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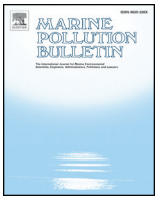

# Examining the utility of coral Ba/Ca as a proxy for river discharge and hydroclimate variability at Coiba Island, Gulf of Chirquí, Panamá

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ABSTRACT

Panamá's extreme hydroclimate seasonality is driven by Intertropical Convergence Zone rainfall and resulting runoff. River discharge (Q) carries terrestrially-derived barium to coastal waters that can be recorded in coral. We present a Ba/Ca record (1996–1917) generated from a *Porites* coral colony in the Gulf of Chiriquí near Coiba Island (Panamá) to understand regional hydroclimate. Here coral Ba/Ca is correlated to instrumental Q ($R = 0.67$, $p < 0.001$), producing a seasonally-resolved Reduced Major Axis regression of Ba/Ca (μmol/mol) = Q ($\mathrm{m^3/s}$) $\times\ 0.006 \pm 0.001$ (μmol/mol)$(\mathrm{m^3/s})^{-1} + 4.579 \pm 0.151$. Our results support work in the neighboring Gulf of Panamá that determined seawater Ba/Ca, controlled by Q, is correlated to coral Ba/Ca (LaVigne et al., 2016). Additionally, the Coiba coral Ba/Ca records at least 5 El Niño events and identified 22 of the 37 wet seasons with below average precipitation. These data corroborate the Q proxy and provide insight into the use of coral Ba/Ca as an El Niño and drought indicator.

## 1. Introduction

### 1.1. Background

Stony corals, also known as hermatypic corals or reef-builders, secrete a hard aragonite ($CaCO_3$) skeleton beneath their ~0.5 to 1 cm thick live tissue. The composition of the skeleton provides a wealth of information in the form of paleoceanographic proxies. Trace metals can replace Ca (ionic radius: 1.00 Å) if they have a similar ionic radius with an apparent temperature, precipitation, and/or salinity dependence. Barium (ionic radius: 1.35 Å), an alkaline earth metal and $2^+$ ion, easily incorporates into coral aragonite (Sinclair and McCulloch, 2004). Coral Ba/Ca, first studied by Bowen (1956) and Harriss and Almy (1964), is thought to reflect ambient seawater conditions, and therefore parallels the environment in which the coral grew. Studies have shown that the Ba/Ca ratio in the coral skeleton is proportional to that which is found in the calcifying fluid (Zhong and Mucci, 1989; Sinclair and McCulloch, 2004; LaVigne et al., 2016). Since corals' calcifying fluid has a similar composition to the ambient seawater (McConnaughey, 1989a, 1989b) the skeleton of near-shore corals mimic the estuarine coastal conditions. Therefore, seawater Ba/Ca can potentially be reconstructed from coral Ba/Ca using the Ba partition coefficient (Sinclair and McCulloch, 2004).

Ba concentrations in seawater are variable throughout the ocean with a stark contrast between coastal and open ocean settings. The surface ocean Ba concentrations are incredibly low at about 34 nmol/kg in the mid- to low-latitude Pacific waters, however, in nearshore waters the concentration is upwards of 150 nmol/kg and can accumulate in organisms, corals and foraminifera alike (Lea and Boyle, 1991; Moyer et al., 2012). Ba in coastal waters is primarily transported by rivers, which carry the trace metal in the form of suspended solids and surface complexes (Hanor and Chan, 1977). Once freshwater encounters the more saline seawater, which has a higher ionic strength, the Ba desorbs from the complexes and can be incorporated into calcifying organisms (Hanor and Chan, 1977; Edmond et al., 1978; Li and Chan, 1979; Elsinger and Moore, 1980; Edmond et al., 1985; Froelich et al., 1985; Carroll et al., 1993; Sinclair and McCulloch, 2004). About 50% (Hanor and Chan, 1977; Li and Chan, 1979) to 75% (Carroll et al., 1993) of the dissolved Ba in coastal regions can be attributed to desorption of Ba from surface complexes, the process that is largely responsible for the higher Ba concentrations compared to the open ocean.

This disparity between coastal and open ocean Ba allowed Shen and Boyle (1988) to determine that terrigenous runoff via riverine flux and sediment input influences the metal's concentration in seawater, providing some of the first evidence for coral Ba/Ca as a Q proxy. In coastal regions readily supplied by rivers, the Ba concentration often noticeably fluctuates throughout the year. Shen and Sanford (1990) first noted that

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corals growing in these coastal habitats recorded the temporal variability in Ba concentration within their annual growth bands, which in their study was attributed to seasonal fluctuations in Amazon River flow. These early findings suggested that coastal corals might be archives of long-term river flux in regions whose climate is largely dominated by precipitation and the consequent variations in river discharge (Q).

Rivers represent a critical component of coastal ecosystems as one of the major sources of nutrients and sediment to the near-shore waters (Troup and Bricker, 1979; Milliman and Meade, 1983; Nittrouer et al., 1994; Milliman et al., 1999). Although nutrients are critical at moderate levels, periods of extreme discharge, such as flood events or a particularly intense wet season, can put coral reefs at risk. Increased nutrient supply can lead to eutrophication (excessive nutrient supply), which encourages excessive algal growth that chokes and out-competes corals (Bell, 1992). Each coral species is suited to a specific salinity range and prolonged freshwater influx can lower local salinity to below the range suitable for that reef, often $<30$, which can lead to massive coral death (Jokiel et al., 1993; Hunter and Evans, 1995; Wilkinson, 1999). Additionally, with increased Q there is an increased suspended sediment load and higher risk of reef sedimentation, which results in the smothering corals and reduced light availability (Rogers, 1990; Woolfe and Larcombe, 1999: Furnas and Mitchell, 2001). Sedimentation prevents photosynthesis and severely inhibits growth.

A robust archive of Q allows for more accurate runoff predictions that could inform decisions regarding environmental policies, potable water storage management, flood insurance, and algal bloom forecasting. Tropical, coastal regions dotted by rivers are prime locations for coral Ba/Ca-based reconstructions of Q. The Pacific coast of Panamá, specifically the Gulf of Chiriquí, provides an ideal study site with 7 major watersheds subjected to seasonal variations in hydroclimate (Valiela et al., 2012).

### 1.2. Study site: Gulf of Chiriquí, Panamá

The Pacific coast of Panamá is characterized by two markedly different gulfs, the Gulfs of Panamá and Chiriquí (Fig. 1). The Gulf of Panamá is an active upwelling zone where cool, nutrient rich water is seasonally brought to the surface, thereby promoting eutrophic conditions that can hinder coral growth (Maté, 2003). Unlike the Gulf of Panamá, in the Gulf of Chiriquí the Central American Cordillera topographically blocks the tradewinds preventing upwelling.

The Gulf of Chiriquí is an ideal low-nutrient environment known as Pacific Panamá's coral "hot spot," with high hermatypic coral diversity home to 19 of the 23 species identified along Panamá's Pacific coast (Maté, 2003). *Pocillopora*, a branching coral, dominates shallow reefs whereas deeper reefs are primarily composed of massive *Porites* or *Pavona* colonies (Maté, 2003). The Gulf of Chiriquí's proximity to the thermal equator and the lack of wind-driven upwelling limits seasonal sea surface temperature (SST) variability to a small and inconsistent 1–2 °C about the ~28 °C mean, with this temperature stability further promoting coral growth. On the contrary, the sea surface salinity (SSS) annual amplitude is large and regular at 3 units, typically ranging from 30.5–33.5 (Delcroix et al., 2011). The hydrologic budget in Central America, in particular Panamá, is dictated by seasonal oscillations in the position of the ITCZ, a band of atmospheric convection cells that encircles the equator. The seasonal northward migration of the ITCZ during the boreal summer stimulates the Central American wet season (May–November) when the ITCZ hovers between 8° N and 12° N (Horel, 1982). Its southward shift in the winter leaves the region dry for months (December–April) (Horel, 1982). Monthly instrumental precipitation data show consistent oscillations in seasonal precipitation with wet season rainfall totaling over 1000 mm and dry season rainfall amounting to a relatively meager 200–500 mm (Fig. 2). With about 90% of Panamá's annual rainfall occurring during the wet season, there is a stark precipitation gradient associated with the meridional ITCZ movement. Two of the eight major rivers in Panamá, Chiriquí and Tabasara, empty into the Gulf of Chiriquí and discharge from these rivers is correlated to precipitation on both monthly ($R = 0.50$, $p < 0.001$) and seasonal ($R = 0.56$, $p < 0.001$) timescales.

The Central American landscape is dynamic, continually altered by active tectonic deformation. In addition to blocking the tradewinds, the Cordillera divides the isthmus in such a way that rivers either flow down the Caribbean or Pacific slope, mostly perpendicular to the coast. The Pacific slope constitutes 70% of the isthmus and is on average 106 km in length with a 2.27% grade (Empresa de Transmisión Eléctrica, S.A.). Panamá's geomorphology is specifically influenced by its collision with South America to the east and the Nazca plate to the south (Marshall, 2007). Western Panamá, which encompasses the Gulf of Chiriquí, lies on the Chorotega Block, a Neogene-Quaternary volcanic

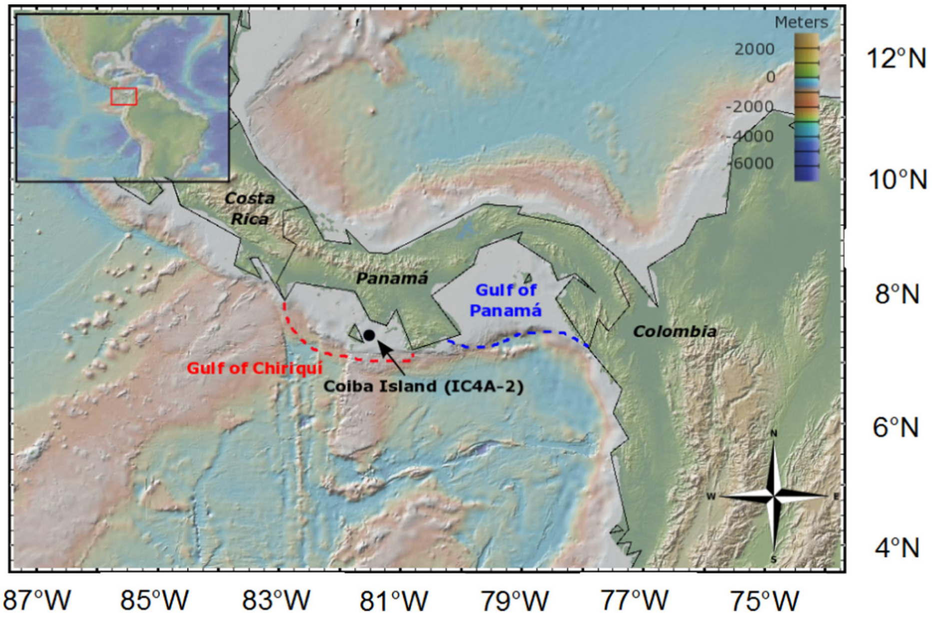

**Fig. 1.** The Isthmus of Panamá and neighboring countries. The coral study site (Coral ID: IC4A-2) is in the Gulf of Chiriquí, 23–25 km offshore mainland Panamá, on the reef surrounding Coiba Island (7°25′ N, 81°42′ W) (black dot). The dotted lines outline the approximate boundaries of the major gulfs along the Pacific coast of Panamá.

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