9.9)			200 (6)	260 (12)	180 (51)
	Aliwal									
Ti	Agalega	0.0012 (0.000033)	0.0012 (0.000012)			0.0012 (5.6E-06)	0.0012 (0.000013)		0.0012 (4.7E-06)	
		0.0012 (0.00001)	0.0012 (5.8E-06)			0.0012 (9.4E-06)	0.0012 (7.3E-06)	0.0012 (3.4E-06)	0.0012 (8.8E-06)	
	Rodrigues	0.0013 (2E-06)				0.0012 (3.4E-06)	0.00079 (0.00052)	0.0012 (0.000017)	0.0012 (5.9E-06)	
		0.041 (0.057)	0.00067 (0.000024)		0.00061 (0.000017)	0.0007 (2.4E-06)		0.00069 (5.3E-06)		
	Sodwana	0.00071 (0.000011)		0.00077 (0.000014)	0.00077 (6.2E-06)			0.00071 (0.000012)	0.00073 (0.00001)	0.00079 (0.000013)
	Aliwal									
Pb	Agalega	0.0073 (0.002)	0.01 (0.0022)			0.01 (0.00026)	0.0094 (0.0011)		0.0078 (0.0043)	
		0.0076 (0.002)	0.44 (0.61)			0.011 (0.00043)	0.0069 (0.0045)	0.012 (0.0013)	0.01 (0.0025)	
	Rodrigues	0.011 (0.0014)				0.0091 (0.0028)	0.011 (0.0016)	0.0098 (0.0027)	0.0069 (0.0043)	
		0.84 (0.12)	0.32 (0.064)		0.23 (0.08)	0.36 (0.15)		0.22 (0.13)		
	Sodwana	0.76 (0.047)		0.50 (0.17)	0.25 (0.1)			0.16 (0.037)	3.1 (4)	0.50 (0.22)
	Aliwal									
Bi	Agalega	0.00072 (0.00018)	0.00087 (8.1E-06)			0.00080 (3.3-E06)	0.00080 (0.000015)		0.00085 (0.000012)	
		0.00081 (0.000038)	0.00081 (0.00003)			0.00082 (4.5E-06)	0.00078 (0.000038)	0.00084 (0.000013)	0.00081 (0.000018)	
	Rodrigues	0.00086 (0.00001)				0.00081 (0.00002)	0.00058 (0.00031)	0.00083 (0.000011)	0.00082 (0.000011)	
		0.43 (0.34)			0.025 (0.019)	0.00030 (8.4E-06)		0.00029 (0.000017)		
	Sodwana	0.00028 (7E-06)	0.025 (0.0095)	0.0001 (0.000043)	0.00016 (0.000016)			0.00029 (6.9E-06)	0.00034 (6.5E-06)	0.00026 (6.9E-05)
	Aliwal									

All post transitional metals reported here are present in the corals collected from South Africa. *Stylophora* from Aliwal had the highest concentration of Pb, but this is an outlier value. Disregarding the particular *Stylophora* colony with 8 mg/kg dm of Pb, *Sinularia* from Sodwana would have the highest Pb concentration. Thallium and Bi had highest concentrations in *Sinularia* Sodwana, and Al in *Sinularia* from Aliwal.

Table 8. Mean concentrations and standard deviation, in brackets, of actinides in corals from the WIO (mg/kg dm).

Actinides										
Element	Location	<i>Sin</i>	<i>Sarco</i>	<i>Eleu</i>	<i>Dendt</i>	<i>Acro</i>	<i>Fun</i>	<i>Poc</i>	<i>Styl</i>	<i>Dendl</i>
Th	Agalega	0.00032	0.00043			0.00019	0.00036		0.00042	
		(0.00012)	(0.000019)			(0.00011)	(0.00002)		(7.1E-06)	
	Rodrigues	0.00025	0.0018			0.00035	0.00037	0.00022	0.00035	
		(0.000095)	(0.0012)			(0.000026)	(0.000031)	(0.000031)	(7.4E-06)	
	SBR	0.00033				0.00039	0.030	0.00027	0.00036	
		(0.0001)				(0.000027)	(0.042)	(0.000027)	(0.000031)	
	Sodwana	0.12	0.08		0.049	0.0074		0.023		
		(0.025)	(0.098)		(0.017)	(0.0011)		(0.0056)		
U	Agalega	0.042		0.044	0.038			0.021	0.014	0.011
		(0.006)		(0.0089)	(0.0021)			(0.0045)	(0.0011)	(0.0031)
	Rodrigues	0.11	0.11			3.1	3.5		2.1	
		(0.1)	(0.078)			(0.23)	(0.4)		(0.19)	
	SBR	0.001	0.026			2.9	2.6	3.6	2.8	
		(0.0012)	(0.023)			(0.3)	(0.2)	(0.41)	(0.16)	
	Sodwana	0.012				3.1	3.0	3.0	2.3	
		(0.017)				(0.53)	(0.6)	(0.15)	(0.25)	
	Aliwal	0.51	0.054		0.073	2.9		2.4		
		(0.066)	(0.0035)		(0.0015)	(0.14)		(0.087)		
		0.29		0.067	0.074			2.1	2.8	2.5
		(0.69)		(0.0052)	(0.0039)			(0.054)	(0.16)	(0.077)

Thorium had the highest concentration in *Sinularia* from Sodwana, and at lowest concentration in *Acropora* from Agalega. Uranium had the highest concentration in *Pocillopora* from Rodrigues. The lowest U value was also from Rodrigues, interestingly enough, in *Sinularia*.

Table 9. Mean concentrations and standard deviation, in brackets, of row 4 transitional metals in corals from the WIO (mg/kg dm).

Transition metals: Row 4										
Element	Location	<i>Sin</i>	<i>Sarco</i>	<i>Eleu</i>	<i>Dendt</i>	<i>Acro</i>	<i>Fun</i>	<i>Poc</i>	<i>Styl</i>	<i>Dendl</i>
Ti	Agalega	2.6 (1.4)	3.3 (1.3)			4.5 (1.2)	5.8 (3.9)		6.8 (1.4)	
		4.5 (1.6)	5.2 (1.1)			2.9 (0.25)	5.3 (2.1)	20 (2.5)	14 (1)	
	Rodrigues	2.8 (0.9)				3.2 (1)	3.8 (1)	23 (4.1)	12 (4.4)	
	SBR	16 (3.1)	6.0 (0.1)		5.3 (0.13)	3.8 (0.8)		18 (4.4)		
	Sodwana	23 (1.5)		11 (0.13)	6.9 (0.18)			8.1 (0.2)	9.3 (0.6)	7.4 (1.9)
	Aliwal									
V	Agalega	0.22 (0.31)	0.16 (0.23)			0.0025 (0.00078)	0.082 (0.11)		0.096 (0.072)	
		0.0012 (0.00039)	0.0013 (0.00093)			0.0037 (0.00041)	0.0052 (0.0045)	1.0 (0.25)	0.48 (0.074)	
	Rodrigues	0.0025 (0.00075)				0.0033 (0.00087)	0.0016 (0.0008)	1.1 (0.34)	0.44 (0.3)	
	SBR	1.7 (0.31)	0.52 (0.039)		0.38 (0.024)	0.31 (0.093)		1.2 (0.27)		
	Sodwana	3.6 (0.22)		0.85 (0.08)	14 (0.66)			0.72 (0.027)	0.95 (0.045)	0.57 (0.13)
	Aliwal									
Cr	Agalega	4.3 (2.1)	6.4 (2.1)			1.8 (1.3)	6.1 (4.2)		13 (2.7)	
		4.5 (0.8)	3.9 (0.4)			0.17 (0.25)	4.7 (2)	26 (5.1)	19 (3.6)	
	Rodrigues	4.0 (0.5)				1.7 (1.4)	4.6 (2.3)	30 (5.8)	18 (5.5)	
	SBR	7.4 (0.4)	6.2 (0.5)		6.8 (0.53)	6.4 (0.03)		22 (5.2)		
	Sodwana	13 (0.7)		8.1 (0.63)	7.8 (0.4)			9.2 (0.1)	8.4 (1.5)	9.2 (1.2)
	Aliwal									
Mn	Agalega	4.9 (6.7)	0.067 (0.046)			0.82 (0.015)	0.53 (0.65)		0.044 (0.026)	
		0.06 (0.026)	0.067 (0.013)			0.099 (0.011)	0.048 (0.011)	17 (5.5)	4.8 (1.9)	
	Rodrigues	0.10 (0.0087)				0.92 (0.0086)	0.067 (0.032)	24 (8.9)	6.4 (4.7)	
	SBR	15.0 (1.6)	4.06 (0.26)		4.6 (0.2)	4.7 (1.2)		27 (8.2)		
	Sodwana	47 (12)		9.3 (3.9)	4.3 (0.6)			9.5 (0.5)	10 (0.65)	8.00 (2.2)
	Aliwal									
Fe	Agalega	430 (160)	510 (96)			630 (84)	870 (260)		940 (180)	
		430 (68)	380 (100)			470 (23)	770 (120)	2200 (280)	1500 (180)	
	Rodrigues	440 (110)				550 (120)	750 (180)	2500 (530)	1400 (370)	
	SBR	1400 (120)	560 (21)		780 (15)	990 (36)		2200 (430)		
	Sodwana	1600 (57)		400 (29)	680 (43)			1200 (21)	1200 (59)	1100 (63)
	Aliwal									
Co	Agalega	0.39 (0.28)	0.31 (0.21)			0.57 (0.13)	1.1 (0.39)		1 (0.31)	
		0.19 (0.15)	0.11 (0.14)			0.012 (0.0019)	0.89 (0.19)	2.9 (0.42)	2 (0.23)	
	Rodrigues	0.27 (0.23)				0.56 (0.24)	0.92 (0.41)	3.5 (0.86)	1.8 (0.55)	
	SBR	17 (0.47)	0.80 (0.026)		1.2 (0.042)	1.59 (0.055)		3.7 (0.71)		
	Sodwana	14 (2.2)		0.66 (0.049)	1.3 (0.1)			1.9 (0.021)	1.9 (0.08)	2 (0.2)
	Aliwal									
Ni	Agalega	4.9 (3.9)	3.8 (2.7)			3.7 (1)	6.7 (4.4)		7.4 (2.2)	
		3 (0.85)	2.6 (1.2)			2.7 (0.87)	5.3 (1.5)	25 (4)	15 (2.2)	
	Rodrigues	1.5 (0.48)				2 (1.3)	4.9 (2.1)	32 (8.3)	15 (5.8)	
	SBR									

	Sodwana	1300 (71)	1.9 (0.1)		3.7 (0.26)	4.1 (0.28)	24 (7.8)		
	Aliwal	630 (120)		1.8 (0.07)	3.3 (0.36)		6 (0.27)	5.7 (0.8)	8.2 (2)
Cu	Agalega	0.13 (0.087)	0.23 (0.0053)			0.23 (0.0053)	0.21 (0.0077)		0.22 (0.028)
	Rodrigues	0.21 (0.016)	0.20 (0.014)			0.21 (0.0006)	0.21 (0.013)	0.21 (0.024)	0.21 (0.04)
	SBR	0.23 (0.011)				0.21 (0.009)	0.23 (0.0058)	0.21 (0.014)	0.23 (0.009)
	Sodwana	4.7 (0.28)	3 (0.43)		2.3 (0.58)	0.98 (0.34)		1.1 (0.22)	
	Aliwal	2.4 (0.33)		4.1 (1.2)	2.1 (0.44)		0.57 (0.17)	0.78 (0.097)	2.2 (1.1)
	Agalega	39 (55)	0.21 (0.0078)			0.16 (0.094)	4 (5.4)		0.22 (0.027)
	Rodrigues	3.3 (4.5)	1 (1.3)			0.17 (0.1)	0.21 (0.02)	0.22 (0.024)	0.22 (0.036)
	SBR	0.22 (0.015)				0.23 (0.0009)	0.11 (0.066)	0.15 (0.07)	0.15 (0.085)
Zn	Sodwana	12 (0.47)	8.6 (1.6)		12 (1.5)	0.016 (0.004)		1.8 (0.6)	
	Aliwal	6.9 (1.4)		52 (1.4)	26 (1)		0.91 (0.56)	1.2 (0.41)	2.8 (1.9)

With the exception of Cr and Fe, all row 4 transitional metals were found at highest concentration at the South African sites.

Table 10. Mean concentrations and standard deviation, in brackets, of row 5 transitional metals in corals from the WIO (mg/kg dm)

Transition metals: Row 5										
Element	Location	<i>Sin</i>	<i>Sarco</i>	<i>Eleu</i>	<i>Dendt</i>	<i>Acro</i>	<i>Fun</i>	<i>Poc</i>	<i>Styl</i>	<i>Dendl</i>
Mo	Agalega	1.5 (2.1)	0.021 (0.00024)			0.02 (0.00025)	0.02 (0.00018)		0.022 (0.00012)	
		0.021 (0.00045)	0.020 (0.0018)			0.02 (0.00007)	0.02 (0.00018)	0.021 (0.00024)	0.021 (0.00072)	
	Rodrigues	0.021 (0.00078)				0.02 (0.0002)	0.015 (0.0074)	0.021 (0.00033)	0.022 (0.00087)	
		0.34 (0.46)	0.021 (0.00086)		0.021 (0.0012)	0.027 (0.0012)		0.027 (0.00017)		
	SBR	0.026 (0.00015)		0.02 (0.00046)	0.025 (0.00032)			0.028 (0.00014)	0.026 (0.0002)	0.027 (0.00078)
	Sodwana									
	Aliwal									
Pd	Agalega	3.3 (0.38)	3.5 (0.31)			8.8 (0.43)	11 (1.1)		11 (0.93)	
		2.6 (0.29)	1.8 (0.83)			8.4 (0.42)	9.4 (0.7)	13 (1.9)	13 (0.81)	
	Rodrigues	3.3 (0.72)				10 (1.6)	11 (1.9)	12 (0.32)	11 (0.45)	
		3.0 (0.16)	2.3 (0.19)		2.9 (0.16)	11 (0.44)		11 (0.47)		
	SBR	1.4 (0.16)		1.5 (0.073)	2.8 (0.2)			11 (0.33)	12 (0.41)	11 (0.48)
	Sodwana									
	Aliwal									
Ag	Agalega	0.18 (0.25)	0.0033 (0.0002)			0.0025 (0.001)	0.0023 (0.00022)		0.0031 (0.0001)	
		0.30 (0.42)	0.0019 (0.001)			0.0028 (0.00017)	0.0024 (0.00012)	0.0035 (0.0004)	0.0038 (0.00031)	
	Rodrigues	0.10 (0.14)				0.0029 (0.00019)	0.0021 (0.00086)	0.0033 (0.00017)	0.43 (0.6)	
		1.5 (0.55)	2.9 (1.9)		2.3 (1.8)	0.80 (0.43)		7.8 (8)		
	SBR	1.1 (0.23)		1.5 (0.58)	1.1 (0.6)			0.5 (0.18)	0.81 (0.17)	6.8 (5.9)
	Sodwana									
	Aliwal									
Cd	Agalega	1.8 (0.9)	0.28 (0.2)			0.17 (0.096)	0.0023 (0.00029)		0.0018 (0.00098)	
		3.6 (2.8)	0.36 (0.26)			0.0044 (0.0042)	0.0025 (0.00032)	0.0021 (0.00039)	0.0029 (0.00037)	
	Rodrigues	2.8 (1.3)				0.001 (0.0003)	0.0016 (0.00025)	0.0027 (0.0001)	0.0022 (0.00033)	
		24 (1.1)	0.75 (0.012)		0.65 (0.023)	0.14 (0.067)		0.043 (0.006)		
	SBR	20 (3.8)		2.1 (0.15)	0.65 (0.053)			0.12 (0.0099)	0.14 (0.0079)	0.44 (0.036)
	Sodwana									
	Aliwal									

There is not a clear pattern regarding the distribution of row 5 transitional metals across the WIO.

Table 11. Mean concentrations and standard deviation, in brackets, of row 6 transitional metals in corals from the WIO (mg/kg dm)

Transition metals: Row 6										
Element	Location	<i>Sin</i>	<i>Sarco</i>	<i>Eleu</i>	<i>Dendt</i>	<i>Acro</i>	<i>Fun</i>	<i>Poc</i>	<i>Styl</i>	<i>Dendl</i>
Pt	Agalega	0.00076 (0.000077)	0.00077 (0.000054)			0.00071 (0.000073)	0.00054 (0.00033)		0.00076 (0.00015)	
		0.00063 (0.00031)	0.00080 (0.000058)			0.00064 (0.00016)	0.00077 (0.000025)	0.00054 (0.00028)	0.0016 (0.001)	
	Rodrigues	0.049 (0.069)				0.0047 (0.0055)	0.00058 (0.00027)	0.00083 (0.000058)	0.00077 (0.000085)	
	SBR	0.094 (0.076)	0.033 (0.023)		0.049 (0.07)	0.024 (0.03)		0.0050 (0.0068)		
	Sodwana	0.033 (0.046)		0.0081 (0.011)	0.033 (0.041)			0.042 (0.06)	0.012 (0.016)	0.013 (0.014)
	Aliwal									
Au	Agalega	0.019 (0.00053)	0.021 (0.00056)			0.02 (0.0012)	0.02 (0.001)		0.022 (0.00015)	
		0.018 (0.001)	0.018 (0.0031)			0.019 (0.00032)	0.019 (0.00078)	0.021 (0.0005)	0.022 (0.00081)	
	Rodrigues	0.021 (0.00023)				0.02 (0.00037)	0.014 (0.0083)	0.021 (0.00066)	0.022 (0.00025)	
	SBR	0.75 (0.89)	0.0038 (0.0027)		0.011 (0.0081)	0.007 (0.00093)		0.0052 (0.0033)		
	Sodwana	0.03 (0.032)		0.0064 (0.0017)	0.32 (0.45)			0.0076 (0.00045)	0.0063 (0.0015)	0.008 (0.00019)
	Aliwal									
Hg	Agalega	0.017 (0.0018)	0.019 (0.000087)			0.017 (0.0012)	0.018 (0.000057)		0.019 (0.00034)	
		0.018 (0.0007)	0.016 (0.0027)			0.018 (0.00015)	0.018 (0.000077)	0.016 (0.00056)	0.019 (0.00035)	
	Rodrigues	0.019 (0.00016)				0.018 (0.00023)	0.012 (0.0083)	0.018 (0.00026)	0.017 (0.0029)	
	SBR	0.19 (0.25)	0.021 (0.0041)		0.021 (0.0012)	0.027 (0.0013)		0.02 (0.0063)		
	Sodwana	0.028 (0.00088)		0.028 (0.00073)	0.027 (0.0015)			0.029 (0.00033)	0.029 (0.0003)	0.018 (0.0077)
	Aliwal									

All row 6 transitional metals were found at highest concentration in *Sinularia* from Sodwana.

Tables 4 to 10 indicate the mean of 31 elements of all nine coral genera from all five collection sites. The highest concentration of a specific metal is highlighted in red. The lowest concentration of a specific metal is highlighted in green. This was done for all 31 metallic elements. After tallying how many times an element was found at the highest concentration for a specific coral, it was expressed as a fraction. The same method was used to express elements of the lowest concentration in corals as a fraction. The fractions were not only calculated for the different corals, but also for the different sampling localities.

However, one alkaline earth metal posed a conundrum for the fraction calculation. Beryllium was found in exactly the same concentration in both *Stylophora* from

Agalega and *Sinularia* from SBR, at 0.0013 mg/kg dm. This also happens to be the highest Be concentration recorded in this study. For this reason, the elements with the highest concentration will be out of a total of 32. The elements with the lowest concentrations did not have any duplicate values and were recorded as a total out of 31.

Sinularia was the coral genus with the highest concentration of most elements (15/32). Strangely enough, it was also the genus with the lowest concentrations for most elements (10/31). The remainder of the corals did not display the same contradiction.

Genera ranked from high to low pertaining the highest concentrations of a particular metallic element, showed the following: *Sinularia* (15/32) > *Pocillopora* (6/32) > *Eleutherobia* (4/32) > *Stylophora* (4/32) > *Sarcophyton*, *Dendronephthya*, and *Acropora* (1/32) > *Fungia* and *Dendrophyllia* (0/32) (Figure 19).

Genera ranked from high to low, pertaining the lowest concentration of a particular metallic element showed the following: *Sinularia* (11/31) > *Acropora* (6/31) > *Pocillopora* (4/31) > *Sarcophyton* and *Fungia* (3/31) > *Eleutherobia* (2/31) > *Dendronephthya* and *Stylophora* (1/31) > *Dendrophyllia* (0/31) (Figure 20).

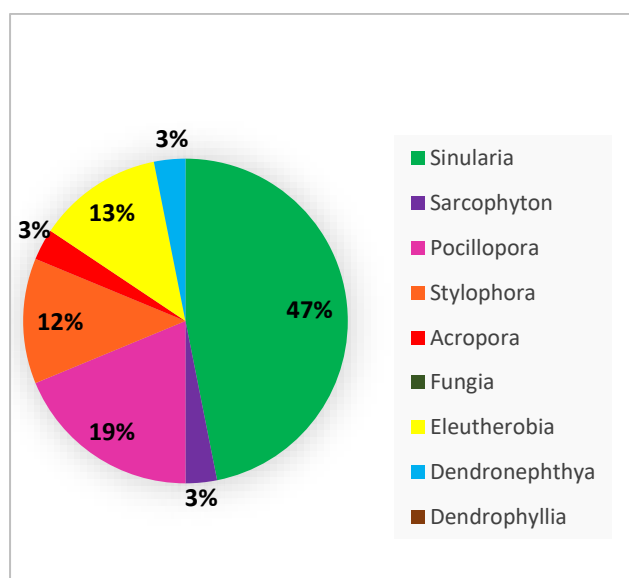


Figure 19. Corals with most elements of the highest concentration

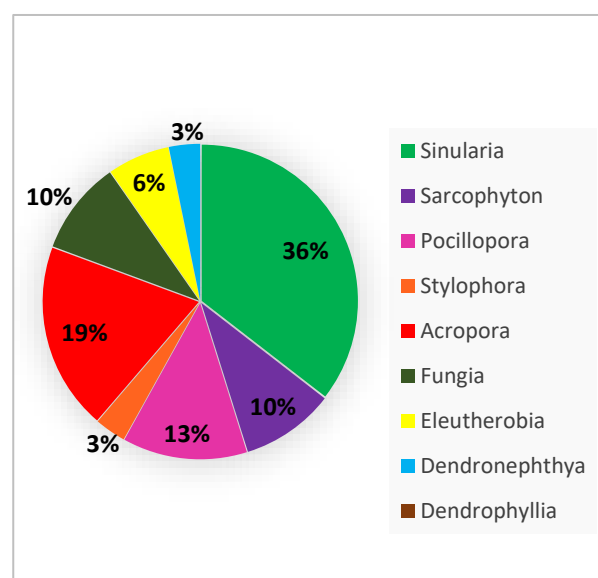


Figure 20. Corals with the most elements of the lowest concentration

Collection sites were similarly ranked from the site with the most elements with the highest concentration to the site with least elements with highest concentration:

Sodwana (11/32) > Aliwal (9/32) > SBR (5/32) > Rodrigues (4/32) > Agalega (3/32) (Figure 20).

The reverse ranking (most elements with the lowest concentration recorded) was the following: Rodrigues (11/31) > Aliwal (7/31) > SBR (5/31) > Agalega and Sodwana (4/31) (Figure 21).

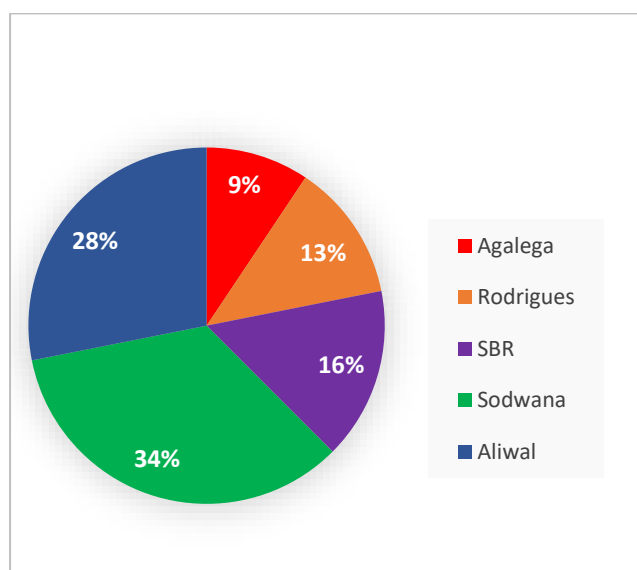


Figure 21. Sites with most elements of the highest concentration

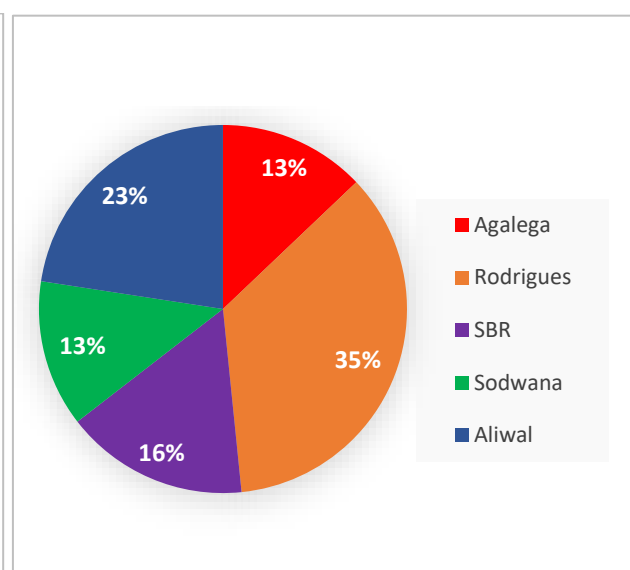


Figure 22. Sites with the most elements of the lowest concentration

3.2 Hard and soft coral

The data for all corals with symbiotic algae were pooled per coral type and per locality. The corals without symbiotic algae –*Eleutherobia*, *Dendronephthya*, and *Dendrophyllia*– were not be considered for this analysis in order to keep all variables constant. The following groups were analysed: Mascarene hard coral (MascHard), Mascarene soft coral (MascSoft), South African hard coral (SAHard), and South African soft coral (SASoft). Hard corals used for this analysis were: *Acropora*, *Pocillopora*, *Stylophora*, and *Fungia*; soft corals were *Sinularia* and *Sarcophyton*.

Figure 23 is a collection of all scatterplot graphs of hard versus soft coral comparisons. Selected individual outlier values were removed for a more accurate view of the relationship of the two coral types relative to each other. Three stars (***) indicated a

p value, ≤ 0.001 for an unpaired, two way, Mann-Whitney, non-parametric test. Two stars (**) indicated a p value between 0.001 and 0.05. One star (*) indicated a $p \leq 0.05$.

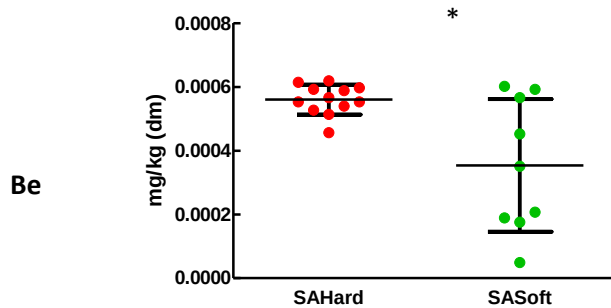


Fig 23.1.a Be in SAHard and SASoft corals

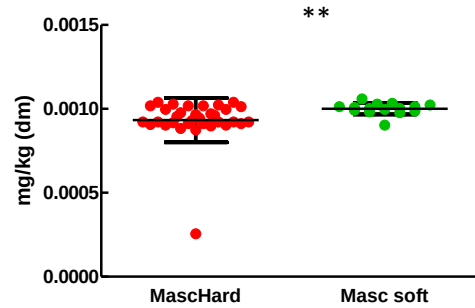


Fig 23.1.b Be in MascHard and MascSoft corals

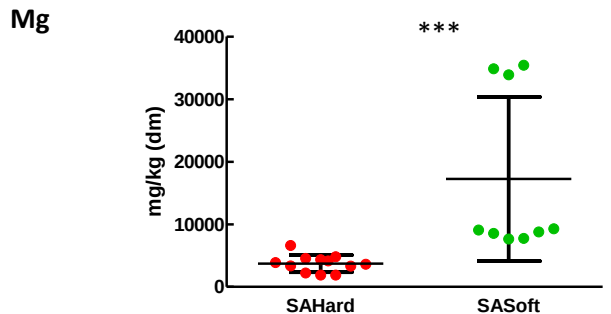


Fig 23.2.a Mg in SAHard and SASoft corals

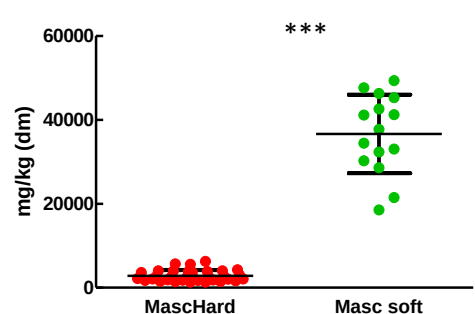


Fig 23.2.b Mg in MascHard and MascSoft corals

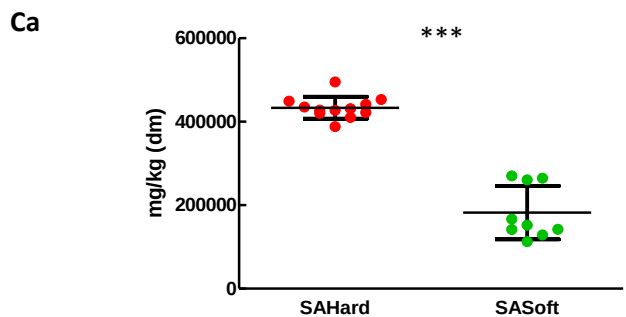


Fig 23.3.a Ca in in SAHard and SASoft corals

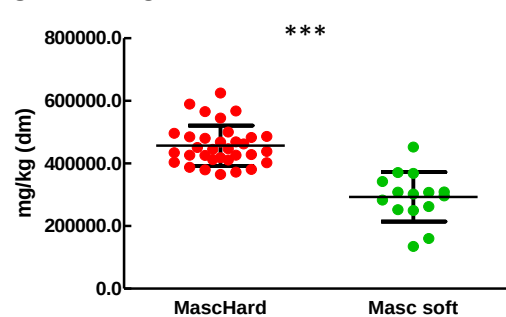


Fig 23.3.b Ca in MascHard and MascSoft corals

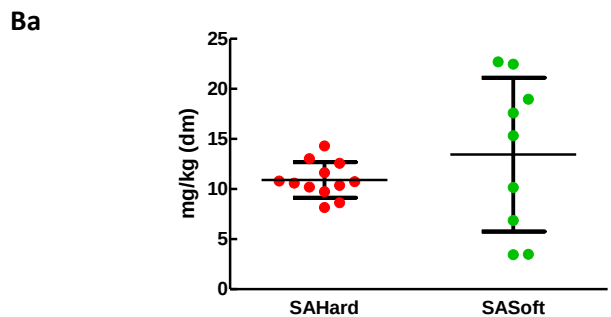


Fig 23.4.a Ba in SAHard and SASoft corals

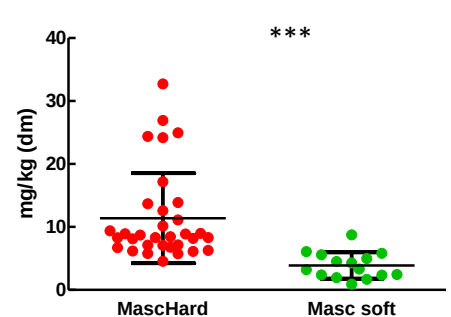


Fig 23.4.b Ba in MascHard and MascSoft corals

B

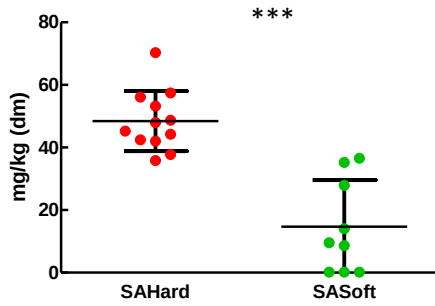


Fig 23.5.a B in in SAHard and SASoft corals

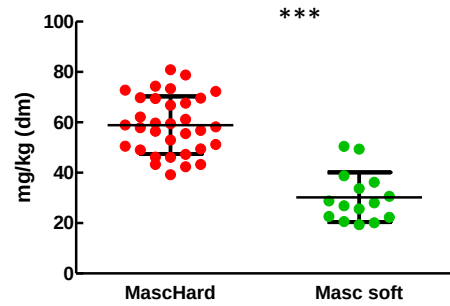


Fig 23.5.b B in MascHard and MascSoft corals

As

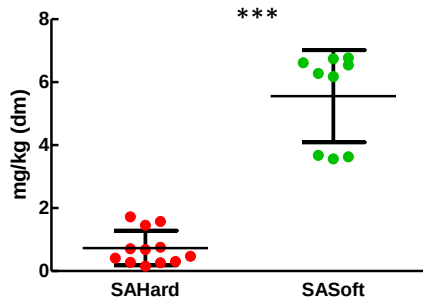


Fig 23.6.a As in SAHard and SASoft corals

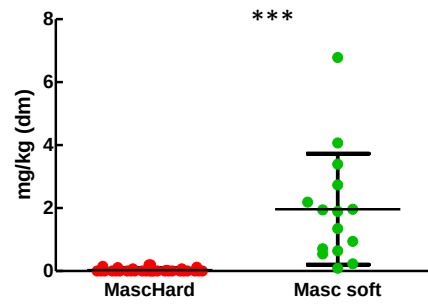


Fig 23.6.b As in MascHard and MascSoft corals

Sb

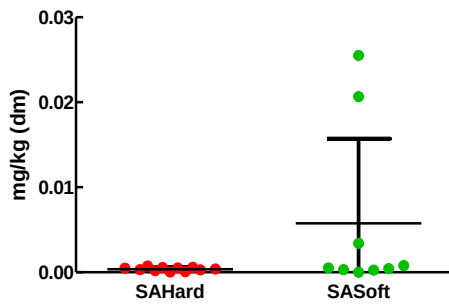


Fig 23.7.a Sb in SAHard and SASoft corals

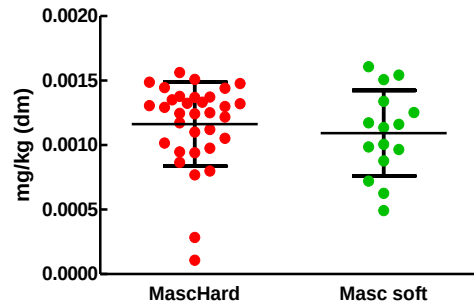


Fig 23.7.b Sb in MascHard and MascSoft corals

Se

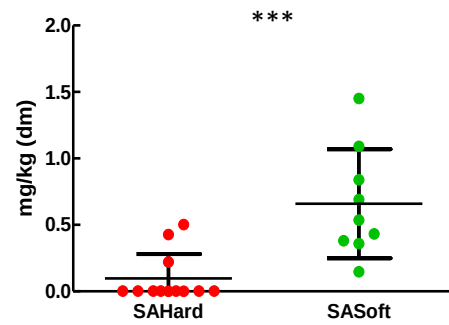


Fig 23.8.a Se in SAHard and SASoft corals

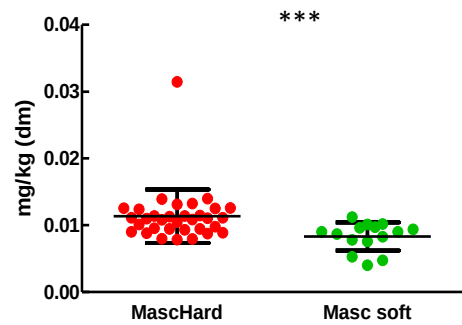


Fig 23.8.b Se in MascHard and MascSoft corals

Al

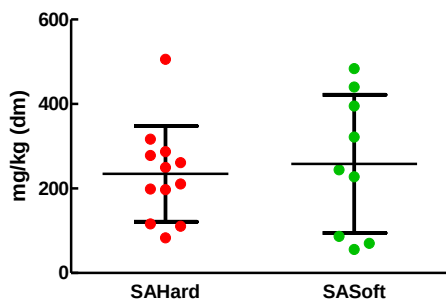


Fig 23.9.a Al in SAHard and SASoft corals

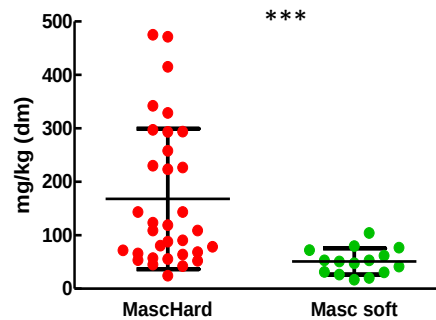


Fig 23.9.b Al in MascHard and MascSoft corals

Tl

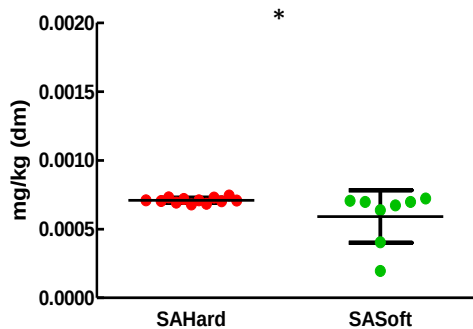


Fig 23.10.a Tl in SAHard and SASoft corals

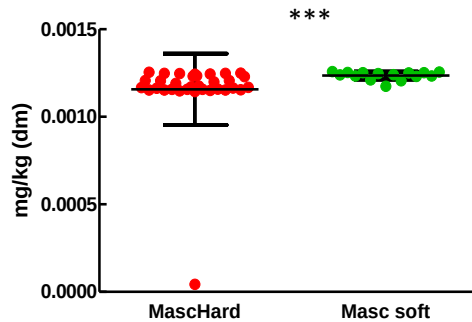


Fig 23.10.b Tl in MascHard and MascSoft corals

Pb

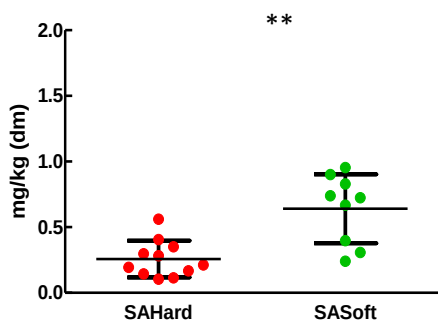


Fig 23.11.a Pb in SAHard and SASoft corals

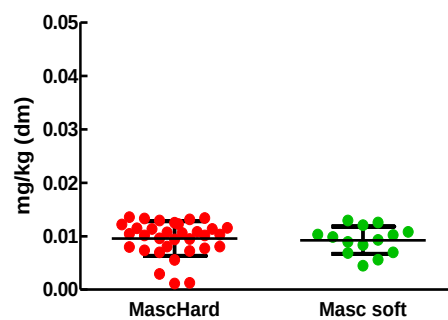


Fig 23.11.b Pb in MascHard and MascSoft corals

Bi

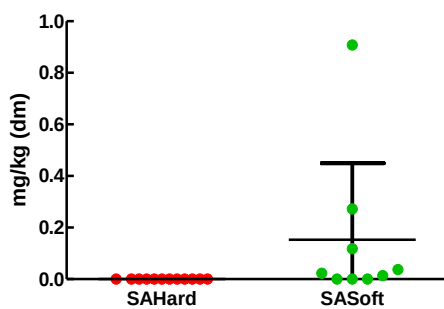


Fig 23.12.a Bi in SAHard and SASoft corals

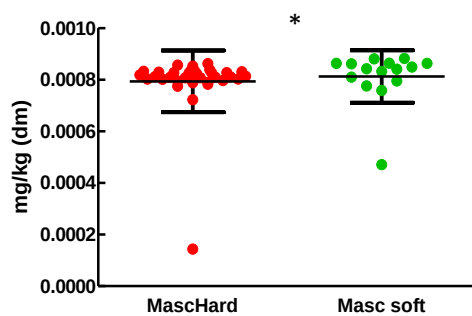


Fig 23.12.b Bi in MascHard and MascSoft corals

Th

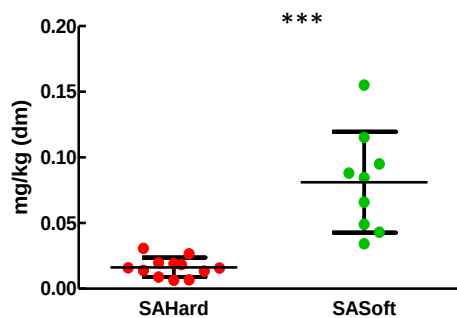


Fig 23.13.a Th in SAHard and SASoft corals

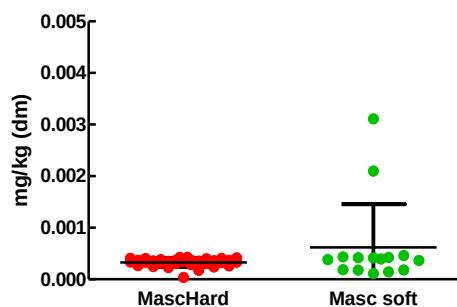


Fig 23.13.b Th in MascHard and MascSoft corals

U

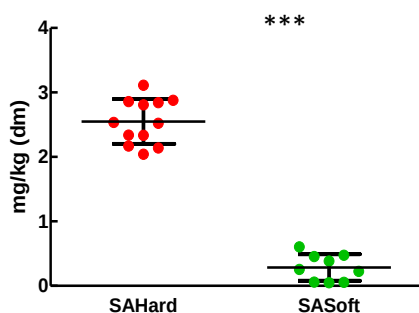


Fig 23.14.a U in SAHard and SASoft corals

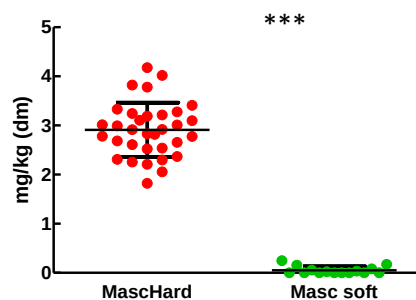


Fig 23.14.b U in MascHard and MascSoft corals

Ti

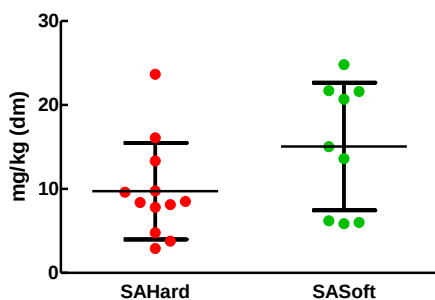


Fig 23.15.a Ti in SAHard and SASoft corals

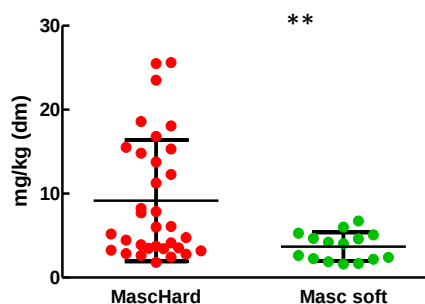


Fig 23.15.b Ti in MascHard and MascSoft corals

V

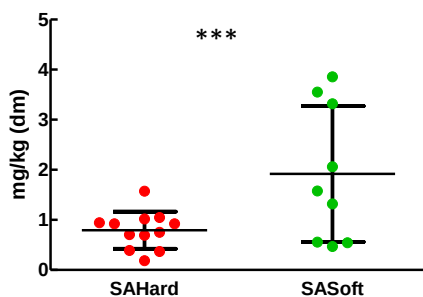


Fig 23.16.a V in SAHard and SASoft corals

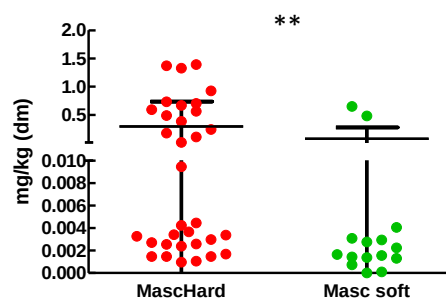


Fig 23.16.b V in MascHard and MascSoft corals

Cr

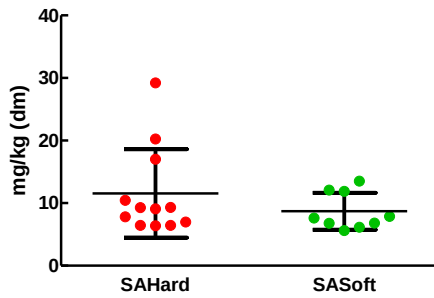


Fig 23.17.a Cr in SAHard and SASoft corals

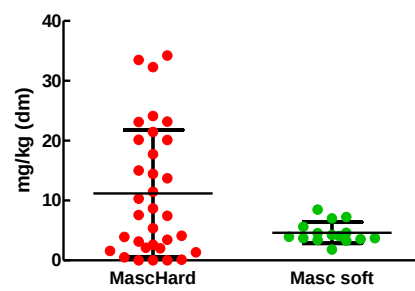


Fig 23.17.b Cr in MascHard and MascSoft corals

Mn

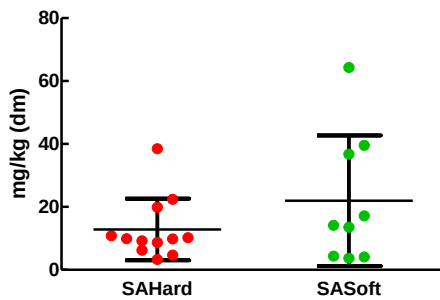


Fig 23.18.a Mn in SAHard and SASoft corals

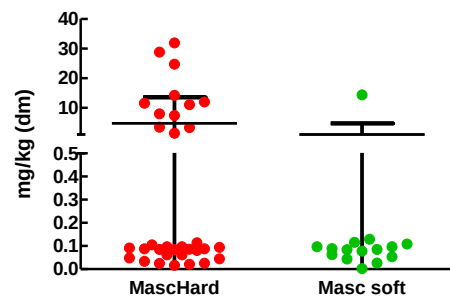


Fig 23.19.b Mn in MascHard and MascSoft corals

Fe

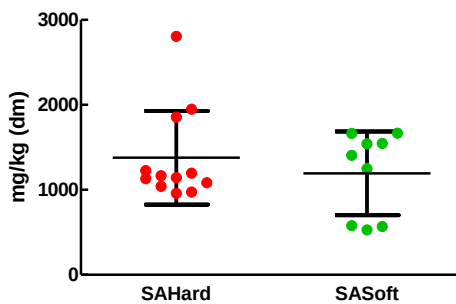


Fig 23.19.a Fe in SAHard and SASoft corals

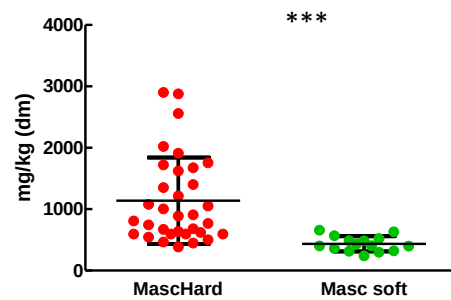


Fig 23.19.b Fe in MascHard and MascSoft corals

Co

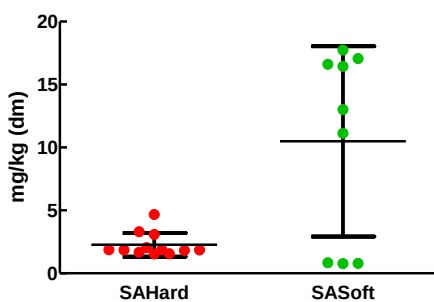


Fig 23.20.a Co in SAHard and SASoft corals

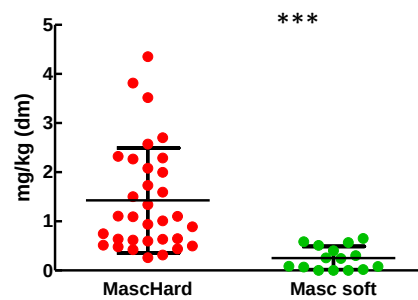
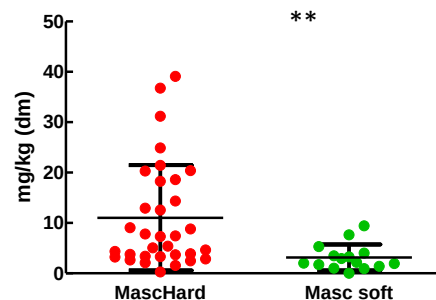
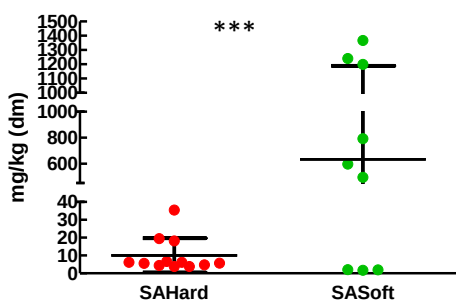


Fig 23.20.b Co in MascHard and MascSoft corals

Ni



Cu

Fig 23.21.a Ni in SAHard and SASoft corals

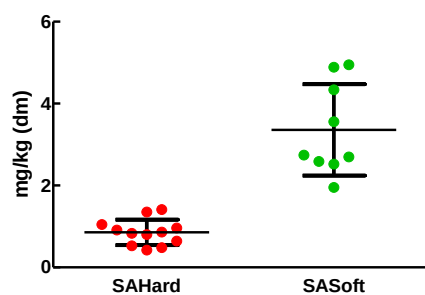
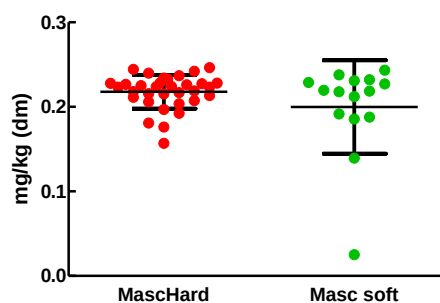


Fig 23.21.b Ni in MascHard and MascSoft corals



Zn

Fig 23.22.a Cu in SAHard and SASoft corals

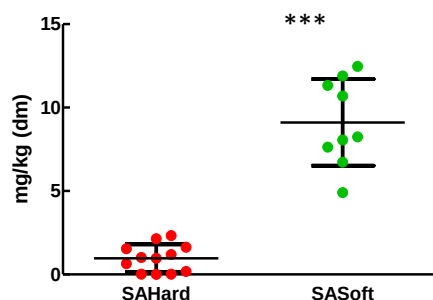
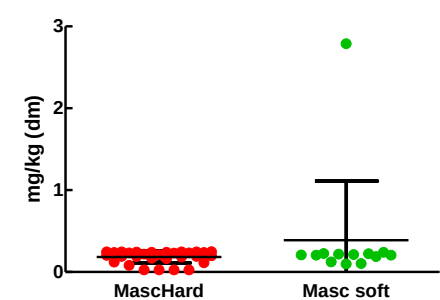


Fig 23.22.b Cu in MascHard and MascSoft corals



Mo

Fig 23.23.a Zn in SAHard and SASoft corals

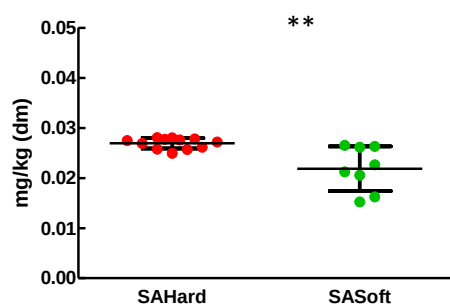
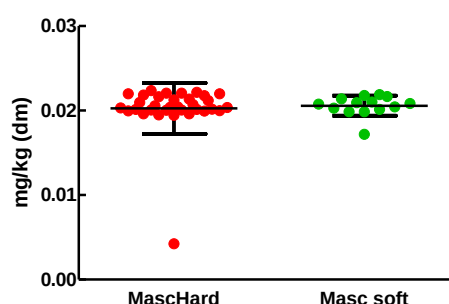


Fig 23.23.b Zn in MascHard and MascSoft corals



Pd

Fig 23.24.a Mo in SAHard and SASoft corals

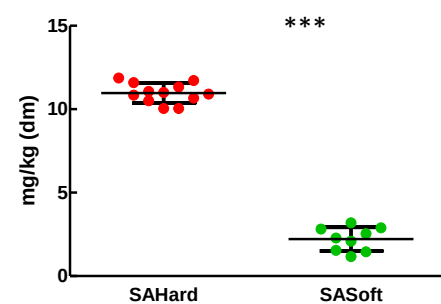
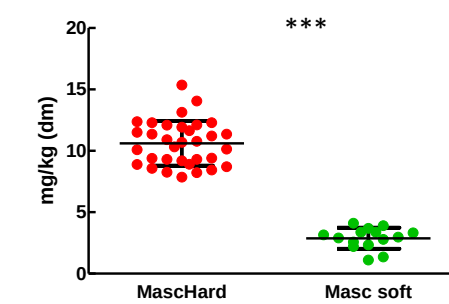


Fig 23.24.b Mo in MascHard and MascSoft corals



Ag

Fig 23.25.a Pd in SAHard and SASoft corals

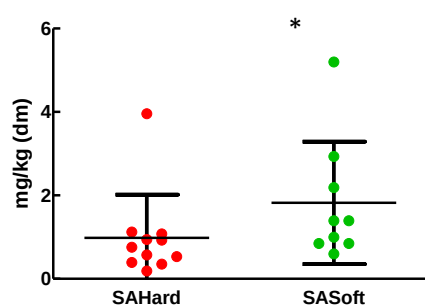


Fig 23.25.b Pd in MascHard and MascSoft corals

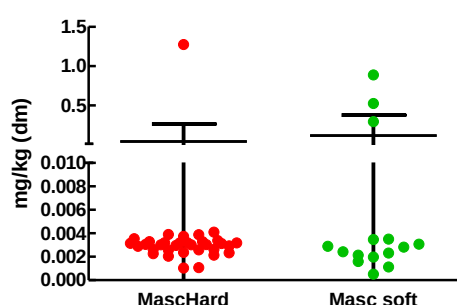


Fig 23.26.a Ag in SAHard and SASoft corals

Fig 23.26.b Ag in MascHard and MascSoft corals

Cd

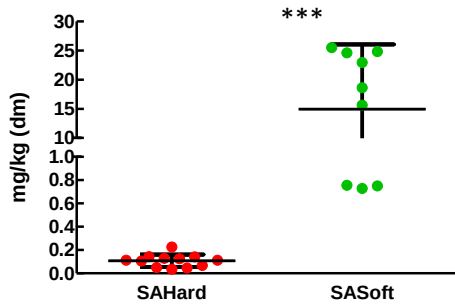


Fig 23.27.a Cd in SAHard and SASoft corals

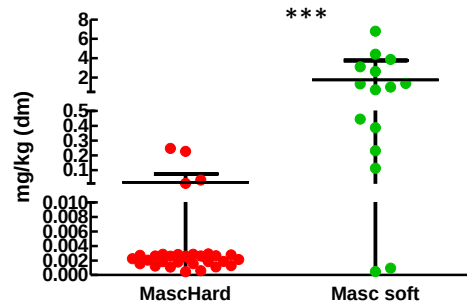


Fig 23.27.b Cd in MascHard and MascSoft corals

Pt

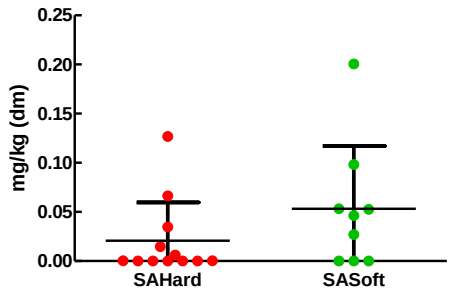


Fig 23.28.a Pt in SAHard and SASoft corals

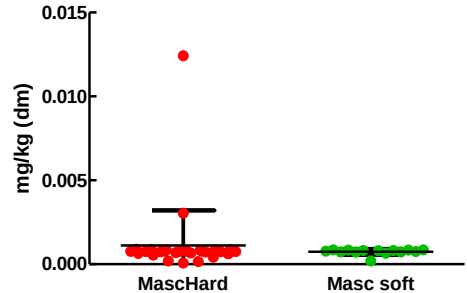


Fig 23.28.b Pt in MascHard and MascSoft corals

Au

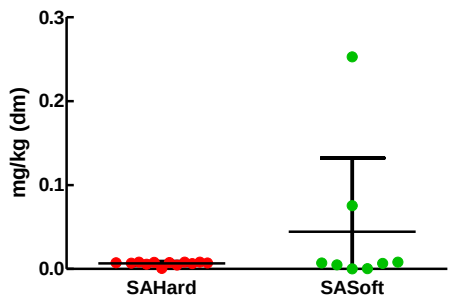


Fig 23.29.a Au in SAHard and SASoft corals

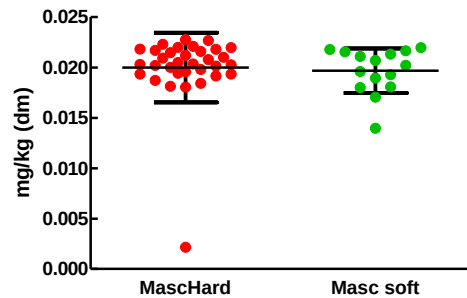


Fig 23.29.b Au in MascHard and MascSoft corals

Hg

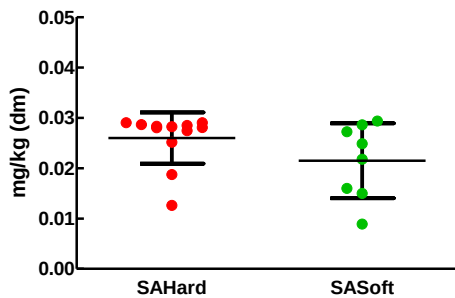


Fig 23.30.a Hg in SAHard and SASoft corals

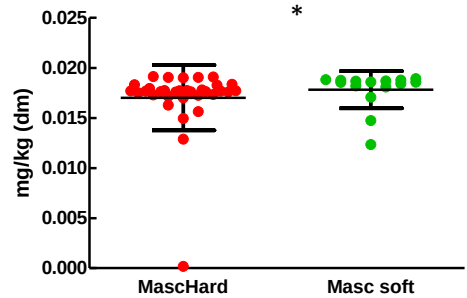


Fig 23.30.b Hg in MascHard and MascSoft corals

Figure 23. Scatterplots and t-tests comparing the hard and soft corals of each region with each other. SAHard versus SASoft corals and MascHard versus MascSoft corals are depicted in scatterplot diagrams. The means and standard deviations are shown.

Figure 24 showed the results of an NMS analysis of the coral type and metallic element profile.

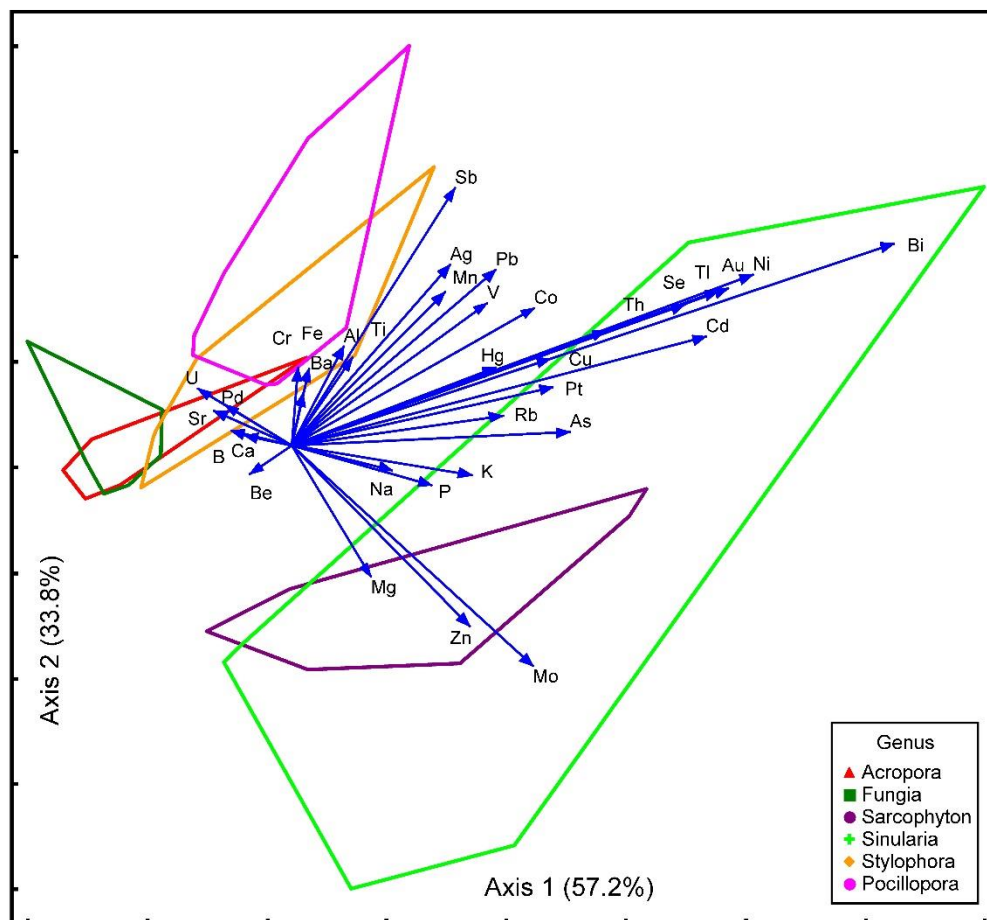


Figure 24. NMS ordination of the distribution of metals and metalloids in corals from the WIO. Convex hulls represent symbiotic coral genera. Axis 1 explained 57.2% of the ordination, and Axis 2, 33.8%. *Acropora*, *Fungia*, *Stylophora*, and *Pocillopora* are hard corals. *Sinularia* and *Sarcophyton* are soft corals.

When the NMS graph (Figure 24) is compared with Figure 23, a correlation was seen. Elements that ordinated between convex hulls, or where the vector was relatively short, were elements that did not have any (or a low) statistical significance in the t-tests.

Sinularia and *Sarcophyton* showed large overlap. Save for *Fungia* and *Pocillopora*, all the hard corals overlapped to an extent. All convex hulls of hard corals were small,

with the two family Pocilloporidae genera– *Stylophora* and *Pocillopora*– being the largest. There was no overlap between the hard and soft genera.

The convex hulls of the hard corals were smaller than that of the soft coral. A smaller convex hull indicates less variation within the grouping. The larger hull of the soft coral indicate a larger variability within the grouping. Figures 19 and 20, showed that *Sinularia* was the coral with the most elements of the highest concentration, as well as the coral with the most elements of the lowest concentration. The large convex hull could be attributed to the contrasting results of *Sinularia* having the most elements of both the highest and lowest concentration.

3.3 Mascarene Islands versus South African sites

All symbiotic hard corals collected from the Mascarene basin were grouped together. This means all *Acropora*, *Fungia*, *Pocillopora*, and *Stylophora* from Agalega, Rodrigues, and SBR were grouped as MascHard. All the above-mentioned corals, save *Fungia* from Sodwana and Aliwal, were grouped as SAHard. *Sinularia* and *Sarcophyton* from Agalega, Rodrigues, and SBR were grouped as MascSoft, and the same corals from Sodwana and Aliwal were grouped as SASoft. Selected individual outlier values were excluded from this analysis to provide a more accurate representation of how the metallic element contents of the Mascarene Islands compared with the South African sites. Three stars (***) indicated a p value, ≤ 0.001 for an unpaired, two way, Mann-Whitney, non-parametric test. Two stars (**) indicated a p value between 0.001 and 0.05. One star (*) indicated a p ≤ 0.05 .

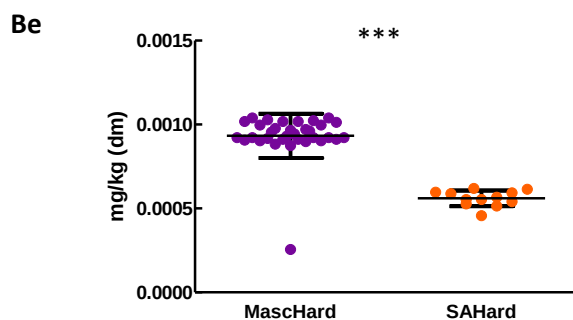


Fig 25.1.a Be in MascHard and SAHard corals

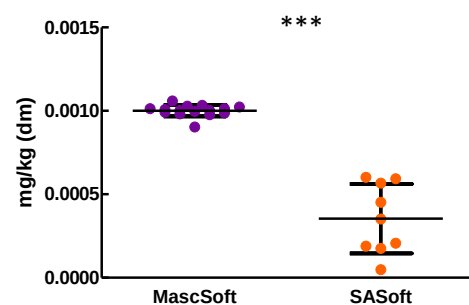


Fig 25.1.b Be in MascSoft and SASoft corals

Mg

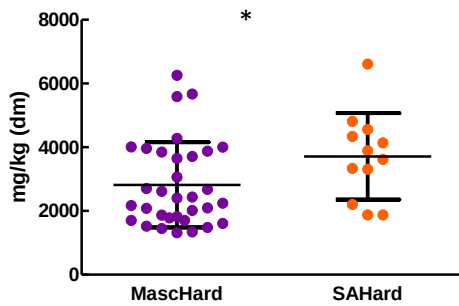


Fig 25.2.a Mg in MascHard and SAHard corals

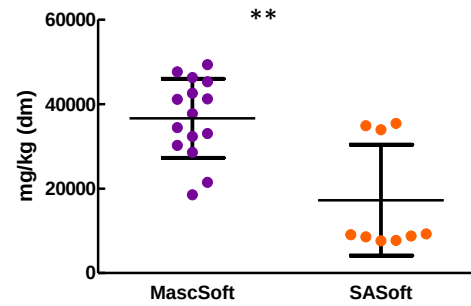


Fig 25.2.b Mg in MascSoft and SASoft corals

Ca

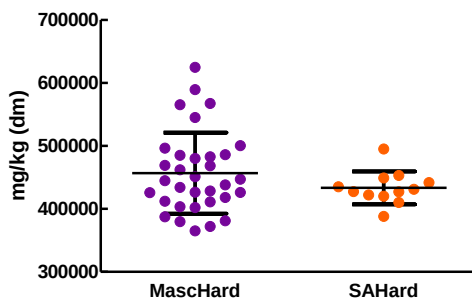


Fig 25.3.a Ca in MascHard and SAHard corals

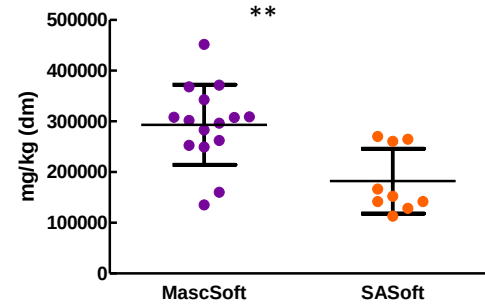


Fig 25.3.b Ca in MascSoft and SASoft corals

Sr

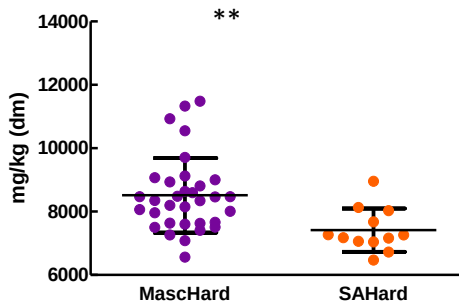


Fig 25.4.a Sr in MascHard and SAHard corals

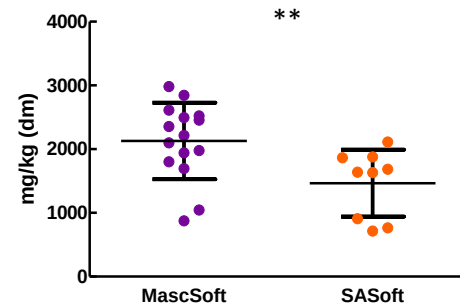


Fig 25.4.b Sr in MascSoft and SASoft corals

Ba

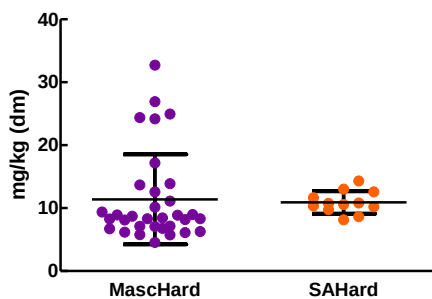


Fig 25.5.a Ba in MascHard and SAHard corals

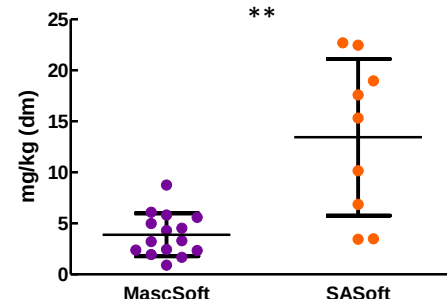
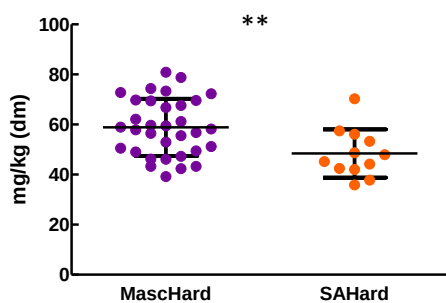
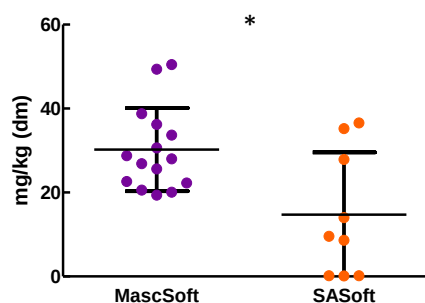
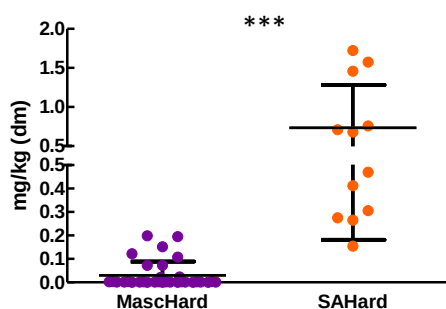
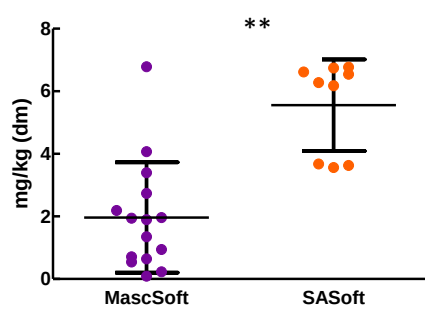
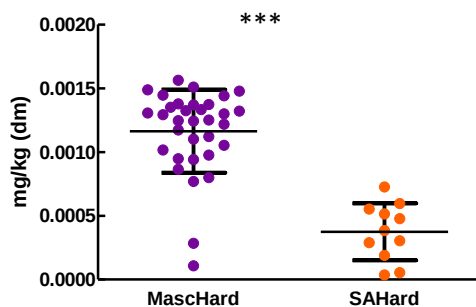
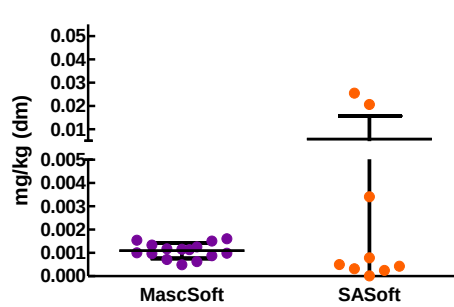
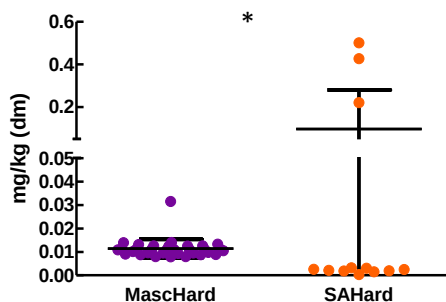
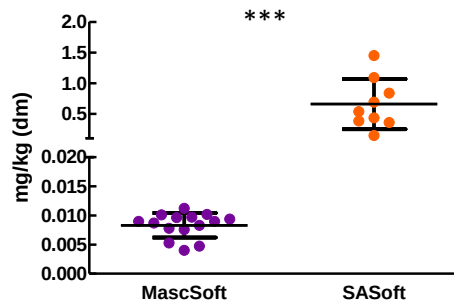


Fig 25.5.b Ba in MascSoft and SASoft corals

B**Fig 25.6.a** B in MascHard and SAHard corals**Fig 25.6.b** B in MascSoft and SASoft corals**As****Fig 25.7.a** As in MascHard and SAHard corals**Fig 25.7.b** As in MascSoft and SASoft corals**Sb****Fig 25.8.a** Sb in MascHard and SAHard corals**Fig 25.8.b** Sb in MascSoft and SASoft corals**Se****Fig 25.9.a** Se in MascHard and SAHard corals**Fig 25.9.b** Se in MascSoft and SASoft corals

Al

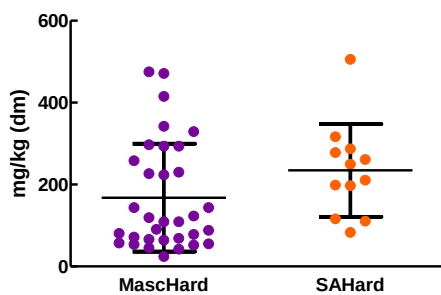


Fig 25.10.a Al in MascHard and SAHard corals

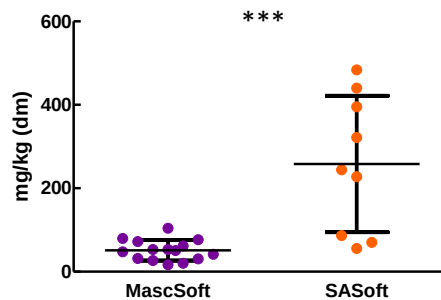


Fig 25.10.b Al in MascSoft and SASoft corals

Tl

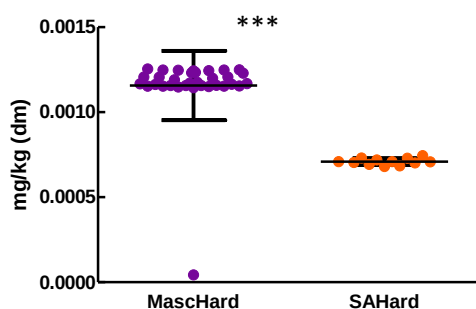


Fig 25.11.a Tl in MascHard and SAHard corals

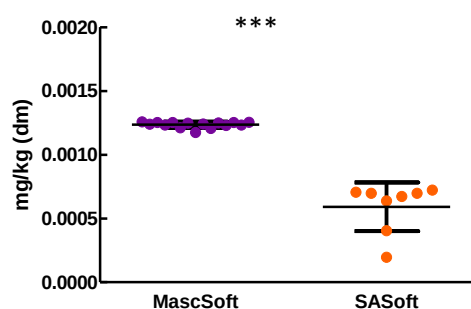


Fig 25.11.b Tl in MascSoft and SASoft corals

Pb

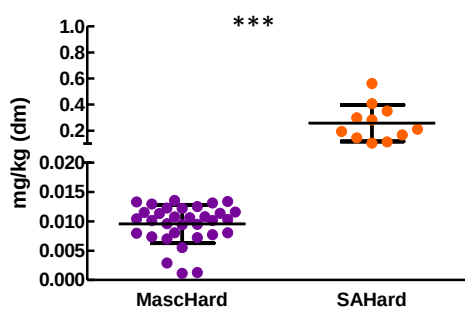


Fig 25.12.a Pb in MascHard and SAHard corals

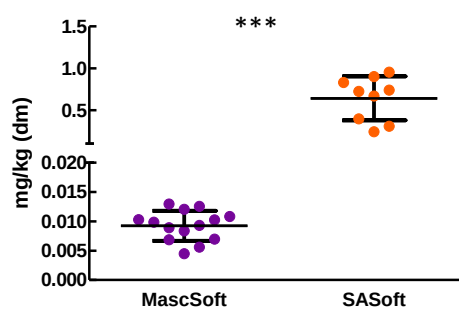


Fig 25.12.b Pb in MascSoft and SASoft corals

Bi

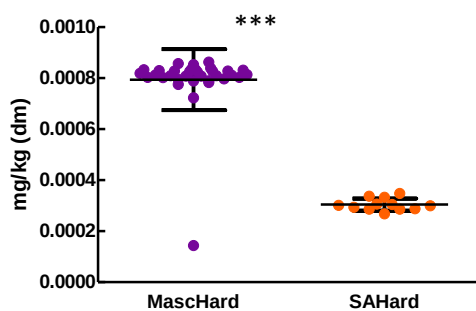


Fig 25.13.a Bi in MascHard and SAHard corals

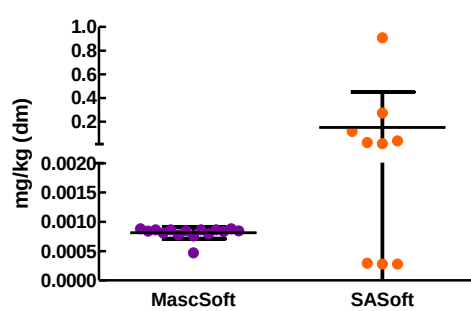


Fig 25.13.b Bi in MascSoft and SASoft corals

Th

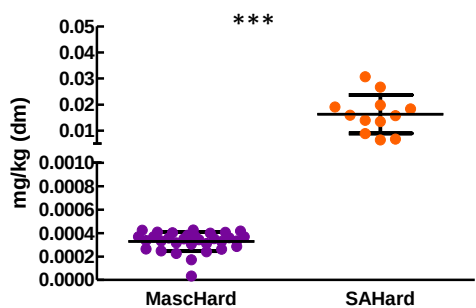


Fig 25.14.a Th in MascHard and SAHard corals

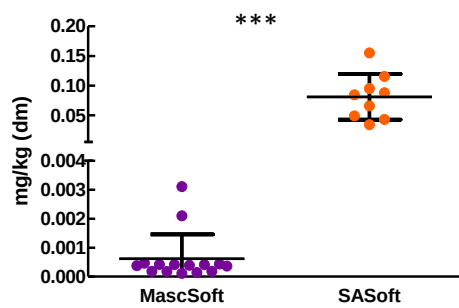


Fig 25.14.b Th in MascSoft and SASoft corals

U

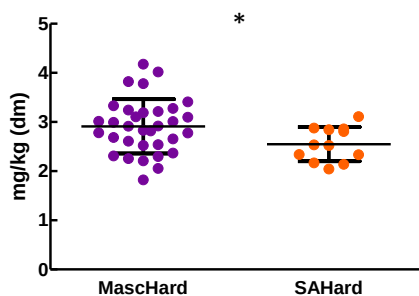


Fig 25.15.a U in MascHard and SAHard corals

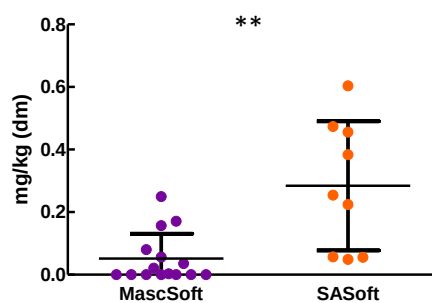


Fig 25.15.b U in MascSoft and SASoft corals

Ti

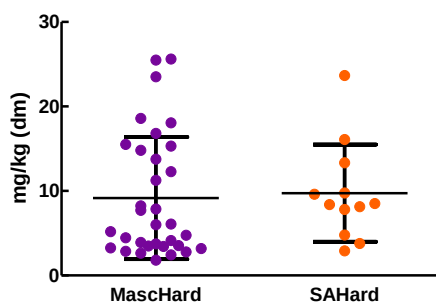


Fig 25.16.a Ti in MascHard and SAHard corals

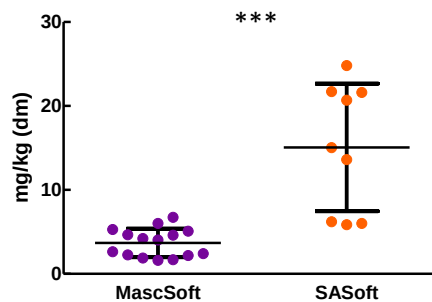


Fig 25.16.b Ti in MascSoft and SASoft corals

V

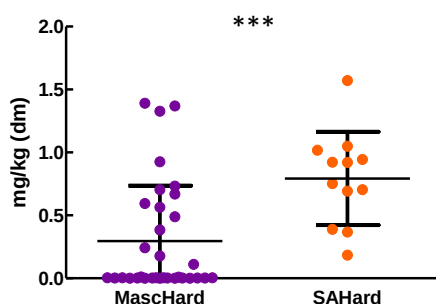


Fig 25.17.a V in MascHard and SAHard corals

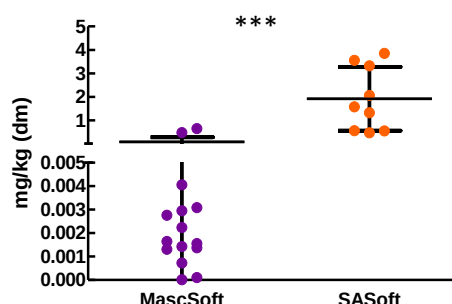


Fig 25.17.b V in MascSoft and SASoft corals

Cr

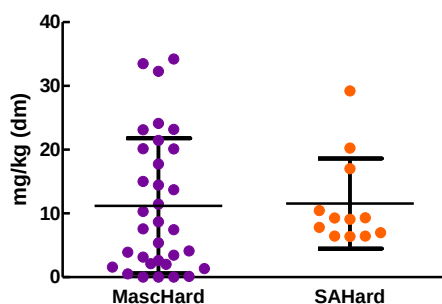


Fig 25.18.a Cr in MascHard and SAHard corals

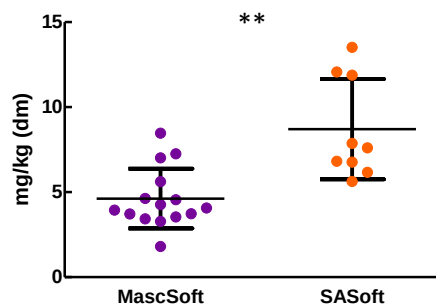


Fig 25.18.b Cr in MascSoft and SASoft corals

Mn

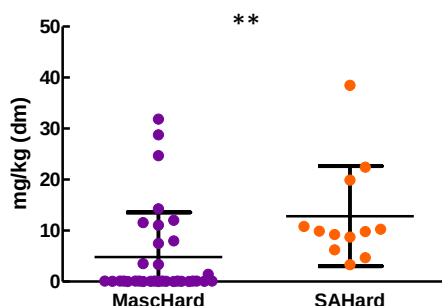


Fig 25.19.a Mn in MascHard and SAHard corals

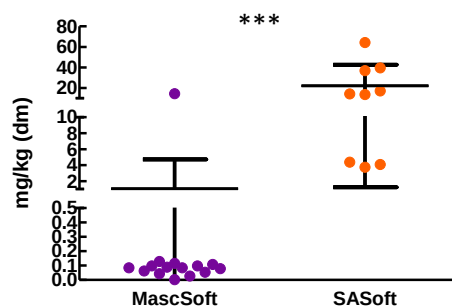


Fig 25.19.b Mn in MascSoft and SASoft corals

Fe

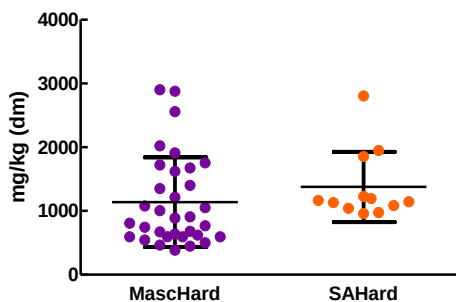


Fig 25.20.a Fe in MascHard and SAHard corals

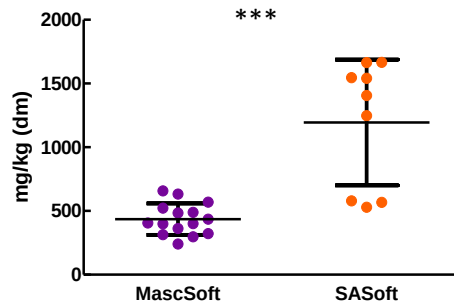


Fig 25.20.a Fe in MascSoft and SASoft corals

Co

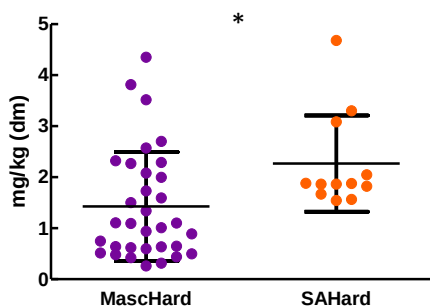


Fig 25.21.a Co in MascHard and SAHard corals

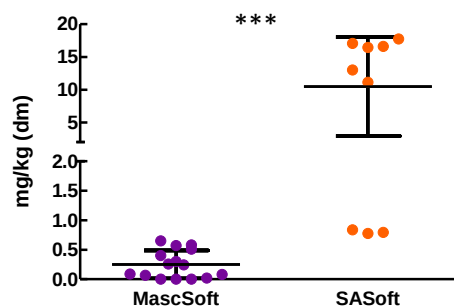


Fig 25.21.b Co in MascSoft and SASoft corals

Ni

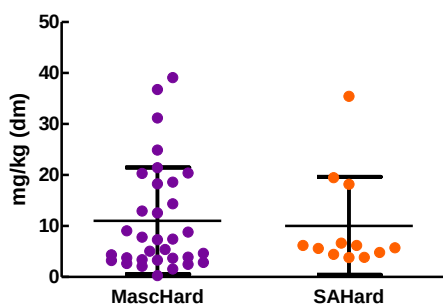


Fig 25.22.a Ni in MascHard and SAHard corals

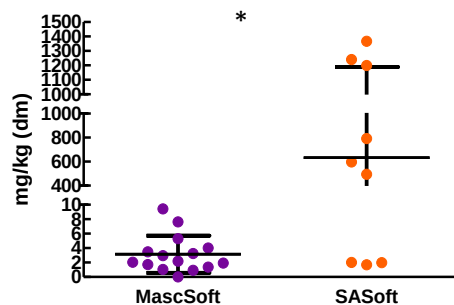


Fig 25.22.b Ni in MascSoft and SASoft corals

Cu

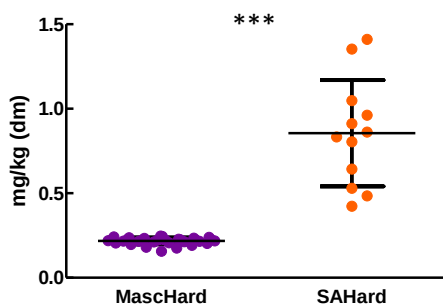


Fig 25.23.a Cu in MascHard and SAHard corals

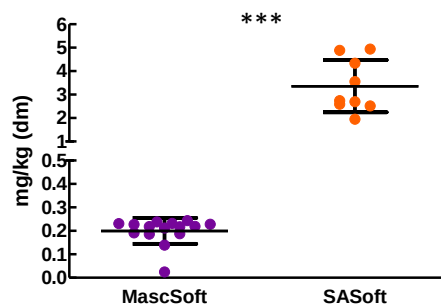


Fig 25.23.b Cu in MascSoft and SASoft corals

Zn

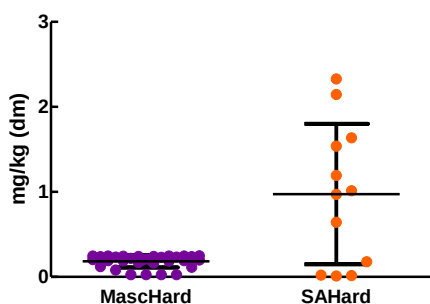


Fig 25.24.a Zn in MascHard and SAHard corals

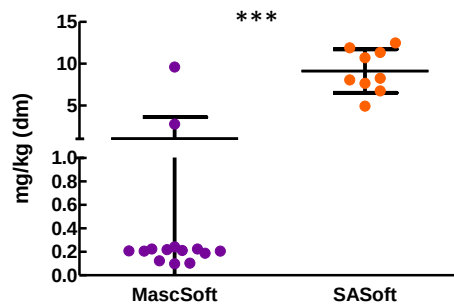


Fig 25.24.b Zn in MascSoft and SASoft corals

Mo

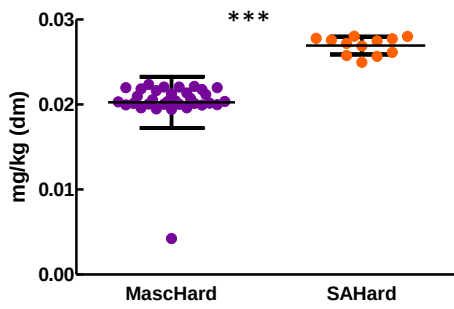


Fig 25.25.a Mo in MascHard and SAHard corals

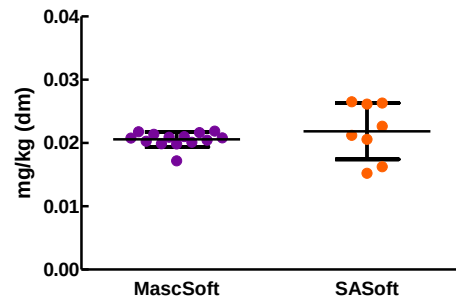


Fig.25.b Mo in MascSoft and SASoft corals

Pd

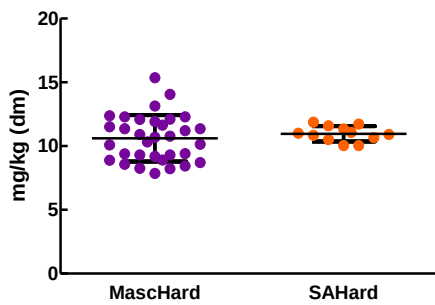


Fig 25.26.a Pd in MascHard and SAHard corals

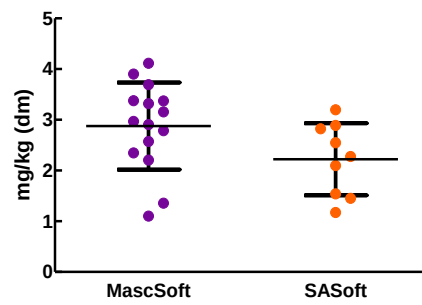


Fig 25.26.b Pd in MascSoft and SASoft corals

Ag

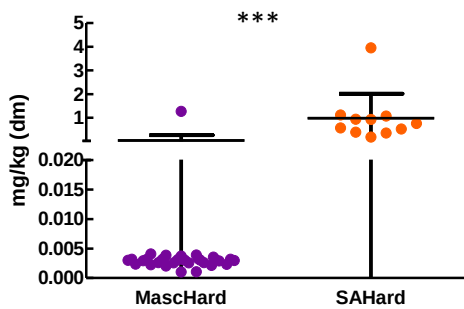


Fig 25.27.a Ag in MascHard and SAHard corals

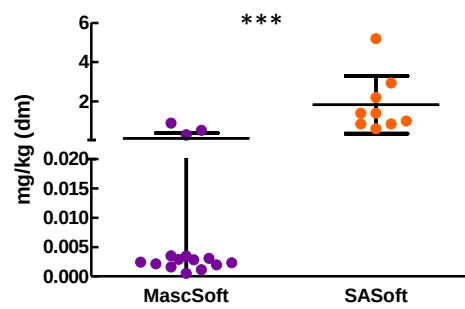


Fig 25.27.b Ag in MascSoft and SASoft corals

Cd

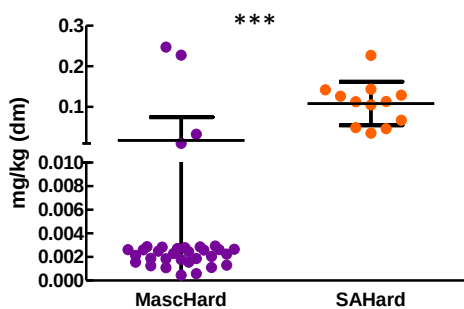


Fig 25.28.a Cd in MascHard and SAHard corals

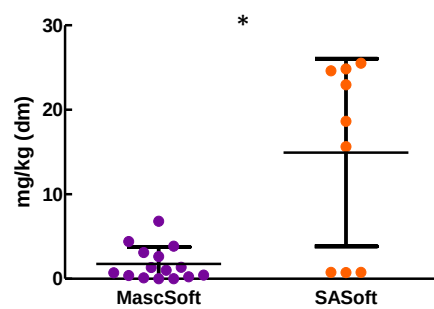


Fig 25.28.b Cd in MascSoft and SASoft corals

Pt

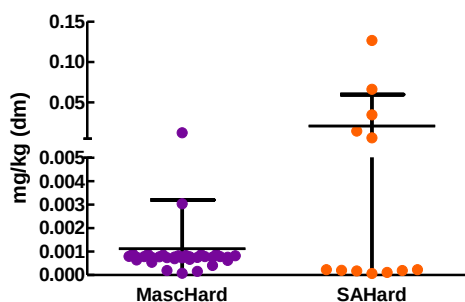


Fig 25.29.a Pt in MascHard and SAHard corals

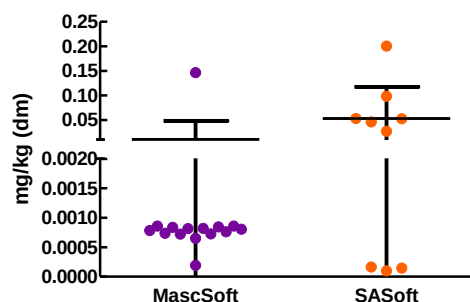


Fig 25.29.b Pt in MascSoft and SASoft corals

Au

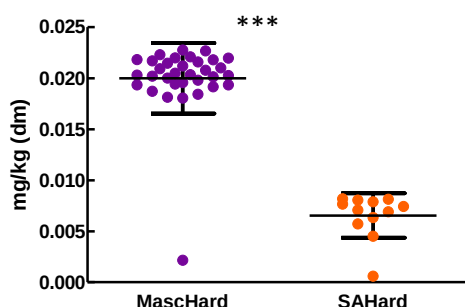


Fig 25.30.a Au in MascHard and SAHard corals

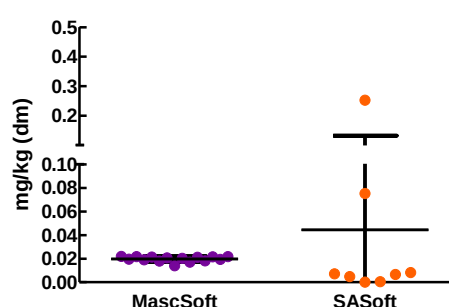


Fig 25.30.b Au in MascSoft and SASoft corals

Hg

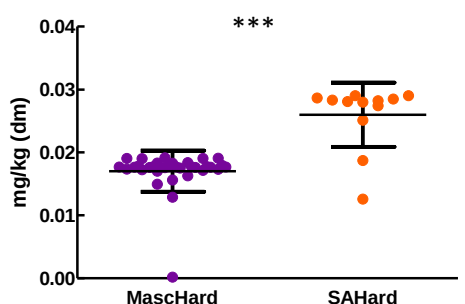


Fig 25.31.a Hg in MascHard and SAHard corals

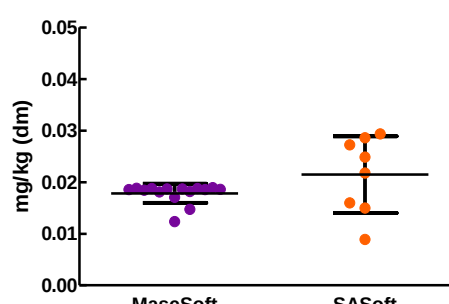


Fig 25.31.b Hg in MascSoft and SASoft corals

Figure 25. Scatterplots and t-tests comparing the metallic element concentration in hard and soft corals of each region with each other. MascHard versus SAHard and MascSoft versus SASoft corals were depicted in scatterplot diagrams. The means and standard deviations were shown.

Figure 26 showed the results of an NMS analysis of the sampling sites and metallic element profile.

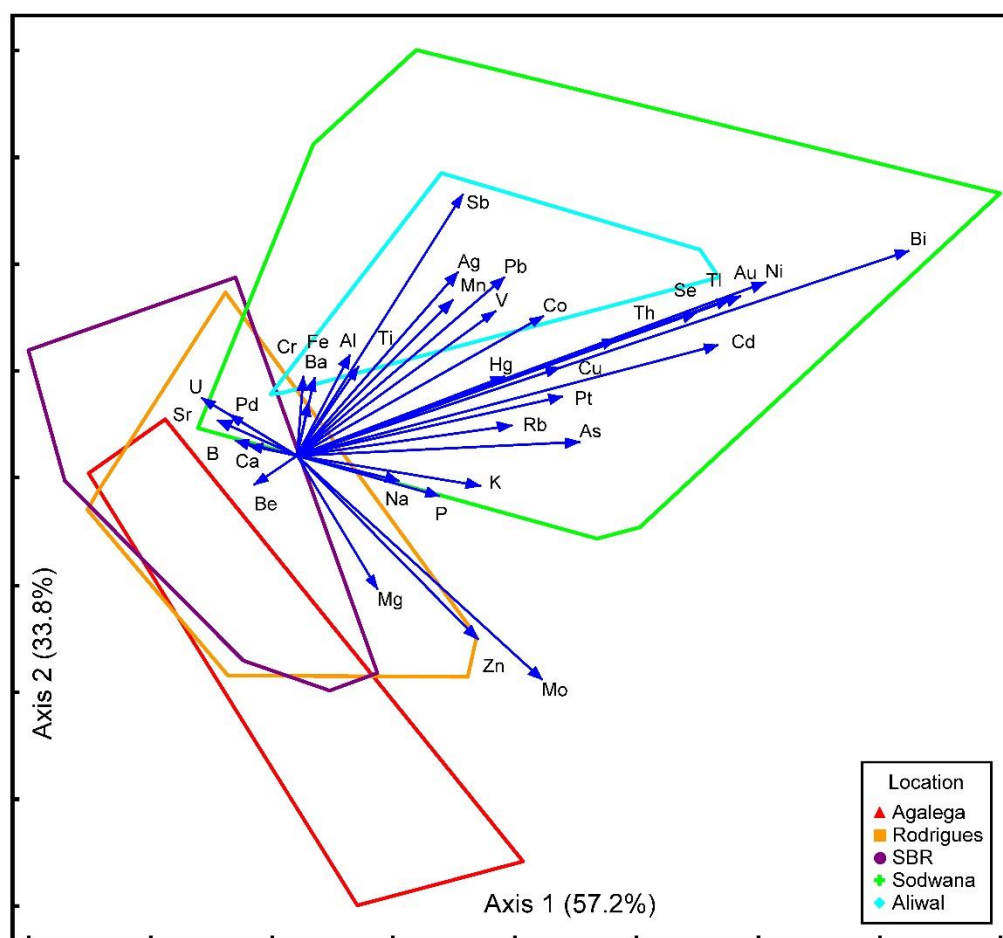


Figure 26 NMS ordination of the distribution of metals and metalloids in corals from the WIO. The convex hulls represent the different sampling localities. Axis 1 explained 57.2% of the ordination, and Axis 2, 33.8%.

There was some overlap between the convex hulls of the different sampling localities. The Mascarene Islands showed a great overlap. The convex hulls of the Mascarene Islands were relatively the same size. Agalega did not overlap with the convex hulls of the South African sites. The convex hulls of Rodrigues and SBR marginally overlapped with Aliwal, and with Sodwana to a greater extent. The convex hulls of Sodwana and Aliwal showed overlapped to the point where Aliwal was included within the large convex hull of Sodwana.

CHAPTER 4: DISCUSSION

This chapter is dedicated to a discussion of the implications of metals and metalloids concentrations found in corals from the WIO, as indicated in Chapter 3.

4.1 General discussion

In order to facilitate the discussion, the results provided in Chapter 3 above, were discussed from different perspectives. In the first instance the results pertaining to the concentration of metallic elements in different symbiotic coral types, namely hard and soft corals, were compared. Thereafter the results pertaining to the concentration of metallic elements present in all symbiotic corals from the different sampling regions were compared. Factors influencing bioaccumulation of metals in corals, different pathways of accumulation of metallic elements into coral tissue and skeleton lattice, a comparison with other studies, and the effects of metallic elements on corals are also themes discussed in this chapter.

4.2 Metals and metalloids in different coral types

The NMS graph in Figure 27 is a simplification of Figure 24 as found in Section 3.1. In order to compile this graph, the results of the symbiotic soft corals (*Sinularia* and *Sarcophyton*) from all five sampling localities were grouped into one convex hull. The results of the symbiotic hard corals (*Acropora*, *Fungia*, *Pocillopora* and *Stylophora*) of all localities were similarly grouped into one convex hull.

All elements of concern that were discussed in this section are metals. Most of the metalloids reported on in Chapter 3 are prevalent in the azooxanthellate soft coral, *Eleutherobia*.

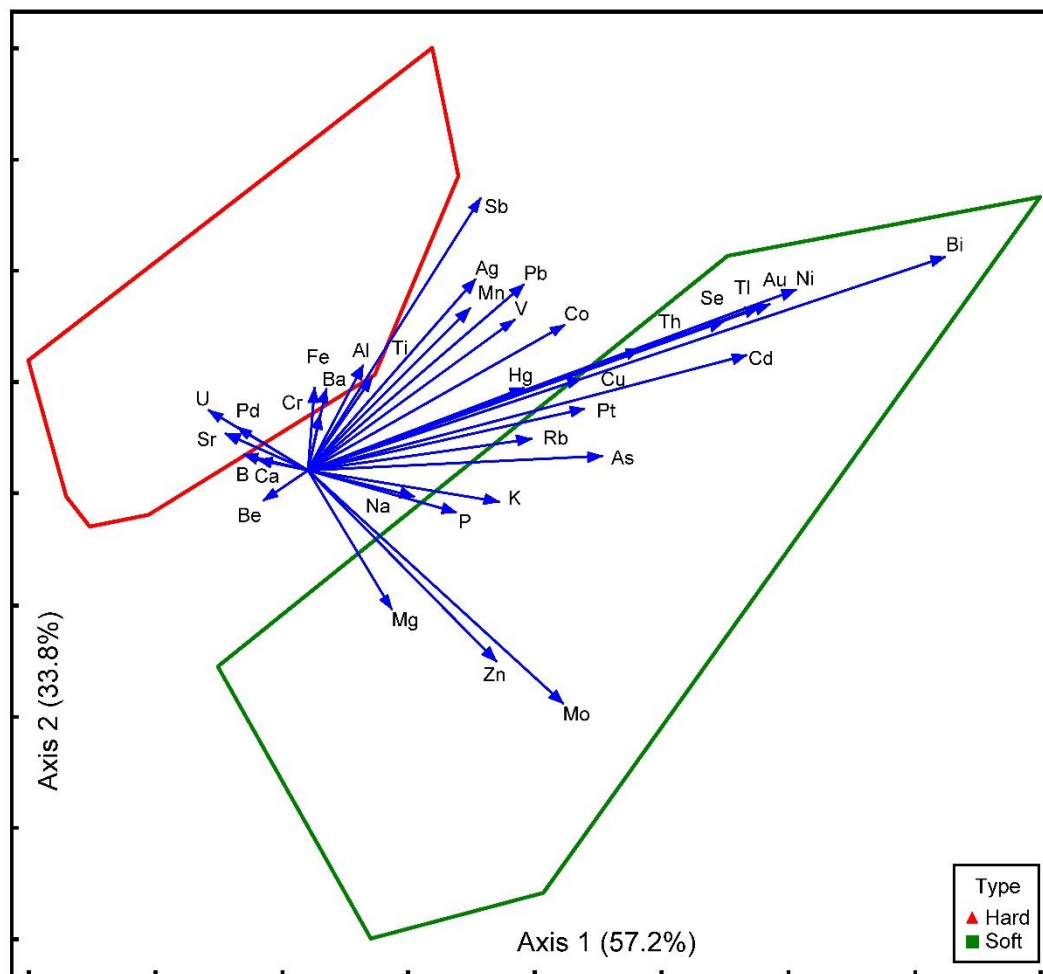


Figure 27. NMS ordination of the distribution of metals and metalloids in hard and soft corals from the WIO. The convex hulls represent the different coral types. Axis 1 explained 57.2% of the ordination, and Axis 2, 33.8%.

It was stated at the onset of this study in Section 1.2.2, that Mg, Fe, Mn, and Zn are elements that readily exchange with Ca in the calcite group. It was also mentioned that in the aragonite group, Ba, Sr, and Pb often exchange with Ca (Klein & Dutrow, 2007). The results as depicted in the NMS graph (Figure 27) correspond to a certain extent with the geochemical principles explained in Section 1.2.2. With the exception of deviations pertaining to Fe and Pb, these results indicated a degree of correlation between geochemical principles and coral skeleton crystallization.

The results indicated that Ba and Sr ordinate towards the hard corals– corals with aragonite skeleton. While I do not propose that the coral skeletons are transformed from aragonite (CaCO_3) to whiterite (BaCO_3) or strontianite (SrCO_3), but rather that

geochemical principles can also affect coral skeleton crystallisation. The same is reflected pertaining to soft corals— with calcite spicules— showing an affinity for Mg, Mn and Zn. The affinity of certain metals to coral types with different crystallography of their CaCO_3 skeletons was noted as early as 1964 (Harriss & Almy Jr., 1964). However, this insight appears very seldom in modern literature.

High concentrations of Fe were measured in hard corals. This occurrence seems to contradict the assumed geochemical principle that Fe should show greater affinity to calcite (soft corals) than to aragonite (hard corals). However, *Pocillopora* (a hard coral) from SBR had exceptionally high levels of Fe (Table 8). This could be ascribed to the presence of approximately fourteen shipwrecks on the atoll where the corals were sampled. The *Pocillopora* were situated in much closer proximity to these shipwrecks than the soft coral sampled from the same site. Most of the shipwrecks are situated on the edge of the atoll. The wrecks suffer substantial wave action that results in faster degradation than submerged wrecks. It would seem that shallow or stranded wrecks are cause for environmental concern. Kelly *et al.* (2012), called the contaminated area surrounding a shallow shipwreck in the Line Islands, “black reefs”. This is an apt name, as the same occurrence was witnessed in SBR during sampling. All corals near the shipwreck of a Taiwanese fishing vessel displayed a black hue (pers. obs.).

The other interesting observation was the outlier value of an exceptionally high concentration of Pb that was found in *Stylophora*. In the NMS (Figure 27), Pb was not associated with hard corals, but ordinated between the hard and soft coral convex hulls. However, one *Stylophora* sample from Aliwal Shoal had 8.7 mg/kg dm Pb. This concentration was two orders of magnitude higher than the concentration of Pb found in any other sample. A possible explanation of this outlier value is that since the outer edges Aliwal are popular fishing sites, a lead fishing sinker might have been caught in the coral colony prior to collection.

Most of the outlier values of this study (individual concentrations that far exceed the average values of the other samples) were found in individual *Sinularia* colonies. One particular *Sinularia* colony from Sodwana had the highest concentration of Au (2 mg/kg dm), Tl (0.5 mg/kg dm) and Hg (0.12 mg/kg dm) with more than an order of magnitude higher than the next highest value. Similarly, a *Sinularia* colony from Agalega had extremely high concentration of Zn (120 mg/kg dm). I speculate that those particular

colonies excreted mucus as a defence mechanism to an external irritation just prior to being sampled. Several metals are present in the water column as small particles, which can be trapped by a mucus layer (Ferrier-Pagès *et al.*, 2005). This might be a reason for *Sinularia* being the coral with the most elements at the highest concentration in this study. *Sinularia* is a large coral that can cover an area of more than two metres, with a long life span (Bastidas *et al.*, 2004). Certain corallites secrete mucus as a defence mechanism when attacked (Brown & Bythell, 2005), perhaps making them more prone to bioaccumulate metals. This could be a factor for future considerations and research.

4.3 Metals and metalloids in corals from different regions

In this section, I will discuss the concentrations of metals in symbiotic hard and soft coral genera sampled from the different regions, Mascarene Islands (Agalega, Rodrigues, and SBR) and South Africa (Sodwana and Aliwal). The results of all symbiotic corals collected from Sodwana and Aliwal were pooled to represent one convex hull. Similarly, the results of all corals collected from the Mascarene Islands were pooled to represent the other convex hull. All corals collected from the Mascarene Islands were symbiotic. Three azooxanthellate coral genera were collected from South Africa, but were excluded from this analysis for consistency.

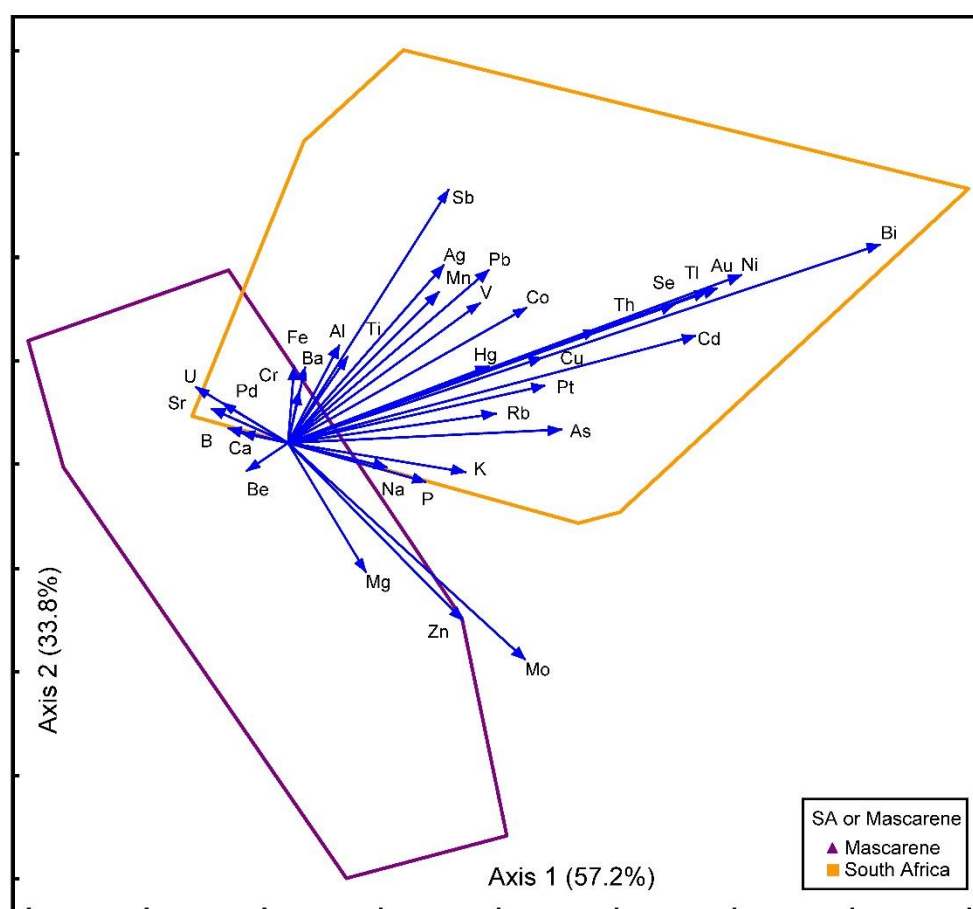


Figure 28. NMS ordination of the distribution of metals and metalloids in corals from different regions in the WIO. The convex hulls represent the region of coral collection. Axis 1 explained 57.2% of the ordination, and Axis 2, 33.8%.

It is evident from the scatterplots and t-test results (Figure 25) and the NMS analysis (Figure 28) that the majority of metal and metalloid contamination occurred in corals from South African Sites.

An obvious explanation for the difference in metals content between the corals from the Mascarene and South Africa could be that South Africa has a higher population and more anthropogenic activities along her coasts than the Mascarene Islands.

The geology of the different regions might also play a role in the metals present in the environment. South Africa has several rivers that empty into the Indian Ocean. Pollution originating inland are transported via river systems and can contaminate

marine life, including coral (Bornman *et al.*, 2017). The catchment areas of these rivers reach inland, and can transport various minerals from central South Africa to the ocean. The Umfolozi River catchment empties near Sodwana. The upper catchment extends to central South Africa, as far as the foothills of the Drakensberg. The Mfolozi Headwaters is also included in the catchment area. Coalmining and suspected illegal gold mining occurs in the catchment area. Large scale plantations and land degradations are also detrimental to the water quality of the catchment area (DAEA&RD, 2010; Colvin *et al.*, 2013). Aliwal Shoal is situated near the mouth of the Umkomaas River. This river also extends inland, although not as far as the Umfolozi. Several industries, that might provide an influx of anthropogenically released metals, are found on the riverbank, including land degradation, large scale plantations, and the SAPPI /Saiccor paper mill. (Stone, 2002; Fathima, 2003; Colvin *et al.*, 2013).

It could be expected that elements from the same geological group would be co-variate in close proximity to one another as vectors of the NMS graph. This is because they are of the same geological origin and the rivers transport these elements from the same geological areas from where they originate. However, in this study, the metals from the same geological groups, such as the gold or platinum groups, did not correlate (see Figure 28). The vectors of the platinum group (Pt, Pd, and Pb) did not co-vary, neither were those of the gold group (Au, Ag, and Cu). If these vectors did co-vary, it could have been assumed that most of the metals were of the same geological formation (Van der Schyff *et al.*, 2016). Because they did not co-vary, it might be deduced that additional anthropogenic input of metals into the environment (particularly Cu) plays a more prominent part in exposing the marine environment to metal influx than geological input does. An additional influx of metals to coral reefs, particularly Sodwana and Aliwal, can be ascribed to deep water upwelling events. Trace metals are transported from the deep ocean beyond the continental shelf. Trace metals that do not have a terrestrial geological origin can be expected to be added to the water column through upwelling events. This can cause algae blooms. Zooplankton feed on the algae, and corals can, in turn, prey on the zooplankton. The trace elements from deep waters are biomagnified in the coral colony through predation on zooplankton, or biomagnified through direct uptake from the water (Sheppard *et al.*, 2009). The process of biomagnification and bioconcentration will be discussed in detail in Section 4.4.

Figure 19 indicated that most metals at the highest concentrations were present in *Sinularia* from Sodwana. The coral cover of Sodwana is primarily composed of soft corals (Riegl, 2003). A significant decrease in *Sinularia* colonies from Sodwana was recorded from 1993 to 2017. No single factor could be directly ascribed to the decline, but pollution is a suggested factor (Porter & Schleyer, 2017). The results of this study support the suggestion that pollution might be a cause of the decline. This will be further discussed in the concluding chapter.

Neither Agalega, nor SBR have rivers. This means minimal terrestrial input of metals can be expected to be found in corals from these islands, save for very little aeolian transportation of fine sediment from the African mainland. Rodrigues has a few rivers, but the geology of the region is rather uniform basalt (Rees *et al.*, 2005), and only elements present in basalt will be transported from the island surface to the marine system. Basalt is a fine grained ferromagnetic extrusive rock. Ferromagnetic is a term for a rock with high concentrations of iron and manganese (Monroe *et al.*, 2007). All corals from the WIO exhibited extraordinary high concentrations of Fe.

Metals associated with hard corals– alkaline earth metals, as well as B, Pd, U, and Sr– were predominant in the Mascarene sites compared with the South African sites. The abovementioned metals can be incorporated into the aragonite skeleton lattice of hard coral by substituting Ca within the crystal lattice of the coral skeleton.

4.4 Bioaccumulation of metals in corals

As noted in Section 1.1, bioaccumulation is the sum accumulation of contaminants in and by an organism from all sources (Newman, 2010). Bioaccumulation is the sum of the mechanisms of bioconcentration (contaminants obtained from water only), and biomagnification (contaminants obtained from food). Corals pose a conundrum to classifying uptake mechanisms. The different methods of metal uptake will briefly be discussed.

1. Biomagnification in corals can occur through both filter and suspension feeding (Anthony, 1999). Most corals are suspension feeders, catching whatever dendritus drifts to the seafloor. Some corals, particularly those that are

azooxanthellate, are filter feeders that actively catch plankton with tentacles (Erhard & Knop, 2005).

2. Bioconcentration through direct uptake of metals in seawater (Ali *et al.*, 2011). Fallon *et al.* (2002) found that metals in corals will consistently show whether metallic element contamination is present in the water of a particular area.
3. Other modes of metal uptake: It is difficult to discern whether the following methods of metal uptake should be categorised as bioconcentration, biomagnification, or something else entirely. They still play a part in bioaccumulation, as corals are exposed to metallic elements through these pathways.
 - a. Zooxanthellae cells are known to accumulate metals irrespective of their host status (Harland & Nganro, 1990). Copper, Fe, and Cd are metals that are noted for accumulating in zooxanthellae cells within coral tissue. These metals can precipitate coral bleaching at high concentrations (Mitchellmore *et al.*, 2007; Van Dam, 2011). Bleaching can thus be seen as a mechanism of regulating metal concentration in total coral tissue (Marshall, 2002). I surmise that the intricacy of the symbiosis between algal cells and coral tissue makes it impossible to separate the metal input of zooxanthellae cells from the total metal load of the coral colony. This interaction is still to be determined in detail and could be part of future studies.
 - b. The defensive mucus layer that corals secrete can also be a possible pathway of metal biomagnification. Marshall (2002) mentioned that the mucus layer might serve as a buffer for metals, preventing particles from coming into contact with corals. However, it can also be seen as a sink (Fallon *et al.*, 2002), trapping metal particles along with zooplankton and other particulate matter to be ingested by corals at a later stage. Assuming Fallon *et al.* (2002) are correct in their assumption that the metal particles trapped by the mucus is similarly ingested by the coral colony as zooplankton, this might be seen as biomagnification. However, biomagnification is traditionally associated with trophic transfer through prey items, and thus the pathway does not fit the normal description. In this case, I propose that this route of uptake be called “particulate

vectored accumulation” that will add to body burden bioaccumulation in addition to biomagnification and bioconcentration.

- c. Corals can include metallic elements into their skeleton lattice by substitution of the original Ca^{2+} cation with divalent metallic elements (Corrège, 2006). “Lattice substitution” might be an apt descriptive term.
- d. Small metal particles in suspension can also simply be lodged within the pores and cavities of the colony skeleton (Corrège, 2006). This pathway might conceivably be considered as bioconcentration, even if it is rather unconventional, as the suspended particles are present in water.

Figure 29 illustrates the processes described above visually.

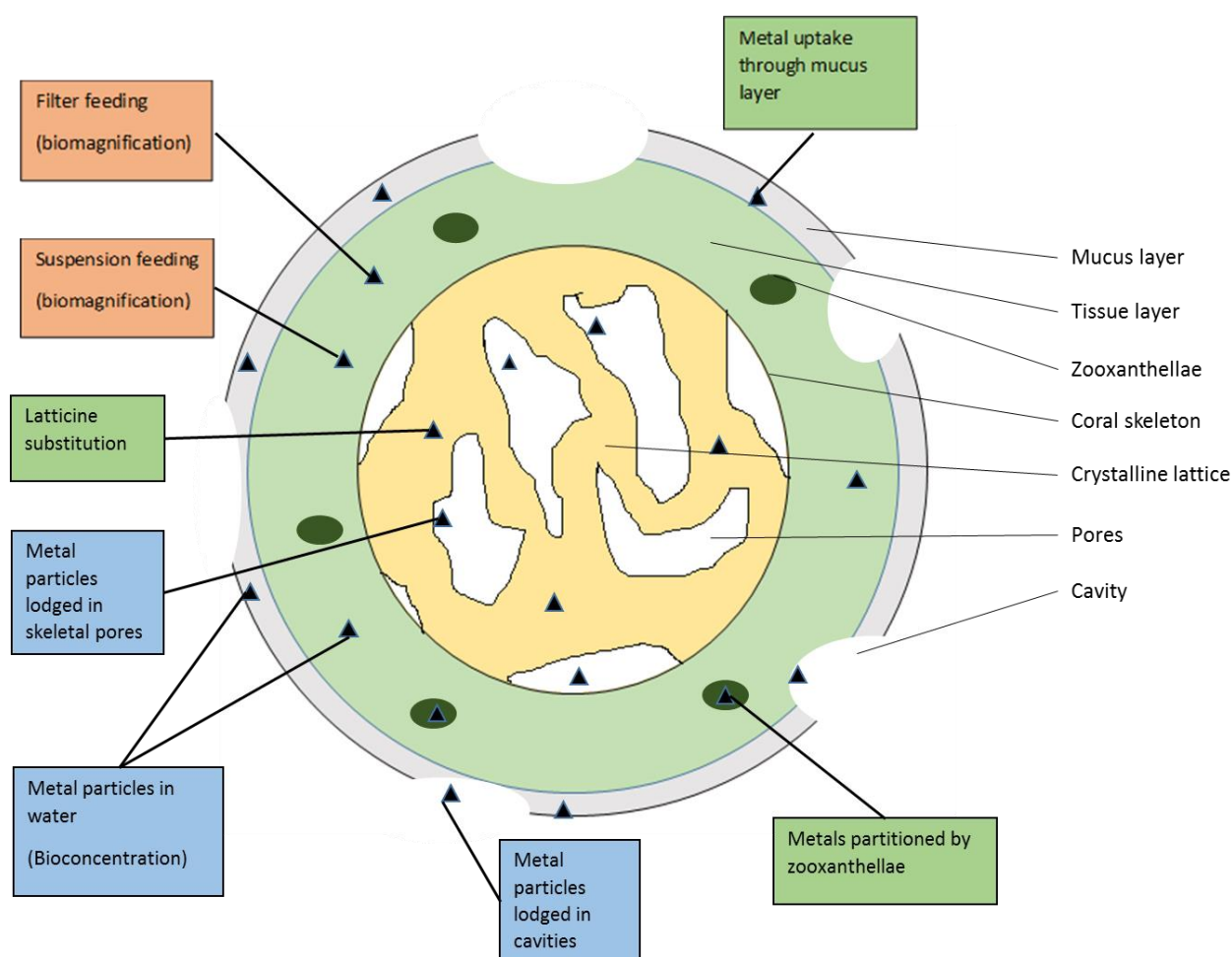


Figure 29. Diagrammatic representation of a cross section of a coral, showing the different routes whereby metallic elements can accumulate into coral. Boxes highlighted in brown pertain to biomagnification; blue, bioconcentration;

and green, an undetermined form of metal uptake, contributing to the bulk of metals accumulated.

4.5 Factors affecting metal accumulation in corals

In the following section, certain pathways that can cause metals to become incorporated into corals will be examined. The theory of these exposure pathways will also be discussed with relation to the corals analysed in this study.

Mohammed and Dar (2010) conducted a study similar to mine that compared metal concentrations in symbiotic hard and soft corals. Their results were similar to the results found in this study. Both studies found higher concentrations of metals such as Zn, Mn, Ni, and Cu, soft corals. Both studies also found Fe prevalent in hard corals.

The differences may be ascribed to several reasons. Dar and Mohammed (2006) identified exposure surface area and organic matrix thickness as morphological features of corals that are directly linked to metal uptake. Soft corals have an increased surface area compared to hard corals, higher levels of organic matter, and a thick, overlaying, mucus layer (Mohammed & Dar, 2010; Fallon et al., 2002). The cumulative result of all these factors cause soft coral to be more susceptible to metal uptake than hard coral. The bulk density of the CaCO_3 skeleton in relation to tissue layer is a morphological feature indirectly linked to metal uptake (Mohammed & Dar, 2010). This means that fewer metals would accumulate in corals with a high carbonate skeleton to organic matrix ratio, such as the case is with most hard corals.

Apart from differences between hard and soft corals, another factor would be exposure to anthropogenic contamination (Dar & Mohammed, 2006). For example, a long-term exposure event, such as mine effluent would be more destructive to coral reefs than a single event such as a shipping accident (David, 2003).

In this study, most of the aforementioned factors come into play. *Sinularia* is the coral with the largest surface areas (some colonies can exceeded two metres in diameter), and the thickest layer of organic matrix. *Sinularia* also had the highest concentration of most metals (Figure 19). In addition, *Sinularia* has the ability to excrete a large volume of mucus through specially adapted sclerites (Sammarco *et al.*, 1987). Whilst a mucus layer is most easily observed in 'leather soft coral', it is present in all corals-

both hard and soft. This mucus layer can trap metal particles from the surrounding seawater (Anu *et al.*, 2007). The mucus layer excreted by soft corals is more prominent than that excreted by hard coral.

The bulk density of CaCO_3 of corals collected was not determined during this study. However, due to its morphological composition, *Fungia* is, at face value, the coral with the highest expected bulk density and it is one of the corals with the lowest concentrations of most metals (Figure 20).

South Africa is a more industrialised country than Mauritius and the Mascarene Islands. A greater steady input of contaminants can be expected through multiple South African rivers emptying into the Indian Ocean, industrial waste, and shipping. Sodwana is particularly susceptible to constant contaminant build-up due to thousands of SCUBA charter boats being launched annually (Schleyer & Tomalin, 2000). One of the most important sources of metals in the coral reef environments is sewage discharge (Bjerregaard *et al.*, 2015). Sewage is one of the main pollution sources in the Red Sea (Ali *et al.*, 2011). The continual expanse of coral reefs in the Red Sea locates the reefs in close proximity to ever expanding anthropogenic input. Sodwana and Aliwal are spared, to an extent, from the additional contamination of raw sewage because of their geographic location in deeper water, and further distance from major cities.

4.6 Comparison with other studies

In this section, the results presented in Chapter 3 were compared with results from other studies that focused on metals in corals. Studies cited in this section are studies that (i) applied similar analytical techniques, and used the entirety of the coral (tissue as well as skeleton) for analysis, (ii) analysed the corals as dry mass, (iii) used the same coral genera that were used in this study, and (iv) only analysed symbiotic corals. All values presented in the following tables have been rounded off to two significant figures and are presented as mg/kg dm. Nine metals that were previously examined by other researchers can be directly compared with my results. (Cu, Cr, Co, Ni, Pb, Zn, Mn, Cd, and Fe). All symbiotic corals examined in this study are compared to the same corals from different localities.

At the onset of this discussion, it should be noted that the iron concentrations found in this study exceeded all other reported values, regardless of coral type or sampling locality. The iron concentrations given in Tables 13 to 18 will be discussed separately in Section 4.5.

Table 12. Metal concentrations in *Sinularia* (mg/kg dm)

Location	Site	Cu	Cr	Co	Ni	Pb	Zn	Mn	Cd	Fe	Source
Red Sea	Wadi El-Gemal	6.8	X	X	19	9	72	5.4	X	39	Mohammed & Dar (2010)
Red Sea	Gola'an	7.7	X	X	15	12	45	6.8	X	31	Mohammed <i>et al.</i> (2010)
Red Sea	Hurghada	12	X	X	16	12	150	8.8	X	18	Mohammed <i>et al.</i> (2010)
Red Sea	Hurghada	5.5	X	7.7	14	36	31	X	3.8	45	Ali <i>et al.</i> (2011)
Red Sea	El-Ain Al-Sukhna	4.1	X	7.1	190	16	140	X	9.6	46	Ali <i>et al.</i> (2011)
Red Sea	El-Tur	9.4	X	7.5	13	32	50	X	3.5	55	Ali <i>et al.</i> (2011)
Red Sea	Sha'b Rashdan	4.9	X	7.7	16	36	31	X	4.1	38	Ali <i>et al.</i> (2011)
Red Sea	Sharm El-Sheikh	2.8	X	5	9.3	28	52	X	2	18	Ali <i>et al.</i> (2011)
Red Sea	Dahab	3.3	X	4.7	12	27	39	X	2.5	57	Ali <i>et al.</i> (2011)
Mascarene	Agalega	0.13	4.3	0.39	4.9	0.0073	40	4.9	1.8	430	This study
Mascarene	Rodrigues	0.21	4.5	0.19	3	0.0076	3.3	0.06	3.6	430	This study
Mascarene	SBR	0.23	4	0.27	1.5	0.01	0.22	0.10	2.8	440	This study
South Africa	Sodwana	4.7	7.4	17	1300	0.84	12	15	24	1400	This study
South Africa	Aliwal	2.4	13	14	630	0.76	6.9	47	20	1600	This study

Mohammed and Dar (2010) studied the ability of coral to accumulate metals in the Red Sea. They reported metal concentrations in corals from Wadi-El Gamal, Gola'an, and Hurghada. Ali *et al.* (2011) conducted a similar study from the same general area of the Red Sea. They sampled corals not only from Hurghada, but also from Al-Ain Al-Sukna, El-Tur, Sha'b Rashdan, Sharm El-Sheikh, and Dahab.

- Cu: All Cu concentrations reported by Ali *et al.* (2011) exceeded the values reported by Mohammed and Dar (2010) and by this study. *Sinularia* from Aliwal had similar concentrations of Cu to *Sinularia* from Sharm El-Sheikh, and *Sinularia* from Sodwana to *Sinularia* from Sukhna and Sha'b Rashdan.

- Cr: Neither of the other studies reported on Cr concentrations in *Sinularia*.
- Co: The *Sinularia* from Mascarene Islands had the lowest concentration of Co, and *Sinularia* from South Africa the highest. *Sinularia* from the Red Sea displayed Co values between those found in *Sinularia* from the other two regions.
- Ni: The high concentration of Ni that was found in *Sinularia* in South Africa is unprecedented. Ali *et al.* (2001) found Ni at 186 µg/g in *Sinularia* from Sukhna, which is an order of magnitude higher than most other results. However does not compare to the 630 mg/kg dm and 1300 mg/kg dm found in *Sinularia* from Aliwal and Sodwana, respectively.
- Pb: *Sinularia* from South Africa and the Mascarene Islands had far lower concentrations of Pb than what was found in *Sinularia* from the Red Sea sites.
- Zn: Agalega had a concentration of Zn in *Sinularia* comparable to what was found in *Sinularia* from the Red Sea. *Sinularia* from the South African sites had a lower concentration of Zn, and *Sinularia* from Rodrigues and SBR, even lower.

Table 13. Metal concentrations in *Sarcophyton* (mg/kg dm)

Location	Site	Cu	Cr	Co	Ni	Pb	Zn	Mn	Cd	Fe	Source
Red Sea	Wadi El-Gemal	9.8	X	X	14	4	50	6.2	X	90	Mohammed & Dar (2010)
Red Sea	Gola'an	8.3	X	X	17	9.9	45	12	X	130	Mohammed & Dar (2010)
Red Sea	Hurghada	13	X	X	17	12	120	15	X	100	Mohammed & Dar (2010)
Red Sea	Hurghada	5	X	3.1	8.6	19	30	X	2.4	36	Ali <i>et al.</i> (2011)
Red Sea	El-Ain Sukhna	14	X	1.4	4.2	12	37	X	0.89	30	Ali <i>et al.</i> (2011)
Red Sea	El-Tur	4.7	X	3.5	3.8	20	75	X	1.6	30	Ali <i>et al.</i> (2011)
Red Sea	Sha'b Rashdan	4.3	X	3.1	3.2	25	59	X	1.7	120	Ali <i>et al.</i> (2011)
Mascarene	Agalega	0.23	6.4	0.31	3.8	0.01	0.21	0.067	0.28	510	This study
Mascarene	Rodrigues	0.20	3.9	0.11	2.6	0.44	1	0.067	0.36	380	This study
South Africa	Sodwana	3	6.2	0.80	1.9	0.32	8.6	4.1	0.75	560	This study

Once again, this study is compared to results found by Mohammed and Dar (2010) and by Ali *et al.* (2011) who collected corals from various locations in the Red Sea.

- Cu: *Sarcophyton* from the Mascarene Islands had the lowest concentration Cu. *Sarcophyton* from Sodwana had higher concentrations, but these concentrations were close to what was found in *Sarcophyton* from Hurghada, El-Tur, and Sha'b Rashdan. All concentrations of Cu in *Sarcophyton* reported by Mohammed and Dar (2011) exceeded the abovementioned values
- Cr: None of the other studies reported on Cr concentrations found in *Sarcophyton*
- Co: The Mascarene Islands had the lowest concentration of Co in *Sarcophyton*, followed by *Sarcophyton* from Sodwana. All values reported by Ali *et al.* (2011) exceeded the abovementioned values.
- Ni: Nickel concentrations were lowest in *Sarcophyton* from Sodwana, followed *Sarcophyton* from by Rodrigues. Nickel in *Sarcophyton* from Agalega was similar to what Ali *et al.* (2011) found in *Sarcophyton* from El-Tur and Sha'b Rashdan.
- Pb: The *Sarcophyton* from Mascarene Islands and Sodwana had far lower concentrations Pb than any *Sarcophyton* reported on from the Red Sea.
- Zn: The Mascarene Islands had the lowest Zn concentration in *Sarcophyton*, followed by *Sarcophyton* from Sodwana. All reported values of *Sarcophyton* from the Red Sea sites greatly exceeds the concentrations of Zn in *Sarcophyton* found in this study.
- Mn: *Sarcophyton* from Rodrigues and Agalega had the lowest concentration of Mn. *Sarcophyton* from Sodwana had the second lowest concentration, but was only slightly less than what was found in *Sarcophyton* from Wadi El-Gemal. The *Sarcophyton* from other Red Sea sites reported by Ali *et al.* (2011) had far higher values of Mn.
- Cd: The Cd concentrations in *Sarcophyton* from the Mascarene Islands were lowest, followed by concentrations of Cd in *Sarcophyton* from Sodwana. The Red Sea values reported by Ali *et al.* (2011) only slightly exceeded these abovementioned values.

Table 14. Metal concentrations in *Acropora* (mg/kg dm)

Location	Site	Cu	Cr	Co	Ni	Pb	Zn	Mn	Cd	Fe	Source
India	Mandapam	2.2	X	1	X	X	2.1	0.82		41	Sreekumaran & Gogate (1972)
Red Sea	Hurghada	3	X	3.1	6.3	14	26	X	1.6	90	Ali et al (2011)
Red Sea	El-Tur	8.7	X	4.5	10	26	57	X	2.1	61	Ali et al (2011)
	Sha'b										
Red Sea	Rashdan	3.3	X	4.1	9.8	26	8.1	X	3.3	20	Ali et al (2011)
	Sharm El-										
Red Sea	Sheikh	1.3	X	5	8.1	25	21	X	2.8	13	Ali et al (2011)
Red Sea	Dahab	1.4	X	5	11	21	3.2	X	1.8	40	Ali et al (2011)
	El										
Red Sea	Hamarwein	2	2.1	12	16	16	35	17	X	70	El-Sorogy <i>et al.</i> (2012)
	Sharm Al										
Red Sea	Bahari	2.3	2.5	14	28	19	35	5.6	X	54	El-Sorogy <i>et al.</i> (2012)
Red Sea	Shalateen	2.5	2	19	19	23	12	7.3	X	67	El-Sorogy <i>et al.</i> (2012)
Australia	Lizard Island	0.21	X	X	0.56	<0.38	0.9	X	0.14	X	Denton & Burdon-Jones (1986)*
	Orpheus										
Australia	Island	0.16	X	X	0.12	<0.30	0.57	X	0.08	X	Denton & Burdon-Jones (1986)*
Australia	Heron Island	0.2	X	X	0.38	<0.35	1.1	X	0.14	X	Denton & Burdon-Jones (1986)*
Mascarene	Agalega	0.23	1.80	0.57	3.7	0.010	0.16	0.08	0.17	630	This study
Mascarene	Rodrigues	0.22	0.18	0.39	2.7	0.011	0.17	0.10	0.004	470	This study
Mascarene	SBR	0.22	0.99	0.48	3.2	0.011	0.16	0.09	0.09	550	This study
South											
Africa	Sodwana	0.98	6.4	1.6	4.0	0.36	0.02	4.7	0.14	990	This study

In addition to Ali *et al.* (2011), El-Sorogy *et al.* (2012) also reported on metals found in corals from the Red Sea. Sreekumaran and Gogate (1972) reported on metal constituents in some species of coral from India. Denton and Burdon-Jones (1986) focussed on trace metals in corals from the Great Barrier Reef (GBR). The sites that Denton and Burdon-Jones (1986) collected coral from, Orpheus-, Lizard-, and Heron Islands are not located in the Indian Ocean, but rather in the Pacific side of the Indo-Pacific belt. All values by Denton & Burdon-Jones (1986) were cited from Reichelt-Brushett & McOrist (2003)

- Cu: Copper concentrations in *Acropora* from this study are approximately the same as that of in *Acropora* reported by Denton & Burdon-Jones (1986) from the GBR, and lower than the reported Cu concentrations in in *Acropora* from the Red Sea. *Acropora* from Sodwana did have higher concentration of Cu than

Acropora from the Mascarene sites. *Acropora* from Sodwana had slightly lower Cu concentrations than in *Acropora* from the Red Sea.

- Cr: El-Sorogy *et al.* (2012) was the only other study to report on Cr concentration in *Acropora*. *Acropora* from Sodwana had higher Cr concentration than what was reported by El-Sorogy *et al.* (2012). The Mascarene Islands had far lower concentrations of Cr in *Acropora* than any of the other studies.
- Co: Concentrations of Co was recorded at the highest concentration in *Acropora* from the Red Sea, and lowest in *Acropora* from the Mascarene sites. *Acropora* from Sodwana had similar values to what was found in *Acropora* from India.
- Ni: The Ni concentration in *Acropora* from the GBR were lower than the values found *Acropora* from this study. *Acropora* from Rodrigues had the second lowest reported Ni concentration, followed by *Acropora* from SBR, Agalega, and Sodwana. The Ni concentration in *Acropora* from Hurghada (Ali *et al.*, 2011) was only slightly higher than that found in this study. The other concentrations of Ni in *Acropora* from the Red Sea are higher than the Hurghada values.
- Pb: This study showed the lowest reported concentrations of Pb in *Acropora*. The values from the Mascarene were similar to concentrations of Pb in *Acropora* found in Sodwana. Values of Pb in *Acropora* reported by Denton and Burdon-Jones (1986) are close to those found in *Acropora* from this study, but their method of reporting the concentrations does not provide a concrete concentration. All Pb values in *Acropora* from the Red Sea were far higher than what was found in *Acropora* from the WIO.
- Zn: Concentration of Zn in *Acropora* from this study (Mascarene Islands, as well as Sodwana) were lower than the other studies. Values from *Acropora* from the GBR were only slightly higher than *Acropora* from the WIO. All concentrations of Zn in *Acropora* from the Red Sea exceeded that which was found in *Acropora* from this study.
- Mn: The Mascarene Islands had the highest concentrations of Zn in *Acropora*, followed by *Acropora* from India. Manganese in *Acropora* from Sodwana was comparable to values found in *Acropora* from Bahari and Shalateen, Red Sea (El-Sorogy *et al.*, 2012).

- Cd: *Acropora* collected from Rodrigues had the lowest concentrations of Cd. *Acropora* from the other Mascarene Islands were comparable to *Acropora* from Sodwana and the GBR. Concentrations of Cd in *Acropora* from the Red Sea (Ali *et al.*, 2011) exceeded the values found at all other sites.

Table 15. Metal concentrations in *Fungia* (mg/kg dm)

Location	Site	Cu	Cr	Co	Ni	Pb	Zn	Mn	Cd	Fe	
Red Sea	El Hamarwein	1.7	1.9	13	15	22	12	63	X	70	El-Sorogy <i>et al.</i> (2012)
Red Sea	Sharm Al Bahari	2.7	2.6	13	19	16	22	5.1	X	61	El-Sorogy <i>et al.</i> (2012)
Red Sea	Shalateen	3.1	2.1	16	28	43	18	5.9	X	45	El-Sorogy <i>et al.</i> (2012)
Australia	Lizard Island	0.38	X	X	0.09	<0.30	1.3	X	0.02	X	Denton & Burdon-Jones (1986)*
Australia	Orpheus Island	0.3	X	X	<0.05	<0.68	0.75	X	0.02	X	Denton & Burdon-Jones (1986)*
Australia	Heron Island	0.27	x	X	<0.15	<0.58	0.74	X	0.09	X	Denton & Burdon-Jones (1986)*
Mascarene	Agalega	0.21	6.1	1.1	6.7	0.0094	4	0.53	0.0023	870	This study
Mascarene	Rodrigues	0.21	4.7	0.89	5.3	0.0069	0.21	0.048	0.0025	770	This study
Mascarene	SBR	0.23	4.6	0.92	4.9	0.011	0.11	0.067	0.0016	750	This study

Selected metal concentrations found in *Fungia* from the Mascarene Islands were compared with concentrations of these metals found in *Fungia* from the Red Sea (El-Sorogy *et al.*, 2012) and the GBR (all values by Denton & Burdon-Jones (1986) were cited from Reichelt-Brushett & McOrist (2003)). No *Fungia* from South Africa was analysed in this study.

- Cu: *Fungia* from the Red Sea had the highest Cu concentrations of the reported studies. The *Fungia* from the Mascarene Islands had the lowest concentrations. The concentrations of Cu found in *Fungia* from the Mascarene Islands are marginally lower than concentrations found in *Fungia* from the GBR.
- Cr: The Mascarene Islands had higher concentrations of Cr in *Fungia* than the GBR.
- Co: Agalega had a higher concentration of Co in *Fungia* than the other Mascarene Islands, but concentrations in *Fungia* from the Red Sea exceeded all the values from the Mascarene.
- Ni: The Mascarene Islands had a higher concentration of Ni in *Fungia* than the GBR samples, but lower than *Fungia* collected from the Red Sea.
- Pb: The method in which Denton and Burdon-Jones (1986) present their results make it hard to say whether their Pb concentrations are higher or lower than

those found in this study. It can be assumed that *Fungia* from the Mascarene Islands had the lowest concentrations of Pb (< 0.05 mg/kg dm). *Fungia* from the Red Sea had the highest concentration of Pb.

- Zn: *Fungia* from Agalega had higher concentrations of Zn than *Fungia* from the other Mascarene Islands. The values of Zn in *Fungia* from Agalega exceed the values found in the GBR *Fungia*. Zinc concentrations in *Fungia* from the Red Sea far exceed all GBR and Mascarene values.
- Mn: Manganese in *Fungia* from the Red Sea far exceed concentrations found in *Fungia* from the Mascarene Islands.
- Cd: Cadmium concentrations in *Fungia* from the GBR exceed the concentrations found in *Fungia* from the Mascarene Islands.

Table 16. Metal concentrations in *Pocillopora* (mg/kg dm)

Location	Site	Cu	Cr	Co	Ni	Pb	Zn	Mn	Cd	Fe	Source
India	Mandapam	1.2	X	0.29	X	X	0.49	X	X	49	Sreekumaran & Gogate (1972)
	Wadi El-										
Red Sea	Gemal	0.88	X	X	6.1	0.25	12	9	X	150	Mohammed & Dar (2010)
Red Sea	Gola'an	2.4	X	X	4.9	2.8	13	7.3	X	18	Mohammed & Dar (2010)
	El										
Red Sea	Hamarwein	1.9	2.5	12	16	17	18	3.8	X	64	El-Sorogy <i>et al.</i> (2012)
	Sharm Al										
Red Sea	Bahari	2.4	2.7	13	30	19	100	5.4	X	49	El-Sorogy <i>et al.</i> (2012)
Red Sea	Shalateen	2.8	2.3	13	15	37	13	6.2	X	37	El-Sorogy <i>et al.</i> (2012)
Mascarene	Rodrigues	0.21	26	2.9	26	0.012	0.22	17	0.002	2200	This study
Mascarene	SBR	0.21	30	3.5	32	0.01	0.15	24	0.003	2500	This study
South											
Africa	Sodwana	1.1	22	3.7	24	0.22	1.8	27	0.043	2200	This study
South											
Africa	Aliwal	0.57	9.2	1.9	6.0	0.16	0.91	9.5	0.12	1200	This study

Other studies that examined metals in *Pocillopora* tissue and skeleton are Sreekumaran and Gogate (1972) in India, and Mohammed and Dar (2010), and El-Sorogy *et al.* (2012) in the Red Sea.

- Cu: The Mascarene Islands and Aliwal had the lowest concentration of Cu in *Pocillopora*. The concentration of Cu in *Pocillopora* from Sodwana had values comparable to those of *Pocillopora* from the Red Sea and India.

- Cr: *Pocillopora* analysed by El-Sorogy *et al.* (2012) had lower concentrations of Cr than *Pocillopora* collected from the WIO. Aliwal had the lowest concentration of Cr in *Pocillopora* from the WIO. *Pocillopora* from SBR contained the highest concentration of Cr.
- Co: *Pocillopora* from Aliwal Shoal had the lowest concentration Co of all the WIO sites. The *Pocillopora* from India had the lowest overall concentration Co. The *Pocillopora* samples from the Red Sea had the highest concentration Co in the reported studies.
- Ni: SBR has the highest recorded concentration Ni in *Pocillopora*. *Pocillopora* from Rodrigues and Sodwana has concentrations of Ni that are comparable to the values El- Sorogy *et al.* (2012) reported. Aliwal had lower concentrations concentration of Ni in *Pocillopora* than the other WIO sites. These values are comparable to what Mohammed and Dar (2010) reported for *Pocillopora*, and higher than the concentrations Ni found in *Pocillopora* from India.
- Pb: Once again, the highest concentrations of Pb was reported from the Red Sea (El- Sorogy *et al.*, 2012). The values of Pb in *Pocillopora*, also from the Red Sea, reported by Mohammed and Dar (2010), lower than the aforementioned study. *Pocillopora* collected from Sodwana had similar concentrations of Pb than *Pocillopora* collected from Wadi El-Gemal (Mohammed & Dar, 2010). *Pocillopora* from the Mascarene Islands and Aliwal had the lowest concentrations Pb recorded.
- Zn: *Pocillopora* collected from the Red Sea (by both studies) had the highest concentration of Zn in their tissue and skeleton. *Pocillopora* from South Africa had higher concentrations than *Pocillopora* from India and the Mascarene Islands. Rodrigues and SBR had the lowest concentration Zn in *Pocillopora*.
- Mn: The highest recorded Mn in *Pocillopora* was from Sodwana, SBR, and Rodrigues. *Pocillopora* from Aliwal had lower concentrations than the other WIO sites. Manganese concentration in *Pocillopora* from Aliwal was in the same range as *Pocillopora* from the Red Sea.
- Cd: The other studies did not investigate Cd concentrations in *Pocillopora*.

Table 17. Metal concentrations in *Stylophora* (mg/kg dm)

Location	Site	Cu	Cr	Co	Ni	Pb	Zn	Mn	Cd	Fe	Source
Red Sea	Wadi El-Gemal	8.8	X	X	15	30	10	5.7	X	32	Mohammed & Dar (2010)
Red Sea	Gola'an	0.56	X	X	3	2.6	7.1	0.44	X	46	Mohammed & Dar (2010)
Red Sea	Hurghada	8.8	X	X	16	11	12	3.5	X	24	Mohammed & Dar. (2010)
Red Sea	Hurghada Ras	2.1	X	1.7	1.6	12	16	X	0.54	17	Ali <i>et al.</i> (2011)
Red Sea	Za'farana	1.7	X	5.3	13	27	9.3	X	3.1	61	Ali <i>et al.</i> (2011)
Red Sea	El-Ain Sukhna	8.4	X	4.6	7.9	7	41	X	1.3	300	Ali <i>et al.</i> (2011)
Red Sea	Sha'b Rashdan	3	X	6	12	29	21	X	3.3	27	Ali <i>et al.</i> (2011)
Red Sea	Sharm El-Sheikh	1.8	X	5.6	13	25	5.7	X	2.9	24	Ali <i>et al.</i> (2011)
Red Sea	Dahab	2.5	X	5.7	14	31	3.2	X	2.8	25	Ali <i>et al.</i> (2011)
Red Sea	El Hamarwein	2.1	2.2	13	37	16	11	25	X	170	El-Sorogy <i>et al.</i> (2012)
Red Sea	Sharm Al Bahari	2.5	2.5	17	27	20	31	5.6	X	66	El-Sorogy <i>et al.</i> (2012)
Red Sea	Shalateen	3.2	2.5	17	31	45	33	5.6	X	89	El-Sorogy <i>et al.</i> (2012)
Mascarene	Agalega	0.2	13	1	7.4	0.0078	0.22	0.04	0.002	940	This study
Mascarene	Rodrigues	0.2	19	2	15	0.01	0.22	4.8	0.003	1500	This study
Mascarene	SBR	0.2	18	1.8	15	0.007	0.15	6.4	0.002	1400	This study
South Africa	Aliwal	0.8	8.4	1.9	5.7	3.1	1.2	10	0.14	1100	This study

Concentrations of metals found in *Stylophora* collected from the WIO were compared with *Stylophora* collected from various sites in the Red Sea by Mohammed and Dar (2010), Ali *et al.* (2011) and El-Sorogy *et al.* (2012).

- Cu: *Stylophora* from the Mascarene Islands contained the lowest reported Cu concentration. *Stylophora* collected Aliwal had slightly higher Cu concentration than those collected from Gola'an (Mohammed & Dar, 2010). All the other Red Sea sites contained higher Cu concentration in *Stylophora*.
- Cr: All *Stylophora* collected from the WIO contained higher concentrations of Cr than that reported by El-Sorogy *et al.* (2012). The *Stylophora* from the Mascarene Islands contained higher concentrations of Cr than *Stylophora* collected from Aliwal.

- Co: Cobalt concentrations in *Stylophora* from the WIO was comparable to what Ali *et al.* (2011) reported in *Stylophora* from Hurghada. All other values reported for *Stylophora* from the Red Sea exceeded what was found in the WIO.
- Ni: The highest values of Ni in *Stylophora* was reported by El-Sorogy *et al.* (2012). All other Ni values in *Stylophora* from the Red Sea, as well as *Stylophora* from the WIO were relatively in the same range.
- Pb: The *Stylophora* collected from the Mascarene Islands had the lowest concentration of Pb present. *Stylophora* from Aliwal had higher concentrations than the Mascarene, but lower a lower concentration than most of the *Stylophora* collected from the Red Sea (save Gola'an).
- Zn: *Stylophora* from the WIO had lower concentration Zn present in their skeleton and tissue than *Stylophora* collected from the Red Sea. *Stylophora* from Aliwal did have a higher concentration Zn present than *Stylophora* from the Mascarene Islands.
- Mn: The concentration Mn in *Stylophora* from the WIO was in a similar range as the concentrations Mn in *Stylophora* reported from the Red Sea. *Stylophora* from Agalega had the lowest concentration of Mn present, followed by *Stylophora* from Gola'an (Mohammed & Dar, 2010). Aliwal had the second highest concentration of Mn in *Stylophora* tissue and skeleton, only exceeded by *Stylophora* collected from El Hamarwein (El-Sorogy *et al.*, 2012).
- Cd: The Mascarene Islands had the lowest concentration of Cd in *Stylophora*, followed by *Stylophora* collected from Aliwal. All the *Stylophora* from the Red Sea had higher concentrations Cd in the skeleton and tissue. *Stylophora* from Hurghada had a concentration close to that found in Aliwal (Ali *et al.* 2011).

4.7 Effects of different metals and metalloids on corals

Section 4.6 contextualised metal concentrations in corals analysed in this study versus metal concentrations present in corals collected from various locations globally. In this section, I will describe the effects that specific metallic elements can have on corals. Not all metals analysed for during this study had previously been experimentally tested on corals. The effects of these minor trace metals, for example, Pd, Au and, Mo, amongst others, are unknown. Most of these metals are however, present at such low

concentrations in the sampled coral fragments that the effect can be considered negligible, pending more information. The effects of Cu, As, Se, Hg, Fe, Ni, Co, Zn, and Cd are discussed.

Corals are most susceptible to the effects of metal contamination during their early life stages. Reduced reproductive success, gamete fertilization inhibition, larval mortality, and reduced larval settlement are common consequences of metal pollution (Reichelt-Brushett & Harison, 1999; Biscéré *et al.*, 2015). Zooxanthellae in coral tissue are also affected by metal pollution, be it by algal mortality or reduced rates of photosynthesis (Ferrier-Pagès, *et al.*, 2001). If the zooxanthellae cells are damaged, coral calcification is limited, and coral growth is inhibited. Some metals might even induce bleaching and coral mortality (Sabdon, 2009).

It is complicated to determine the toxicological effects of all metallic elements on corals. There is no precedent for toxicity reference values in corals (Apeti *et al.*, 2014). In most natural occurrences, metals are bound to other elements to form complexes with other compounds. When complexes are broken, metals are present as free concentrations. Metals in the form of free concentrations are toxic to biota. (Millero *et al.*, 2009). Elevated seawater temperature can lead to the breakdown of complex compounds and contribute to the release of toxic free concentrations of metals (Chang & Reinfelder, 2000). In the following discussion, possible negative effects of individual metallic elements are highlighted.

4.7.1 Copper

The negative effect of Cu on coral is twofold. Firstly, Cu obstructs coral reproduction and skeleton growth (Bielmyer *et al.*, 2010). High concentration of Cu impedes coral fertilization and reduces larvae settlement (Reichelt-Brushett & Harrison, 2000). The consequence is that live coral cover decreases as Cu concentrations increase (Ali *et al.* 2010). Secondly, Cu attacks the critically important zooxanthellae in coral tissue. This makes sense, as Cu is a constituent of certain biocides, particularly algaecides (Haynes & Johnson, 2000). A significant decline in chlorophyll in algae cells can be observed at a Cu concentration of 50 µg/L in coral tissue (Yorst *et al.*, 2010). Bielmyer *et al.* (2010) proposed that different corals have different susceptibility to Cu toxicity, seeing that *Acropora* and *Montastraea* accumulated more Cu in their tissue than *Pocillopora*. This was not the case in this study. Copper concentrations were relatively

homogenous across all hard corals from the Mascarene Islands. A higher concentration was found in corals from South Africa. Because of the known toxicity that Cu pose to coral, the concentration of Cu in South African corals can be seen as a cause for concern.

4.7.2 Arsenic

Arsenic is naturally released by certain shallow hydrothermal vents. Most natural As is co-precipitated with hydrous ferric oxide (an form of iron oxide) and is not biologically available to most biota. However, a percentage of As released from hydrothermal vents are still biologically available. Phytoplankton are known to be exposed to natural As in surface seawaters (Price & Pichler, 2005). The coral with the highest concentration As, found in this study, was *Eleutherobia* from Aliwal Shoal. *Eleutherobia* is a small soft coral without symbiotic zooxanthellae. Due to its habitat preference, living in caves and under overhangs, *Eleutherobia* cannot house zooxanthellae and can subsequently not gain nutrients from photosynthesis. It relies on active predation on plankton for all nutritional needs. Arsenic might be biomagnified in this coral through planktonic prey. Not all As detected in this study can be attributed to natural hydrothermal activities. Arsenic is also introduced into the environment through anthropogenic sources (Van Dam, 2011). Because As concentrations are significantly higher in corals from South Africa compared to corals from the Mascarene Islands (figure 25.7.), it can be surmised that additional anthropogenic input of As is present in South Africa. Fungicides are a known source of As in the marine environment (Van Dam, 2011). Arsenic concentrations exceeding international food quality guidelines had been found in juvenile angling fish from South African estuaries (Bornman *et al.* 2017). It is interesting to note that arsenic can act as a buffer against selenium toxicity (Hamilton, 2004).

4.7.3 Selenium

Selenium shares similar properties with arsenic. This toxic non-metal is a by-product of gold and nickel mining (Newman, 2010). The results shown in figure 25 are to be expected, as there is substantial gold mining present in central South Africa, from

which the by-products can be expected to reach the ocean through rivers. An ilmenite mine— a suspected source of Ni— will be discussed in Section 4.7.6. Selenium might be expected to be present in the effluent of this industry. Other studies have attempted to evaluate the effect of Se in corals (e.g. Apeti *et al.*, 2014). However the lack of toxicity reference values and limited symptoms shown by corals make this a difficult task.

4.7.4 Mercury

Guzmán and García (2002) stated that 18.9 ppb (0.0189 mg/kg) of Hg in constitutes as 'high' levels of pollution in coral tissue. According to this guideline, most of the corals from the WIO are highly polluted by Hg. All corals collected from South Africa (save *Dendrophyllia* from Aliwal) exceeded 0.019 mg/kg dm Hg. Most of the corals from the Mascarene Islands also contained similar concentrations of Hg. Long range transport of pollutants across oceans by means of oceans currents is the proposed means of transfer of Hg to coral reef habitats (Guzmán & García, 2002; & Bouwman *et al.*, 2015). In a study, examining Hg in growth rings of massive corals, *Siderastrea sidereal* and *Montastraea faveolata*, Hg in input into the marine environment had been traced back to the 1930s in Venezuela (Ramos *et al.*, 2009). During this period, gold was mined in central Venezuela. The gold was purified using Hg. The reason for the Hg accumulation in the said corals can therefore be ascribed to gold mining and influxes in Hg occasioned by large scale flooding in the 1950s and 1970s carrying the pollution from inland sources to the marine environment. If such an experiment were to be conducted in South Africa, similar results might be expected. Illegal gold mining is an issue in South Africa. Miners use Hg to purify the collected gold (Lusilao-Makiese *et al.*, 2014). The Hg may similarly be transported through the river systems to the ocean and the associated ecosystems, such as coral reefs.

4.7.5 Iron

Iron occurs naturally in low concentrations in the coral reef ecosystem. However, it was found that Fe concentrations are elevated after shipwrecks occur in an area. Kelly *et al.* (2012) reported an incident which is very similar to what we had experienced in

SBR – the blackening of coral in the area of a recent shipwreck. Elevated Fe concentrations can lead to enhanced microbial activity that enhances the growth of macro-algae. Macro-algae in proximity to corals is found to increase stress and mortality rates of corals (Smith *et al.*, 2006). Iron is a metal which is known to induce coral bleaching (Van Dam, 2011). Iron was constantly found in considerably higher concentrations in all the corals from the sampling locations of the WIO than in any other study. The other studies sampled corals from the Red Sea, conducted sampling on reefs in relatively close proximity to the mainland (Mohammed & Dar, 2010; Ali *et al.*, 2011; El-Sorogy *et al.*, 2012). The reason for the high Fe levels found in this study can be attributed to two main reasons. The first pertains to Sodwana and Aliwal. Although Sodwana and Aliwal are located close to the shore and are geographically located on the continental crust, which is primarily composed of granite (Monroe *et al.*, 2007). The Red Sea and GBR sites that were examined in Section 4.6 are also situated on the continental crust. Fe was found in higher concentration in South Africa than the other countries. Iron in corals from South Africa could have been transported via the river systems that extend far inland and flow over bedrock with a high natural Fe concentration (DAEA&RD, 2010). The Mascarene Islands, however, are located beyond the continental margin of Africa. The oceanic crust is mostly basalt. Basalt has very high levels of iron and manganese (Monroe *et al.*, 2007). I surmise that the high levels of iron in corals from the WIO could be from weathered basaltic particles that become incorporated into coral skeletons.

4.7.6 Nickel

The Ni concentrations found specifically in *Sinularia* in South Africa were exceptionally high. Nickel is an important constituent of crude oil (Metwally *et al.*, 1997). The large volume of boat traffic in Sodwana and Aliwal is an external anthropogenic source of Ni in the marine environment. In addition, an ilmenite mine is located in Richards Bay, more or less between Sodwana and Aliwal (Creamer, 2016). Depending on the prevailing currents, mining effluent carrying Ni may be distributed in the direction of both these sites. Goh (1991) reported a 50% mortality in *Pocillopora* planulae after 36 hours of 9 mg/kg Ni exposure during an experiment. However, she mentioned that stress from the experiment might have played a role in the larvae mortality. All values

reported in this study and other studies on Ni in *Pocillopora* exceeded 9 mg/kg dm. It is unclear whether the fertilization success of all coral from all the sampling sites were affected by the Ni concentration. However, Porter and Schleyer (2017) reported a decline in soft coral cover in Sodwana in the last twenty years. Nickel concentration in *Sinularia* from Sodwana was exceptionally high. It is proposed that fertilization success of the genus in Sodwana is impaired by Ni pollution. This may be a reason for the reported decline in soft coral cover in Sodwana. Not all animals are equally susceptible to Ni toxicity (DeForest & Schlekot, 2013). As mentioned in Section 4.4, different physiological attributes of corals determine the concentration of metals that can be accumulated in its tissue. *Sinularia* is a large coral with a long life span, and produce a thick mucus layer as a defensive strategy. Nickel is present in the marine environment as small suspended particles (Weast, 1980). In addition to bioaccumulation of Ni from prey items, the suspended particles might become entrapped in the mucus layer of the *Sinularia*. Ali *et al.* (2011) found a significant correlation between dead coral cover on reefs in the Red Sea, and high Ni and Co concentrations.

4.7.7 Cobalt

Cobalt is a metal that shows greater affinity to coral skeleton, rather than to coral tissue (Anu *et al.*, 2007). Even though it is more associated with the CaCO₃ comprising coral skeletons, the zooxanthellae are also affected by a high Co concentration. In a laboratory study, it was found that Co decreased the photosynthetic rate of the symbiotic algae in *Acropora* and *Stylophora*. Because of this, the growth rate of these corals are inhibited (Ali *et al.*, 2011). Cobalt is often associated with Ni (Biscéré *et al.*, 2015). The high Ni concentration in South Africa might be a reason for the elevated Co concentration. At the correct concentration, Co is an essential trace element for living organisms (Ali *et al.*, 2011).

4.7.8 Zinc

Zinc plays a crucial role in activating the metalloenzymes and other enzymes in the digestive tract of corals (Chan *et al.*, 2014). Because the digestive tract is the most prominent organ in a coral polyp, it stands to reason that Zn is an essential element for coral growth (Ferrier-Pagés *et al.*, 2005). Along with Ca, Sr, and Mg, Zn is usually found in paleo and modern coral skeletons (Fallon *et al.*, 2002). In moderate concentrations, Zn and Cd do not pose significant threats to coral fertilization (Reichelt-Burshett & Harrison, 1999). Ali *et al.* (2011) however, found a positive correlation between high Zn concentration in seawater and dead coral cover. It is proposed that corals are exposed to Zn through their prey, indicating bioaccumulation (Mokhtar *et al.*, 2012). Zinc can enter the marine system through agricultural runoff—particularly fungicides and fertilizers (Van Dam, 2011).

4.7.9 Cadmium

Cadmium is rarely found in unpolluted seawater (Reichelt-Burshett, 1999). Small concentrations of the Cd in skeleton of massive corals indicate upwelling of deep water. Cadmium is easily depleted in surface the layer through biological activity and naturally replenished through upwelling of deep ocean waters (Matthews *et al.*, 2008). Cadmium can enter the marine system anthropogenically as components of fungicides (Van Dam, 2011). Although Cd is less toxic to coral gametes than Cu, it can also impair fertilization success. Similar to Cu, cadmium is a metal which is known to incur coral bleaching (Mitchelmore *et al.*, 2007). The toxicity of Cd is increased with a rise in ocean temperature and ocean acidification (Reichelt-Burshett, 1999).

All the metals discussed above pose a hazard to coral, and other marine life. As ocean temperature rises and ocean acidification increases, metals can become more bioavailable. Conservation efforts and legislation need to address the issue of metal accumulation in corals in order to effectively promote the conservation of coral reefs.

Chapter 5: Conclusion

Two hypotheses were presented (Section 1.6)

The results of this study confirm that both hypotheses can be accepted.

5.1 First hypothesis

1. The corals collected in South Africa will contain a higher concentration of metals and metalloids than those from the Mascarene Basin.

The highest concentration of alkaline earth metals were found in corals from the Mascarene Basin (Table 4). For all other elemental groups, the highest concentrations were found corals from South Africa. This hypothesis was accepted.

5.2 Second hypothesis

2. Soft corals will accumulate a higher concentration of metals and metalloids than hard corals.

The mineralogy/crystallography of coral skeletons play a large role in the types of metals that accumulate in corals. The aragonite skeleton of hard corals respond differently to metals than the calcite of soft corals. Hard corals show an affinity for alkaline earth metals (Table 4). Soft corals show a greater affinity to metallic elements than hard corals (Figure 27). However, several metals do not have a specific affinity to a certain coral type. Transitional metals, which is the group with the most known toxic elements, are prevalent in soft corals. This hypothesis was accepted.

5.3 General findings

In Section 1.3.4 (Threats to coral reefs), the process of ocean acidification was discussed. It was mentioned in Section 4.4 (Effects of different metals and metalloids on corals) that metals are only toxic to marine organisms when present as free elements. As the ocean's temperature rises and pH levels decreases more metals are

be freed from chemical compounds. This increases the toxicity and bioavailability of these pollutants.

Concentrations of metals in *Sinularia* from South Africa are a cause of concern. It has been indicated that the number of *Sinularia* colonies have decreased over the past twenty years in Sodwana (Porter & Schleyer, 2017). Porter and Scleyer did not attribute this decrease to a particular factor. Thus, metal concentration in the colonies could be a proposed reason, or at least a factor, for the decline, particularly because of the potential impeded fertilization of *Sinularia* colonies caused by very high Ni concentrations.

Because of rising anthropogenic pressure on the oceans, caused by, amongst other, overexploitation, overpopulation, global warming, and chemical pollution, coral reefs are predicted to be subjected to more stress in the nearby future. It is vital for the survival of coral reefs to integrate the knowledge of not only the concentration of metals and metalloid in corals from the WIO, but also the dangers posed thereby, into future conservation strategies.

Even though it is complicated to attribute specific symptoms of coral reef degradation, certain metals are toxic to corals and warrant special attention from a conservation standpoint. Copper, Hg, Fe, Ni, and Cd are the five metals that I consider most detrimental to coral reef health. Copper, Fe, and Cd can cause bleaching. Even though corals from South Africa recovered from a bleaching event in the past, it cannot be a certainty that the corals will recover every time, and all precautions should be taken to prevent a future bleaching event.

The high Ni concentrations in Sodwana should be considered as a great concern. Nickel was present in hard coral, and at very high concentration in soft corals. No data could be found regarding Ni contamination in other organisms from Sodwana. If fish from Sodwana exhibit the same level of contamination, it could be detrimental to the health of communities living in the area that rely on marine resources for a livelihood.

The geographic differences in accumulation patterns in metals and metalloids in corals from the WIO is very clear. Iron is the most widespread high concentration metal that occurs in both the Mascarene Islands and South African reefs. The high concentration of Fe and Cr in *Pocillopora* from SBR have a clear pollution source, namely the shallow wrecks on the atoll's edge. A prior study on the long range transport of plastic identified

marine debris as a vector for Hg contamination in remote oceanic islands (Bouwman *et al.* 2016). The issue of plastic pollution is currently one of the greatest environmental concerns. The probability that marine plastic debris could serve as a vector for metallic element contamination to remote islands is another factor in an already long list of reasons that this should be a primary conservation issue.

Even though metals are present in corals from the remote WIO locations, most of the metals were present as levels below environmental concern. Marine contamination is so widespread in modern times that no site in the ocean can be considered as free from at least a measure of contamination. The islands of Agalega and Rodrigues can be considered as reference sites for future studies in the WIO because they exhibited low metal concentrations.

Chapter 6: Recommendations

This study was intended as a pioneer study to determine the metal and metalloid content in hard and soft corals from the WIO. It is the first of its sort, and will contribute to the science of marine ecotoxicology in the region. Some recommendations may benefit similar studies in the future.

- Certain corals showed an affinity to specific metal groups. As an alternative to collecting nine coral genera, the number of target coral genera can be narrowed down, depending on the compound to be investigated. *Sinularia* is a widespread, easily available coral with the highest accumulation of most metals. *Pocillopora* is also widely available and easy to collect. For metals with an affinity to hard coral, such as U, Fe, and most of the alkaline earth metals, *Pocillopora* would be an ideal study genus. *Sinularia* could serve as a study genus for most other metals. Azooxanthellate corals, particularly *Eleutherobia*, would be the ideal study genus for metalloids. In the absence of *Eleutherobia*, most other corals without zooxanthellae could be considered.
- This study has shown a significant differentiation between sub classes of coral (Scleractinian and Alcyonarian) in the same class, and a difference in metal accumulation between different genera. This study could be extended to species level to determine the most vulnerable species that are most susceptible to metal contamination. This species specific study should at first be contained to Sodwana due to the logistical problems that the remoteness of the Mascarene Islands pose. Species specific collection should only be conducted by a researcher thoroughly proficient in coral identification.
- In future studies, abiotic factors of the environment should be recorded. Water temperature, salinity, and pH can all play a role in the solubility of metals in the surrounding water. Water and sediment from the site of collection should also be analysed for metallic element concentrations. This way a bioconcentration factor can be determined.
- This study should be incorporated into all conservation plans concerning St Brandon's Atoll. The concentration of Fe and Cr in *Pocillopora* from SBR are some of the highest in recorded literature. The removal of the wreck of the racing yacht from SBR in 2014 mentioned in Section 2.1.3, was conducted

without much difficulty or harm to the environment. It is recommended that a similar process should be implemented by the governing body of SBR to remove all other wrecks from the atoll.

- No part of the ocean is completely free of the influence of anthropogenic activity. However, Agalega Island could be considered a candidate for a reference site for future toxicological studies due to its remoteness and the lack of industrial activities.
- This study was the first to determine the concentration of metals and metalloids in corals from the WIO. Metals and metalloids are unfortunately not the only contaminants in the ocean. Long range transport of plastic in the Indian Ocean is currently being investigated. However, the concentrations of persistent organic pollutants in low trophic organisms in the WIO remains a mystery. POPs have been found in bird eggs from Rodrigues (Bouwman *et al.*, 2012). The next step should be to analyse corals and corallivorous fish for POPs. Corallivorous fish should also be analysed for metals and metalloid content to examine the bioaccumulative impacts that these toxicants have.
- A mercury analysis of the corals and corallivorous fish should be conducted.
- The high concentrations of Ni in *Sinularia* from South Africa, and the decline of soft corals in Sodwana, warrants further investigation.
- The ilmenite mine located near Richards Bay is the speculated source of several metals found at high concentrations from South Africa. Littoral drift, as discussed in Section 1.4, can potentially transport metals associated with ilmenite further north. This has yet to be concretely proven. I recommend that a follow-up environmental impact assessment should be conducted to confirm, or rule out, the mine, and other dune mining practices at other locations in KwaZulu-Natal and Mozambique as contamination sources.

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Appendix 1

Acropora (n=3 per site)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Agalega	76	66	54	110	24	31
	Rodrigues	50	52	42	55	6	11
	SBR	56	64	24	78	23	41
	Sodwana	100	110	83	120	14	14
Ti	Agalega	4.5	3.9	3.4	6.1	1.2	26
	Rodrigues	2.9	2.9	2.6	3.2	0.25	9
	SBR	3.2	3.5	1.8	4.1	1	31
	Sodwana	3.8	3.8	2.9	4.8	0.8	20
V	Agalega	0.0025	0.0026	0.0015	0.0034	0.00078	32
	Rodrigues	0.0037	0.0037	0.0033	0.0043	0.00041	11
	SBR	0.0033	0.0030	0.0024	0.0045	0.00087	27
	Sodwana	0.31	0.37	0.18	0.39	0.093	30
Cr	Agalega	1.8	2.1	0.1	3.1	1.3	70
	Rodrigues	0.17	0.0025	0.00013	0.52	0.25	140
	SBR	1.7	1.6	0.011	3.4	1.4	84
	Sodwana	6.4	6.4	6.4	6.5	0.03	0.5
Mn	Agalega	0.82	0.088	0.061	0.096	0.015	18
	Rodrigues	0.099	0.097	0.086	0.11	0.011	11
	SBR	0.92	0.088	0.085	0.1	0.0086	9
	Sodwana	4.7	4.7	3.3	6.2	1.2	25
Fe	Agalega	630	600	540	740	84	14
	Rodrigues	470	470	450	500	23	5
	SBR	550	600	390	670	120	22
	Sodwana	990	970	960	1040	36	4
Co	Agalega	0.57	0.52	0.44	0.75	0.13	23
	Rodrigues	0.012	0.013	0.0095	0.014	0.0019	16
	SBR	0.56	0.48	0.31	0.89	0.24	43
	Sodwana	1.6	1.6	1.5	1.7	0.055	3
Ni	Agalega	3.7	3.3	2.7	5.1	1	27
	Rodrigues	2.7	2.9	1.6	3.7	0.87	32
	SBR	2	2.5	0.27	3.4	1.3	34
	Sodwana	4.1	3.9	3.8	4.5	0.28	7
Cu	Agalega	0.23	0.23	0.22	0.24	0.0053	2
	Rodrigues	0.21	0.22	0.21	0.23	0.006	3
	SBR	0.21	0.22	0.22	0.22	0.009	1
	Sodwana	0.98	1.1	0.53	1.4	0.34	35
Zn	Agalega	0.16	0.20	0.026	0.24	0.094	60
	Rodrigues	0.17	0.23	0.025	0.25	0.10	60
	SBR	0.23	0.23	0.22	0.24	0.009	4
	Sodwana	0.02	0.015	0.011	0.022	0.004	28
As	Agalega	0.025	0.0017	0.00007	0.073	0.034	137
	Rodrigues	0.009	0.0018	0.00054	0.023	0.010	122
	SBR	0.041	0.0015	0.0012	0.12	0.057	137

	Sodwana	0.300	0.28	0.15	0.47	0.130	43
Se	Agalega	0.010	0.011	0.0079	0.011	0.0015	15
	Rodrigues	0.012	0.013	0.0095	0.014	0.0019	16
	SBR	0.0091	0.0089	0.0079	0.010	0.0011	12
	Sodwana	0.0023	0.0025	0.0019	0.0026	0.0003	13
Sr	Agalega	8000	8100	7603	8500	350	4
	Rodrigues	7600	7600	7100	8000	370	5
	SBR	8900	8500	7400	11000	1500	16
	Sodwana	8400	8100	8000	9000	420	5
Ag	Agalega	0.0025	0.0032	0.0011	0.0033	0.0010	41
	Rodrigues	0.0028	0.0029	0.0026	0.003	0.00017	6
	SBR	0.0029	0.0030	0.0026	0.003	0.00019	7
	Sodwana	0.80	1.1	0.2	1.1	0.43	54
Cd	Agalega	0.17	0.23	0.033	0.25	0.096	57
	Rodrigues	0.0044	0.0018	0.0011	0.01	0.0042	95
	SBR	0.0010	0.0011	0.0006	0.0013	0.0003	30
	Sodwana	0.14	0.11	0.067	0.23	0.067	49
Au	Agalega	0.020	0.020	0.081	0.021	0.0012	6
	Rodrigues	0.019	0.019	0.019	0.019	0.00032	2
	SBR	0.020	0.020	0.02	0.020	0.00037	2
	Sodwana	0.007	0.0074	0.0057	0.0079	0.00093	13
Hg	Agalega	0.017	0.017	0.015	0.018	0.0012	7
	Rodrigues	0.018	0.018	0.017	0.018	0.00015	1
	SBR	0.018	0.018	0.017	0.018	0.00023	1
	Sodwana	0.027	0.027	0.025	0.028	0.0013	5
Pb	Agalega	0.01	0.01	0.01	0.011	0.00026	3
	Rodrigues	0.011	0.011	0.01	0.011	0.00043	4
	SBR	0.0091	0.010	0.0055	0.012	0.0028	30
	Sodwana	0.36	0.30	0.21	0.56	0.15	42
U	Agalega	3.1	2.9	2.9	3.4	0.23	8
	Rodrigues	2.9	3.1	2.5	3.2	0.30	10
	SBR	3.1	3.0	2.5	3.8	0.53	17
	Sodwana	2.9	2.8	2.8	3.1	0.14	5
Tl	Agalega	0.0012	0.0012	0.0012	0.0012	5.6E-06	0.5
	Rodrigues	0.0012	0.0012	0.0011	0.0012	9.4E-06	1
	SBR	0.0012	0.0012	0.0012	0.0012	3.4E-06	0.3
	Sodwana	0.0007	0.0007	0.0007	0.0007	2.4E-06	0.3
Be	Agalega	0.00091	0.00092	0.00088	0.00092	0.000018	2
	Rodrigues	0.00092	0.00092	0.00087	0.00095	0.000033	4
	SBR	0.00091	0.00091	0.00090	0.00092	9.7E-06	1
	Sodwana	0.00060	0.00059	0.00059	0.00061	0.000012	2
B	Agalega	45	42	39	53	5.9	13
	Rodrigues	47	46	43	51	3.0	6
	SBR	55	47	46	72	12.0	22
	Sodwana	61	57	56	70	6.4	10
Mg	Agalega	1900	1800	1800	2100	140	7
	Rodrigues	1500	1500	1500	1500	29	2

	SBR	1800	1700	1300	2200	380	22
	Sodwana	2000	1900	1900	2200	150	8
Mo	Agalega	0.02	0.02	0.019	0.02	0.00025	1
	Rodrigues	0.02	0.02	0.02	0.02	0.00007	0.3
	SBR	0.02	0.02	0.0196	0.0201	0.0002	1
	Sodwana	0.027	0.027	0.025	0.028	0.0012	4
Pd	Agalega	8.8	8.9	8.3	9.3	0.43	5
	Rodrigues	8.4	8.4	7.9	8.9	0.42	5
	SBR	9.9	9.3	8.2	12	1.6	16
	Sodwana	11	11	10	12	0.44	4
Sb	Agalega	0.0013	0.0014	0.0012	0.0014	0.00011	9
	Rodrigues	0.0013	0.0013	0.0011	0.0015	0.00018	14
	SBR	0.0008	0.001	0.0003	0.0012	0.00040	48
	Sodwana	0.0005	0.0005	0.0004	0.0006	0.00009	18
Ba	Agalega	8.1	7.2	7.1	10	1.4	18
	Rodrigues	17	17	8.1	27	7.7	44
	SBR	27	25	24	33	3.8	14
	Sodwana	10	8.6	8.2	14	2.8	27
Pt	Agalega	0.00071	0.00069	0.00062	0.00080	0.000073	10
	Rodrigues	0.00064	0.00075	0.00041	0.00076	0.00016	25
	SBR	0.0047	0.00079	0.00075	0.012	0.0055	118
	Sodwana	0.024	0.0061	0.00011	0.066	0.03	124
Bi	Agalega	0.00080	0.00080	0.0008	0.0008	3.3E-06	0.4
	Rodrigues	0.00082	0.00083	0.00082	0.00083	4.5E-06	0.5
	SBR	0.00081	0.00080	0.00078	0.00083	0.00002	2
	Sodwana	0.00030	0.00029	0.00029	0.00031	8.4E-06	3
Th	Agalega	0.00019	0.00026	0.000034	0.00029	0.00011	59
	Rodrigues	0.00035	0.00036	0.00031	0.00037	0.000026	7
	SBR	0.00039	0.00037	0.00037	0.00043	0.000027	7
	Sodwana	0.0074	0.0068	0.0065	0.0089	0.0011	15

Fungia (n=3 per site)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Agalega	120	88	45	230	79	65
	Rodrigues	100	91	69	140	31	31
	SBR	79	72	57	110	22	27
Ti	Agalega	5.8	3.7	2.4	11	3.9	67
	Rodrigues	5.3	4.5	3.2	8.2	2.1	41
	SBR	3.8	3.5	2.8	5.2	1.0	26
V	Agalega	0.082	0.0034	0.0017	0.24	0.11	137
	Rodrigues	0.0052	0.0026	0.0015	0.011	0.0045	86
	SBR	0.0016	0.0011	0.0010	0.0027	0.0008	51
Cr	Agalega	6.1	5.4	1.3	11	4.2	69
	Rodrigues	4.7	3.9	2.6	7.5	2.0	44
	SBR	4.6	4.1	2.0	7.6	2.3	50
Mn	Agalega	0.53	0.091	0.045	1.5	0.65	123
	Rodrigues	0.048	0.048	0.034	0.062	0.011	24
	SBR	0.067	0.084	0.022	0.095	0.032	48
Fe	Agalega	870	810	590	1200	260	29
	Rodrigues	770	770	620	910	120	15
	SBR	750	640	600	1000	180	25
Co	Agalega	1.1	1.10	0.65	1.6	0.39	35
	Rodrigues	0.89	0.94	0.64	1.1	0.19	21
	SBR	0.92	0.63	0.62	1.5	0.41	45
Ni	Agalega	6.7	5.4	2.1	12	4.4	65
	Rodrigues	5.3	4.7	3.9	7.4	1.5	28
	SBR	4.9	3.8	3.2	7.8	2.1	42
Cu	Agalega	0.21	0.21	0.20	0.22	0.0077	4
	Rodrigues	0.21	0.21	0.19	0.22	0.013	6
	SBR	0.23	0.23	0.22	0.23	0.0058	3
Zn	Agalega	4.0	0.20	0.16	12	5.4	135
	Rodrigues	0.21	0.21	0.19	0.24	0.020	9
	SBR	0.11	0.11	0.026	0.19	0.066	61
As	Agalega	0.0026	0.0029	0.0017	0.0032	0.00065	25
	Rodrigues	0.0022	0.0032	0.00012	0.0034	0.0015	67
	SBR	0.12	0.15	0.021	0.20	0.075	61
Se	Agalega	0.010	0.0095	0.0090	0.013	0.0016	15
	Rodrigues	0.011	0.010	0.0093	0.013	0.0017	16
	SBR	0.017	0.011	0.0088	0.031	0.010	60
Sr	Agalega	9400	9100	8500	11000	870	9
	Rodrigues	8200	8200	7500	9000	610	7
	SBR	9100	8300	7500	11000	1700	19
Ag	Agalega	0.0023	0.0023	0.0020	0.0026	0.00022	10
	Rodrigues	0.0024	0.0024	0.0023	0.0026	0.00012	5
	SBR	0.0021	0.0021	0.0010	0.0031	0.00086	41
Cd	Agalega	0.0023	0.0023	0.0019	0.0026	0.00029	13
	Rodrigues	0.0025	0.0026	0.0020	0.0028	0.00032	13
	SBR	0.0016	0.0016	0.0012	0.0019	0.00025	16

Au	Agalega	0.020	0.020	0.018	0.020	0.0010	5
	Rodrigues	0.019	0.020	0.018	0.020	0.00078	4
	SBR	0.014	0.019	0.0022	0.020	0.0083	60
Hg	Agalega	0.018	0.018	0.018	0.018	0.000057	0.3
	Rodrigues	0.018	0.018	0.018	0.018	0.000077	0.4
	SBR	0.012	0.018	0.00018	0.018	0.0083	70
Pb	Agalega	0.0094	0.0094	0.008	0.011	0.0011	12
	Rodrigues	0.0069	0.0074	0.0013	0.012	0.0045	64
	SBR	0.011	0.012	0.0095	0.013	0.0016	14
U	Agalega	3.5	3.2	3.1	4.0	0.4	12
	Rodrigues	2.6	2.7	2.3	2.8	0.2	8
	SBR	3.0	2.8	2.4	3.8	0.6	20
Tl	Agalega	0.0012	0.0012	0.0011	0.0012	0.000013	1
	Rodrigues	0.0012	0.0012	0.0012	0.0012	7.3E-06	1
	SBR	0.00079	0.0012	0.00004	0.0012	0.00052	67
Be	Agalega	0.00091	0.00091	0.00091	0.00092	5.9E-06	1
	Rodrigues	0.00092	0.00091	0.00090	0.00093	0.000012	1
	SBR	0.00069	0.00090	0.00026	0.00092	0.00031	45
B	Agalega	62	57	49	79	12	20
	Rodrigues	53	56	43	60	7	13
	SBR	68	73	49	81	14	20
Mg	Agalega	2200	2200	1700	2700	410	19
	Rodrigues	1900	1900	1300	2400	430	23
	SBR	2100	2100	1600	2600	410	20
Mo	Agalega	0.02	0.02	0.020	0.021	0.00018	1
	Rodrigues	0.02	0.02	0.02	0.02	0.00018	1
	SBR	0.015	0.019	0.004	0.02	0.0074	50
Pd	Agalega	11	10	9.4	12	1.1	10
	Rodrigues	9.4	9.2	8.7	10	0.7	7
	SBR	11	14	8.6	13	1.9	17
Sb	Agalega	0.0012	0.0011	0.0011	0.0013	0.00010	9
	Rodrigues	0.0010	0.0009	0.0008	0.0013	0.00022	22
	SBR	0.0007	0.0008	0.0001	0.0013	0.00049	67
Ba	Agalega	7.9	8.2	6.8	8.7	0.81	10
	Rodrigues	6.7	6.7	6.3	7.1	0.34	5
	SBR	7.1	6.2	5.8	9.4	1.6	23
Pt	Agalega	0.00054	0.00076	0.000074	0.00079	0.00033	61
	Rodrigues	0.00077	0.00078	0.00073	0.00079	0.000025	3
	SBR	0.00058	0.00076	0.00019	0.00078	0.00027	47
Bi	Agalega	0.00080	0.00081	0.00078	0.00081	0.000015	2
	Rodrigues	0.00078	0.00079	0.00072	0.00081	0.000038	5
	SBR	0.00058	0.00080	0.00014	0.00081	0.00031	53
Th	Agalega	0.00036	0.00037	0.00033	0.00038	0.00002	6
	Rodrigues	0.00037	0.00036	0.00033	0.00041	0.000031	9
	SBR	0.030	0.00040	0.00032	0.090	0.042	140

<i>Pocillopora</i> (n=3 per site)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Rodrigues	360	340	330	420	38	10
	SBR	42	470	300	480	83	20
	Sodwana	370	320	290	510	97	26
	Aliwal	200	200	200	210	6	3
Ti	Rodrigues	20	19	18	24	2.5	12
	SBR	23	26	17	26	4.1	18
	Sodwana	18	16	13	24	4.4	25
	Aliwal	8.1	8.1	7.8	8.4	0.2	3
V	Rodrigues	1.0	0.93	0.73	1.3	0.25	25
	SBR	1.1	1.4	0.67	1.4	0.34	29
	Sodwana	1.2	1.1	0.94	1.6	0.27	23
	Aliwal	0.72	0.70	0.69	0.75	0.027	4
Cr	Rodrigues	26	24	20	32	5.1	20
	SBR	30	34	22	34	5.8	20
	Sodwana	22	20	17	29	5.2	23
	Aliwal	9.2	9.3	9.1	9.3	0.1	1
Mn	Rodrigues	17	14	12	25	5.5	32
	SBR	24	29	12	32	8.9	37
	Sodwana	27	22	20	39	8.2	31
	Aliwal	9.5	9.8	8.7	9.9	0.5	6
Fe	Rodrigues	2200	2000	1900	2600	280	13
	SBR	2500	2900	1800	2900	530	21
	Sodwana	2200	2000	1900	2800	430	19
	Aliwal	1200	1200	1100	1200	21	2
Co	Rodrigues	2.9	2.7	2.6	3.5	0.42	14
	SBR	3.5	3.8	2.3	4.4	0.86	25
	Sodwana	3.7	3.3	3.1	4.7	0.71	19
	Aliwal	1.9	1.9	1.8	1.9	0.021	1
Ni	Rodrigues	26	25	22	31	4	16
	SBR	32	37	20	39	8.3	26
	Sodwana	24	20	18	36	7.8	32
	Aliwal	6.0	6.2	5.6	6.2	0.27	5
Cu	Rodrigues	0.21	0.23	0.18	0.23	0.024	11
	SBR	0.21	0.21	0.20	0.23	0.014	6
	Sodwana	1.1	0.96	0.91	1.4	0.22	20
	Aliwal	0.57	0.48	0.42	0.80	0.17	29
Zn	Rodrigues	0.22	0.24	0.19	0.25	0.024	11
	SBR	0.15	0.12	0.082	0.25	0.070	46
	Sodwana	1.8	2.2	0.97	2.3	0.60	33
	Aliwal	0.91	1.0	0.18	1.5	0.56	62
As	Rodrigues	0.0017	0.0021	0.00090	0.0022	0.00058	34
	SBR	0.0018	0.0019	0.0013	0.0021	0.00036	20
	Sodwana	0.33	0.31	0.27	0.41	0.062	19
	Aliwal	0.72	0.71	0.68	0.76	0.032	4
Se	Rodrigues	0.0092	0.0088	0.008	0.011	0.0012	13

	SBR	0.010	0.0098	0.0096	0.011	0.00084	8
	Sodwana	0.0028	0.0030	0.0021	0.0032	0.00049	18
	Aliwal	0.0012	0.0014	0.0003	0.0018	0.00065	55
Sr	Rodrigues	9500	9100	8200	11000	1300	14
	SBR	8600	8600	8500	8800	140	2
	Sodwana	7400	7300	7200	7700	220	3
	Aliwal	6900	7100	6700	7100	160	2
Ag	Rodrigues	0.0035	0.0037	0.0030	0.0039	0.00040	11
	SBR	0.0033	0.0032	0.0032	0.0035	0.00017	5
	Sodwana	7.8	4	0.53	19	8	102
	Aliwal	0.50	0.39	0.35	0.76	0.18	36
Cd	Rodrigues	0.0021	0.0021	0.0016	0.0025	0.00039	19
	SBR	0.0027	0.0027	0.0026	0.0029	0.00010	4
	Sodwana	0.043	0.046	0.035	0.049	0.0060	14
	Aliwal	0.12	0.11	0.10	0.13	0.0099	9
Au	Rodrigues	0.021	0.021	0.021	0.022	0.0005	2
	SBR	0.021	0.022	0.020	0.022	0.00066	3
	Sodwana	0.0052	0.0069	0.0006	0.008	0.0033	63
	Aliwal	0.0076	0.0076	0.0071	0.0082	0.00045	6
Hg	Rodrigues	0.016	0.016	0.016	0.017	0.00056	3
	SBR	0.018	0.018	0.017	0.018	0.00026	1
	Sodwana	0.020	0.019	0.013	0.028	0.0063	32
	Aliwal	0.029	0.029	0.028	0.029	0.00033	1
Pb	Rodrigues	0.012	0.013	0.01	0.013	0.0013	11
	SBR	0.0098	0.008	0.0077	0.014	0.0027	28
	Sodwana	0.22	0.14	0.11	0.41	0.13	59
	Aliwal	0.16	0.17	0.10	0.19	0.037	24
U	Rodrigues	3.6	3.3	3.3	4.2	0.41	11
	SBR	3.0	3.0	2.8	3.2	0.15	5
	Sodwana	2.4	2.3	2.3	2.5	0.087	4
	Aliwal	2.1	2.1	2.0	2.2	0.054	3
Tl	Rodrigues	0.0012	0.0012	0.0012	0.0012	3.4E-06	0
	SBR	0.0012	0.0012	0.0012	0.0012	0.000017	1
	Sodwana	0.00069	0.00068	0.00068	0.00069	5.3E-06	1
	Aliwal	0.00071	0.00071	0.00070	0.00073	0.000012	2
Be	Rodrigues	0.00098	0.00097	0.00097	0.001	0.000014	1
	SBR	0.00099	0.001	0.00094	0.001	0.000038	4
	Sodwana	0.00058	0.00057	0.00054	0.00062	0.000033	6
	Aliwal	0.00056	0.00055	0.00053	0.00060	0.000028	5
B	Rodrigues	67	70	62	70	3.6	5
	SBR	70	69	68	74	2.9	4
	Sodwana	48	48	42	53	4.6	10
	Aliwal	45	45	42	49	2.6	6
Mg	Rodrigues	4600	4300	4000	56000	690	15
	SBR	5300	5700	4000	6300	970	18
	Sodwana	5300	4800	4600	6600	920	17
	Aliwal	4100	4100	3900	4300	180	4

Mo	Rodrigues	0.021	0.021	0.021	0.021	0.00024	1
	SBR	0.021	0.021	0.021	0.022	0.00033	2
	Sodwana	0.027	0.028	0.027	0.028	0.00017	1
	Aliwal	0.028	0.028	0.028	0.028	0.00014	0
Pd	Rodrigues	13	12	11	15	1.9	15
	SBR	12	11	11	12	0.32	3
	Sodwana	11	11	10	11	0.47	4
	Aliwal	11	11	10	11	0.33	3
Sb	Rodrigues	0.0014	0.0014	0.0014	0.0015	0.000035	2
	SBR	0.0013	0.0013	0.00094	0.0016	0.00026	20
	Sodwana	0.049	0.00073	0.00055	0.15	0.069	140
	Aliwal	0.00018	0.00019	0.000054	0.0003	0.0001	56
Ba	Rodrigues	17	14	13	24	5.2	31
	SBR	11	11	8.9	14	2	18
	Sodwana	11	11	11	13	1.2	11
	Aliwal	11	11	9.7	12	1.2	11
Pt	Rodrigues	0.00054	0.00064	0.00016	0.00082	0.00028	51
	SBR	0.00083	0.00083	0.00075	0.00090	0.000058	7
	Sodwana	0.0050	0.00019	0.000069	0.015	0.0068	138
	Aliwal	0.042	0.00023	0.00017	0.13	0.06	141
Bi	Rodrigues	0.00084	0.00084	0.00082	0.00086	0.000013	2
	SBR	0.00083	0.00083	0.00081	0.00084	0.000011	1
	Sodwana	0.00029	0.0003	0.00027	0.00030	0.000017	6
	Aliwal	0.00029	0.00029	0.00029	0.00030	6.93E-06	2
Th	Rodrigues	0.00022	0.00023	0.00017	0.00025	0.000031	15
	SBR	0.00027	0.00026	0.00024	0.00031	0.000027	10
	Sodwana	0.023	0.019	0.018	0.031	0.0056	25
	Aliwal	0.021	0.020	0.016	0.027	0.0045	22

Stylophora (n=3 per site)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Agalega	120	120	80	140	26	23
	Rodrigues	240	230	220	260	15	7
	SBR	240	300	120	290	82	35
	Aliwal	260	260	250	280	12	4
Ti	Agalega	6.8	7.7	4.8	7.9	1.4	21
	Rodrigues	14	14	12	15	1.0	8
	SBR	12	15	6	16	4.4	36
	Aliwal	9.3	9.6	8.5	9.8	0.6	6
V	Agalega	0.096	0.11	0.0015	0.18	0.072	75
	Rodrigues	0.48	0.49	0.38	0.56	0.074	15
	SBR	0.44	0.59	0.0095	0.7	0.3	70
	Aliwal	0.95	0.92	0.92	1	0.045	5
Cr	Agalega	13	14	8.7	15	2.7	22
	Rodrigues	19	18	14	23	3.6	20
	SBR	18	20	10	23	5.5	31
	Aliwal	8.4	7.8	7	11	1.5	18
Mn	Agalega	0.044	0.025	0.025	0.081	0.026	60
	Rodrigues	4.8	3.5	3.4	7.5	1.9	40
	SBR	6.4	8.0	0.016	11	4.7	73
	Aliwal	10	10	9.2	11	0.65	6
Fe	Agalega	940	1100	680	1100	180	19
	Rodrigues	1500	1400	1400	1700	140	10
	SBR	1400	1600	890	1700	370	26
	Aliwal	1200	1100	1100	1200	59	5
Co	Agalega	1	1.1	0.6	1.3	0.31	31
	Rodrigues	2	2	1.7	2.3	0.23	11
	SBR	1.8	2.1	1.0	2.3	0.55	31
	Aliwal	1.9	1.9	1.9	2.0	0.08	4
Ni	Agalega	7.4	8.8	4.3	9.0	2.2	29
	Rodrigues	15	14	13	18	2.2	15
	SBR	15	19	7.3	20	5.8	37
	Aliwal	5.7	5.7	4.8	6.7	0.8	13
Cu	Agalega	0.22	0.23	0.18	0.25	0.028	13
	Rodrigues	0.21	0.24	0.16	0.24	0.04	19
	SBR	0.23	0.23	0.22	0.24	0.009	4
	Aliwal	0.78	0.83	0.64	0.86	0.097	12
Zn	Agalega	0.22	0.23	0.18	0.25	0.027	12
	Rodrigues	0.22	0.24	0.17	0.25	0.036	16
	SBR	0.15	0.20	0.025	0.21	0.085	58
	Aliwal	1.2	1.2	0.64	1.6	0.41	35
As	Agalega	0.0019	0.0024	0.00087	0.0024	0.00074	38
	Rodrigues	0.06	0.072	0.00085	0.11	0.044	74
	SBR	0.066	0.0018	0.0014	0.19	0.091	138
	Aliwal	1.6	1.6	1.5	1.7	0.11	7

Se	Agalega	0.011	0.011	0.011	0.011	0.00011	1
	Rodrigues	0.012	0.011	0.011	0.013	0.00067	6
	SBR	0.013	0.013	0.012	0.014	0.00065	5
	Aliwal	0.38	0.43	0.22	0.5	0.12	31
Sr	Agalega	7500	7700	6600	8400	740	10
	Rodrigues	9100	8900	8600	9700	450	5
	SBR	7600	7600	7300	8000	300	4
	Aliwal	7000	7200	6500	7300	360	5
Ag	Agalega	0.0031	0.0031	0.0029	0.0032	0.0001	3
	Rodrigues	0.0038	0.0039	0.0034	0.0041	0.00031	8
	SBR	0.43	0.0033	0.0031	1.3	0.6	140
	Aliwal	0.81	0.93	0.57	0.94	0.17	21
Cd	Agalega	0.0018	0.0024	0.00046	0.0026	0.00098	53
	Rodrigues	0.0029	0.0029	0.0028	0.0029	0.000037	1
	SBR	0.0022	0.0022	0.0018	0.0027	0.00033	15
	Aliwal	0.14	0.14	0.13	0.14	0.0079	6
Au	Agalega	0.022	0.022	0.021	0.022	0.00015	1
	Rodrigues	0.022	0.023	0.021	0.023	0.00081	4
	SBR	0.022	0.022	0.022	0.022	0.00025	1
	Aliwal	0.0063	0.0063	0.0045	0.0081	0.0015	23
Hg	Agalega	0.019	0.019	0.018	0.019	0.00034	2
	Rodrigues	0.019	0.018	0.018	0.019	0.00035	2
	SBR	0.017	0.019	0.013	0.019	0.0029	17
	Aliwal	0.029	0.028	0.028	0.029	0.0003	1
Pb	Agalega	0.0078	0.0072	0.0029	0.013	0.0043	55
	Rodrigues	0.01	0.011	0.007	0.013	0.0025	24
	SBR	0.0069	0.0081	0.0012	0.012	0.0043	62
	Aliwal	3.1	0.35	0.28	8.7	4.0	127
U	Agalega	2.1	2.2	1.8	2.3	0.19	9
	Rodrigues	2.8	2.8	2.6	3.0	0.16	6
	SBR	2.3	2.3	2.1	2.7	0.25	11
	Aliwal	2.8	2.9	2.5	2.9	0.16	6
Tl	Agalega	0.0012	0.0012	0.0012	0.0013	4.701E-06	0
	Rodrigues	0.0012	0.0012	0.0012	0.0013	8.795E-06	1
	SBR	0.0012	0.0012	0.0012	0.0013	5.903E-06	0
	Aliwal	0.00073	0.00073	0.00072	0.00074	0.00001	1
Be	Agalega	0.001	0.001	0.001	0.001	8.471E-06	1
	Rodrigues	0.001	0.001	0.00098	0.001	0.000021	2
	SBR	0.001	0.001	0.00096	0.001	0.000026	3
	Aliwal	0.00051	0.00051	0.00046	0.00055	0.00004	8
B	Agalega	57	59	51	59	3.8	7
	Rodrigues	66	67	58	73	6.1	9
	SBR	59	58	56	61	2.0	3
	Aliwal	39	38	36	44	3.6	9
Mg	Agalega	2600	2700	2000	3100	430	17
	Rodrigues	3800	3700	3700	4000	160	4

	SBR	3400	3900	2400	3900	670	20
	Aliwal	3400	3300	3300	3600	140	4
Mo	Agalega	0.022	0.022	0.0221	0.0224	0.00012	1
	Rodrigues	0.021	0.022	0.020	0.022	0.00072	3
	SBR	0.022	0.022	0.0218	0.0221	0.000087	0
	Aliwal	0.026	0.026	0.026	0.026	0.0002	1
Pd	Agalega	11	11	9.4	12	0.93	9
	Rodrigues	13	12	12	14	0.81	6
	SBR	11	11	10	11	0.45	4
	Aliwal	12	12	11	12	0.41	4
Sb	Agalega	0.0014	0.0013	0.0013	0.0015	0.000081	6
	Rodrigues	0.0013	0.0012	0.001	0.0015	0.0002	16
	SBR	0.0012	0.0012	0.00095	0.0014	0.00017	14
	Aliwal	0.00028	0.00029	0.000036	0.00051	0.00020	70
Ba	Agalega	6.2	5.8	4.5	8.3	1.6	25
	Rodrigues	8.6	8.4	8.3	9.0	0.29	3
	SBR	7.8	8.3	6.1	8.9	1.2	16
	Aliwal	11	11	10	12	0.59	5
Pt	Agalega	0.00076	0.00085	0.00055	0.00088	0.00015	20
	Rodrigues	0.0016	0.00087	0.00083	0.003	0.001	65
	SBR	0.00077	0.00077	0.00067	0.00088	0.000085	11
	Aliwal	0.012	0.00023	0.00021	0.035	0.016	139
Bi	Agalega	0.00085	0.00085	0.00083	0.00086	0.000012	1
	Rodrigues	0.00081	0.00083	0.00079	0.00083	0.000018	2
	SBR	0.00082	0.00081	0.00081	0.00083	0.000011	1
	Aliwal	0.00034	0.00034	0.00033	0.00035	6.456E-06	2
Th	Agalega	0.00042	0.00042	0.00041	0.00042	7.062E-06	2
	Rodrigues	0.00035	0.00035	0.00034	0.00035	7.409E-06	2
	SBR	0.00036	0.00034	0.00033	0.0004	0.000031	9
	Aliwal	0.014	0.014	0.013	0.016	0.0011	7

Sinularia (n=3 per site)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Agalega	49	51	17	80	26	52
	Rodrigues	58	53	48	72	11	18
	SBR	35	31	20	53	14	39
	Sodwana	270	240	230	320	41	16
	Aliwal	440	440	400	480	36	8
Ti	Agalega	2.6	1.7	1.6	4.6	1.4	53
	Rodrigues	4.5	5.3	2.3	6.0	1.6	36
	SBR	2.8	2.4	1.9	4.0	0.9	33
	Sodwana	16	15.0	14	21	3.1	19
	Aliwal	23	22	22	25	1.5	7
V	Agalega	0.22	0.0041	0.0028	0.65	0.31	139
	Rodrigues	0.0012	0.0014	0.00072	0.0016	0.00039	31
	SBR	0.0025	0.0029	0.0014	0.0031	0.00075	30
	Sodwana	1.7	1.6	1.3	2.1	0.31	19
	Aliwal	3.6	3.6	3.3	3.9	0.22	6
Cr	Agalega	4.3	3.9	1.8	7.0	2.1	50
	Rodrigues	4.5	4.3	3.7	5.6	0.8	17
	SBR	4.0	4.1	3.3	4.6	0.5	14
	Sodwana	7.4	7.6	6.8	7.9	0.4	6
	Aliwal	13	12	12	14	0.7	6
Mn	Agalega	4.9	0.13	0.044	14	6.7	139
	Rodrigues	0.06	0.078	0.027	0.085	0.026	41
	SBR	0.10	0.097	0.097	0.12	0.0087	8
	Sodwana	15	14	14	17	1.6	11
	Aliwal	47	40	37	64	12	26
Fe	Agalega	430	320	300	660	160	39
	Rodrigues	430	400	360	520	68	16
	SBR	440	440	310	570	110	24
	Sodwana	1400	1400	1300	1500	120	9
	Aliwal	1600	1700	1600	1700	57	3
Co	Agalega	0.39	0.51	0.00077	0.65	0.28	72
	Rodrigues	0.19	0.087	0.067	0.40	0.15	83
	SBR	0.27	0.24	0.00051	0.57	0.23	86
	Sodwana	17	17	17	18	0.47	3
	Aliwal	14	13	11	16	2.2	16
Ni	Agalega	4.9	5.3	0.0033	9.4	3.9	79
	Rodrigues	3.0	2.9	1.9	4	0.85	29
	SBR	1.5	1.4	1.03	2.2	0.48	32
	Sodwana	1300	1200	1200	1400	71	6
	Aliwal	630	600	500	790	120	20
Cu	Agalega	0.13	0.14	0.025	0.24	0.087	65
	Rodrigues	0.21	0.21	0.19	0.23	0.016	8
	SBR	0.23	0.23	0.22	0.24	0.011	5
	Sodwana	4.7	4.9	4.3	4.9	0.28	6
	Aliwal	2.4	2.5	2.0	2.7	0.33	14

Zn	Agalega	39	0.22	0.21	120	55	141
	Rodrigues	3.3	0.19	0.10	9.6	4.5	135
	SBR	0.22	0.22	0.21	0.24	0.015	7
	Sodwana	12	12	11	13	0.47	4
	Aliwal	6.9	7.6	4.9	8.1	1.4	20
As	Agalega	1.1	0.7	0.54	1.9	0.60	57
	Rodrigues	1.4	1.4	0.65	2.2	0.63	45
	SBR	1.6	1.9	0.94	2.0	0.48	29
	Sodwana	6.5	6.6	6.3	6.7	0.20	3
	Aliwal	6.5	6.5	6.2	6.8	0.24	4
Se	Agalega	0.0081	0.0094	0.0053	0.0097	0.0020	25
	Rodrigues	0.0057	0.0047	0.0040	0.0083	0.0019	33
	SBR	0.0096	0.0090	0.0087	0.011	0.0011	12
	Sodwana	1.1	1.1	0.84	1.5	0.25	22
	Aliwal	0.54	0.54	0.38	0.69	0.13	24
Sr	Agalega	2400	2500	2100	2600	220	9
	Rodrigues	1900	1900	1700	2000	130	7
	SBR	2400	2500	1800	3000	480	20
	Sodwana	2000	1900	1900	2100	110	6
	Aliwal	800	770	720	910	81	10
Ag	Agalega	0.18	0.0028	0.0016	0.52	0.25	140
	Rodrigues	0.30	0.0024	0.0011	0.89	0.42	141
	SBR	0.10	0.0021	0.002	0.29	0.14	138
	Sodwana	1.5	1.4	0.85	2.2	0.55	37
	Aliwal	1.1	1.00	0.85	1.4	0.23	21
Cd	Agalega	1.8	1.3	1.0	3.1	0.9	51
	Rodrigues	3.6	3.9	0.00096	6.8	2.8	78
	SBR	2.8	2.6	1.4	4.4	1.3	45
	Sodwana	24	25	23	26	1.1	4
	Aliwal	20	19	16	25	3.8	19
Au	Agalega	0.019	0.019	0.019	0.02	0.00053	3
	Rodrigues	0.018	0.018	0.017	0.02	0.001	6
	SBR	0.021	0.021	0.021	0.022	0.00023	1
	Sodwana	0.75	0.25	0.0004	2	0.89	118
	Aliwal	0.03	0.0081	0.0071	0.075	0.032	106
Hg	Agalega	0.017	0.019	0.015	0.019	0.0018	11
	Rodrigues	0.018	0.018	0.017	0.019	0.0007	4
	SBR	0.019	0.019	0.019	0.019	0.00016	1
	Sodwana	0.19	0.016	0.0089	0.54	0.25	132
	Aliwal	0.028	0.029	0.027	0.029	0.00088	3
Pb	Agalega	0.0073	0.0084	0.0045	0.0089	0.002	27
	Rodrigues	0.0076	0.0069	0.0056	0.01	0.002	26
	SBR	0.011	0.01	0.0098	0.013	0.0014	13
	Sodwana	0.84	0.9	0.67	0.96	0.12	15
	Aliwal	0.76	0.74	0.72	0.83	0.047	6
U	Agalega	0.11	0.08	0.00022	0.25	0.10	95
	Rodrigues	0.001	0.00018	0.00015	0.0028	0.0012	119

	SBR	0.012	0.00036	0.00016	0.036	0.017	138
	Sodwana	0.51	0.47	0.46	0.60	0.066	13
	Aliwal	0.29	0.25	0.22	0.38	0.069	24
Ti	Agalega	0.0012	0.0012	0.0012	0.0013	0.000033	3
	Rodrigues	0.0012	0.0012	0.0012	0.0013	0.00001	1
	SBR	0.0013	0.0013	0.0013	0.0013	2.04E-06	0
	Sodwana	0.041	0.00040	0.00020	0.12	0.057	140
	Aliwal	0.00071	0.00071	0.00070	0.00072	0.000011	2
Be	Agalega	0.00099	0.001	0.000903	0.0011	0.000066	7
	Rodrigues	0.00099	0.00099	0.00097	0.001	0.000011	1
	SBR	0.001	0.001	0.001	0.001	4.18-06	0
	Sodwana	0.00028	0.00035	0.000049	0.00045	0.00017	60
	Aliwal	0.00019	0.00019	0.00018	0.00021	0.000013	7
B	Agalega	25	22	20	34	6.0	23
	Rodrigues	23	23	21	27	2.6	11
	SBR	27	26	19	37	7.0	26
	Sodwana	11	9.6	8.6	14	2.4	22
	Aliwal	0.16	0.17	0.14	0.18	0.013	8
Mg	Agalega	34000	34000	29000	38000	3800	11
	Rodrigues	35000	33000	30000	43000	5300	15
	SBR	40000	41000	32000	45000	5400	14
	Sodwana	8300	8600	7600	8800	490	6
	Aliwal	8700	9000	7800	9300	680	8
Mo	Agalega	1.5	0.022	0.020	4.5	2.1	139
	Rodrigues	0.021	0.021	0.020	0.021	0.00045	2
	SBR	0.021	0.021	0.020	0.022	0.00078	4
	Sodwana	0.34	0.016	0.015	0.99	0.46	135
	Aliwal	0.026	0.026	0.026	0.027	0.00015	1
Pd	Agalega	3.3	3.4	2.8	3.7	0.38	11
	Rodrigues	2.6	2.6	2.2	2.9	0.29	11
	SBR	3.3	3.3	2.3	4.1	0.72	22
	Sodwana	3.0	2.9	2.8	3.2	0.16	5
	Aliwal	1.4	1.5	1.2	1.5	0.16	11
Sb	Agalega	0.0011	0.0010	0.00099	0.0013	0.00012	11
	Rodrigues	0.00079	0.00072	0.00049	0.0012	0.00028	35
	SBR	0.0012	0.0013	0.00063	0.0016	0.00041	35
	Sodwana	0.016	0.021	0.00043	0.026	0.011	70
	Aliwal	0.0013	0.00032	0.00025	0.0034	0.0015	111
Ba	Agalega	4.7	5.6	2.3	6.1	1.7	36
	Rodrigues	3.3	3.2	2.4	4.3	0.8	23
	SBR	3.7	3.3	1.9	5.8	1.6	44
	Sodwana	21	23	19	23	1.7	8
	Aliwal	14	15	10	18	3.1	22
Pt	Agalega	0.00076	0.00081	0.00065	0.00082	0.000077	10
	Rodrigues	0.00063	0.00084	0.00019	0.00086	0.00031	49
	SBR	0.049	0.00078	0.00076	0.15	0.069	139
	Sodwana	0.094	0.053	0.027	0.20	0.076	82

	Aliwal	0.033	0.00015	0.000099	0.098	0.046	141
Bi	Agalega	0.00072	0.00080	0.00047	0.00088	0.00018	25
	Rodrigues	0.00081	0.00083	0.00076	0.00084	0.000038	5
	SBR	0.00086	0.00086	0.00084	0.00086	0.00001	1
	Sodwana	0.43	0.27	0.12	0.91	0.34	79
	Aliwal	0.00028	0.00028	0.00028	0.00029	6.95E-06	2
Th	Agalega	0.00032	0.00039	0.00014	0.00041	0.00012	39
	Rodrigues	0.00025	0.00018	0.00018	0.00038	0.000095	38
	SBR	0.00033	0.00037	0.00019	0.00043	0.0001	32
	Sodwana	0.12	0.12	0.095	0.16	0.025	20
	Aliwal	0.042	0.043	0.034	0.049	0.006	15

Sarcophyton (n=3 per site)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Agalega	58	42	27	100	34	59
	Rodrigues	57	62	32	77	19	33
	Sodwana	71	70	56	87	13	18
Ti	Agalega	3.3	2.6	2.2	5.1	1.3	38
	Rodrigues	5.2	4.7	4.2	6.7	1.1	21
	Sodwana	6.0	6.0	5.9	6.2	0.1	2
V	Agalega	0.16	0.0013	0.00011	0.48	0.23	141
	Rodrigues	0.0013	0.0016	0.000012	0.0022	0.00093	73
	Sodwana	0.52	0.55	0.47	0.56	0.039	7
Cr	Agalega	6.4	7.3	3.4	8.5	2.1	34
	Rodrigues	3.9	3.7	3.6	4.6	0.4	11
	Sodwana	6.2	6.2	5.6	6.8	0.5	8
Mn	Agalega	0.067	0.089	0.0024	0.11	0.046	69
	Rodrigues	0.067	0.063	0.053	0.084	0.013	19
	Sodwana	4.1	4.1	3.7	4.4	0.26	6
Fe	Agalega	510	480	400	630	96	19
	Rodrigues	380	400	240	490	100	27
	Sodwana	560	570	530	580	21	4
Co	Agalega	0.31	0.26	0.081	0.58	0.21	68
	Rodrigues	0.11	0.021	0.0029	0.3	0.14	126
	Sodwana	0.80	0.79	0.78	0.84	0.026	3
Ni	Agalega	3.8	2.0	1.7	7.6	2.7	71
	Rodrigues	2.6	3.3	0.9	3.5	1.2	45
	Sodwana	1.9	2.0	1.7	2	0.1	8
Cu	Agalega	0.23	0.23	0.22	0.23	0.0053	2
	Rodrigues	0.20	0.19	0.19	0.22	0.014	7
	Sodwana	3	2.7	2.6	3.6	0.43	15
Zn	Agalega	0.21	0.21	0.21	0.23	0.0078	4
	Rodrigues	1	0.12	0.098	2.8	1.26	126
	Sodwana	8.6	8.2	6.7	11	1.6	19
As	Agalega	3.6	4.1	0.09	6.8	2.7	75
	Rodrigues	2.1	2.7	0.23	3.4	1.4	64
	Sodwana	3.6	3.6	3.6	3.7	0.05	1
Se	Agalega	0.0089	0.009	0.0076	0.01	0.001	12
	Rodrigues	0.0092	0.01	0.0078	0.01	0.001	11
	Sodwana	0.31	0.36	0.15	0.43	0.12	39
Sr	Agalega	2600	2500	2400	2800	210	8
	Rodrigues	1400	1100	870	2200	600	43
	Sodwana	1700	1600	1600	1700	24	1
Ag	Agalega	0.0033	0.0035	0.0031	0.0035	0.0002	6
	Rodrigues	0.0019	0.0023	0.00051	0.0029	0.001	53
	Sodwana	2.9	2.9	0.60	5.2	1.9	65
Cd	Agalega	0.28	0.39	0.00048	0.44	0.2	71

	Rodrigues	0.36	0.23	0.11	0.72	0.26	74
	Sodwana	0.75	0.75	0.73	0.76	0.012	2
Au	Agalega	0.021	0.022	0.021	0.022	0.00056	3
	Rodrigues	0.018	0.018	0.014	0.022	0.0031	17
	Sodwana	0.0038	0.0048	0.00017	0.0065	0.0027	70
Hg	Agalega	0.019	0.019	0.019	0.019	0.000087	0
	Rodrigues	0.016	0.018	0.012	0.018	0.0027	17
	Sodwana	0.021	0.022	0.015	0.025	0.0041	20
Pb	Agalega	0.01	0.011	0.007	0.012	0.0022	22
	Rodrigues	0.44	0.013	0.0093	1.3	0.61	138
	Sodwana	0.32	0.31	0.24	0.4	0.064	20
U	Agalega	0.11	0.16	0.00012	0.17	0.078	71
	Rodrigues	0.026	0.021	0.000097	0.057	0.023	90
	Sodwana	0.054	0.056	0.049	0.057	0.0035	6
Tl	Agalega	0.0012	0.0012	0.00121	0.00123	0.000012	1
	Rodrigues	0.0012	0.0012	0.0012	0.0013	5.81E-06	0
	Sodwana	0.00067	0.00067	0.00064	0.0007	0.000024	4
Be	Agalega	0.001	0.001	0.001	0.001	4.287E-06	0
	Rodrigues	0.00099	0.00099	0.00098	0.001	6.459E-06	1
	Sodwana	0.00059	0.00059	0.00057	0.0006	0.000015	3
B	Agalega	33	31	29	39	4.3	13
	Rodrigues	43	49	28	50	10	24
	Sodwana	33	35	28	37	3.8	11
Mg	Agalega	46000	48000	41000	49000	3500	8
	Rodrigues	29000	21000	19000	46000	12000	43
	Sodwana	35000	35000	34000	35000	620	2
Mo	Agalega	0.021	0.021	0.020	0.021	0.00024	1
	Rodrigues	0.020	0.020	0.017	0.022	0.0018	9
	Sodwana	0.021	0.021	0.021	0.023	0.00086	4
Pd	Agalega	3.5	3.4	3.2	3.9	0.31	9
	Rodrigues	1.8	1.4	1.1	3	0.83	46
	Sodwana	2.3	2.3	2.1	2.6	0.19	8
Sb	Agalega	0.0014	0.0015	0.0012	0.0015	0.00017	12
	Rodrigues	0.0010	0.0010	0.0009	0.0011	0.00011	11
	Sodwana	0.00044	0.00050	0.000017	0.00079	0.00032	73
Ba	Agalega	4.0	4.5	2.4	5.0	1.1	28
	Rodrigues	3.8	1.7	0.9	8.8	3.5	94
	Sodwana	4.6	3.5	3.4	6.9	1.6	35
Pt	Agalega	0.00077	0.00074	0.00073	0.00085	0.000054	7
	Rodrigues	0.00080	0.00082	0.00072	0.00086	0.000058	7
	Sodwana	0.033	0.046	0.00017	0.053	0.023	71
Bi	Agalega	0.00087	0.00086	0.00086	0.00088	8.134E-06	1
	Rodrigues	0.00081	0.00081	0.00078	0.00085	0.00003	4
	Sodwana	0.025	0.023	0.014	0.037	0.0095	38
Th	Agalega	0.00043	0.00042	0.00042	0.00046	0.000019	4
	Rodrigues	0.0018	0.0021	0.00011	0.0031	0.0012	70

	Sodwana	0.08	0.085	0.066	0.088	0.0098	12
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Dendronephthya (n=3 per site)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Sodwana	83	84	80	86	2.6	3
	Aliwal	80	75	71	94	9.9	12
Ti	Sodwana	5.3	5.4	5.2	5.5	0.13	2
	Aliwal	6.9	6.8	6.8	7.2	0.18	3
V	Sodwana	0.38	0.37	0.36	0.41	0.024	6
	Aliwal	14	14	13	14	0.66	5
Cr	Sodwana	6.8	6.5	6.3	7.5	0.53	8
	Aliwal	7.8	7.8	7.4	8.4	0.40	5
Mn	Sodwana	4.6	4.6	4.3	4.8	0.2	4
	Aliwal	4.3	3.9	3.7	5.2	0.6	15
Fe	Sodwana	780	780	770	800	15	2
	Aliwal	680	650	650	740	43	6
Co	Sodwana	1.2	1.2	1.2	1.3	0.042	3
	Aliwal	1.3	1.2	1.1	1.4	0.1	8
Ni	Sodwana	3.7	3.7	3.4	4.1	0.26	7
	Aliwal	3.3	3.2	2.9	3.7	0.34	10
Cu	Sodwana	2.3	2.3	1.5	3.0	0.58	26
	Aliwal	2.1	1.9	1.8	2.7	0.44	21
Zn	Sodwana	12	11	10	14.0	1.5	13
	Aliwal	26	25	24	27	1.0	4
As	Sodwana	2.4	2.5	2.3	2.5	0.085	3
	Aliwal	4.3	4.3	4.0	4.5	0.19	4
Se	Sodwana	0.79	0.74	0.69	0.9	0.11	14
	Aliwal	0.97	0.94	0.85	1.1	0.12	13
Sr	Sodwana	2100	2100	2000	2300	89	4
	Aliwal	1800	1800	1700	1800	79	4
Ag	Sodwana	2.3	1.3	0.83	4.8	1.8	77
	Aliwal	1.1	0.93	0.59	1.9	0.6	49
Cd	Sodwana	0.65	0.66	0.62	0.67	0.023	4
	Aliwal	0.65	0.64	0.59	0.72	0.053	8
Au	Sodwana	0.011	0.0059	0.0048	0.023	0.0081	73
	Aliwal	0.32	0.0081	0.0067	0.96	0.45	138
Hg	Sodwana	0.021	0.021	0.020	0.022	0.0012	6
	Aliwal	0.027	0.028	0.025	0.029	0.0015	5
Pb	Sodwana	0.23	0.28	0.12	0.29	0.08	35
	Aliwal	0.25	0.19	0.16	0.40	0.10	41
U	Sodwana	0.073	0.073	0.072	0.075	0.0015	2
	Aliwal	0.074	0.073	0.070	0.079	0.0039	5
Tl	Sodwana	0.00061	0.00062	0.00059	0.00063	0.000017	3

	Aliwal	0.00077	0.00077	0.00076	0.00077	6.2E-06	1
Be	Sodwana	0.00059	0.00059	0.00057	0.00061	0.000014	2
	Aliwal	0.00059	0.00060	0.00056	0.00061	0.000019	3
Be	Sodwana	14	13	12	18	2.9	20
	Aliwal	12	12	11	14	1.4	12
Mg	Sodwana	34000	34000	32000	37000	1900	6
	Aliwal	34000	35000	32000	35000	1500	4
Mo	Sodwana	0.021	0.022	0.02	0.022	0.0012	6
	Aliwal	0.025	0.025	0.024	0.025	0.00032	1
Pd	Sodwana	2.9	2.8	2.8	3.1	0.16	6
	Aliwal	2.8	2.7	2.6	3.0	0.20	7
Sb	Sodwana	0.022	0.0097	0.00037	0.056	0.024	110
	Aliwal	0.00062	0.00058	0.00052	0.00076	0.0001	16
Ba	Sodwana	5.8	5.8	5.8	5.9	0.048	1
	Aliwal	4.9	4.8	4.5	5.3	0.34	7
Pt	Sodwana	0.049	0.00020	0.000096	0.15	0.070	141
	Aliwal	0.033	0.0074	0.00020	0.09	0.041	125
Bi	Sodwana	0.025	0.014	0.0096	0.052	0.019	76
	Aliwal	0.00016	0.00017	0.00014	0.00018	0.000016	10
Th	Sodwana	0.049	0.042	0.032	0.072	0.017	34
	Aliwal	0.038	0.038	0.035	0.041	0.0021	6

Dendrophyllia (n=3)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Aliwal	180	190	110	240	51	29
Ti	Aliwal	7.4	7.9	4.8	9.4	1.9	26
V	Aliwal	0.57	0.58	0.40	0.73	0.13	23
Cr	Aliwal	9.2	9.4	7.6	10.5	1.2	13
Mn	Aliwal	8.00	8.9	4.9	10.2	2.2	28
Fe	Aliwal	1100	1100	990	1100	63	6
Co	Aliwal	2.0	2.0	1.8	2.2	0.2	8
Ni	Aliwal	8.2	8.8	5.5	10	2.0	24
Cu	Aliwal	2.2	2.4	0.8	3.5	1.1	49
Zn	Aliwal	2.8	3.2	0.3	4.9	1.9	69
As	Aliwal	3.6	3.6	2.3	5.0	1.1	31
Se	Aliwal	0.29	0.35	0.00053	0.51	0.21	74
Sr	Aliwal	7100	7100	6700	7500	330	5
Ag	Aliwal	6.8	4.8	0.7	15	5.9	88
Cd	Aliwal	0.44	0.42	0.41	0.49	0.036	8
Au	Aliwal	0.008	0.008	0.0078	0.0082	0.00019	2
Hg	Aliwal	0.018	0.012	0.012	0.029	0.0077	44
U	Aliwal	2.5	2.6	2.4	2.6	0.077	3
Tl	Aliwal	0.00079	0.00080	0.00077	0.00080	0.000013	2
Be	Aliwal	0.00054	0.00054	0.00053	0.00056	0.000013	2
B	Aliwal	30	30	27	34	2.7	9
Mg	Aliwal	2900	3000	2300	3300	390	13
Mo	Aliwal	0.027	0.028	0.026	0.028	0.00078	3
Pd	Aliwal	11	11	11	12	0.48	4
Sb	Aliwal	0.00067	0.00065	0.00063	0.00073	0.000041	6
Ba	Aliwal	16	16	16	16	0.32	2
Pt	Aliwal	0.013	0.0052	0.00015	0.033	0.014	112
Bi	Aliwal	0.00026	0.00030	0.00017	0.00032	6.9E-05	26
Th	Aliwal	0.011	0.0098	0.0078	0.015	0.0031	29

Eleutherobia (n=3 pooled samples)							
Element	Location	Mean	Median	Min	Max	SD	%CV
Al	Aliwal	80	80	60	110	18	22
Ti	Aliwal	11	1	11	12	0.13	1
V	Aliwal	0.85	0.82	0.78	0.96	0.08	9
Cr	Aliwal	8.1	8.2	7.3	8.8	0.63	8
Mn	Aliwal	9.3	6.9	6.3	15	3.9	41
Fe	Aliwal	400	390	370	440	29	7
Co	Aliwal	0.66	0.66	0.61	0.73	0.049	7
Ni	Aliwal	1.8	1.8	1.7	1.8	0.07	4
Cu	Aliwal	4.1	3.6	2.9	5.7	1.2	29
Zn	Aliwal	52	51	50	53	1.4	3
As	Aliwal	27	27	26	28	1.1	4
Se	Aliwal	3.3	3.4	2.9	3.6	0.31	9
Sr	Aliwal	980	1000	860	1100	94	10
Ag	Aliwal	1.5	1.9	0.7	2	0.58	37
Cd	Aliwal	2.1	2	2	2.3	0.15	7
Au	Aliwal	0.0064	0.0073	0.004	0.0078	0.0017	26
Hg	Aliwal	0.028	0.029	0.027	0.029	0.00073	3
Pb	Aliwal	0.50	0.52	0.28	0.7	0.17	34
U	Aliwal	0.067	0.064	0.063	0.074	0.0052	8
Tl	Aliwal	0.00077	0.00077	0.00076	0.00079	0.000014	2
Be	Aliwal	0.00056	0.00056	0.00053	0.00058	0.000022	4
B	Aliwal	0.11	0.0084	0.0048	0.31	0.14	133
Mg	Aliwal	20000	19000	19000	21000	780	4
Mo	Aliwal	0.02	0.02	0.019	0.02	0.00046	2
Pd	Aliwal	1.5	1.6	1.4	1.6	0.073	5
Sb	Aliwal	0.094	0.046	0.00068	0.24	0.10	108
Ba	Aliwal	12	13	11	13	0.76	6
Pt	Aliwal	0.0081	0.00020	0.00018	0.024	0.011	138
Bi	Aliwal	0.0001	0.000092	0.000052	0.00016	0.000043	43
Th	Aliwal	0.044	0.039	0.037	0.057	0.0089	20

SDG