Marine Pollution Bulletin 131 (2018) 441–452

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

An environmental magnetism approach to assess impacts of land-derived sediment disturbances on coral reef ecosystems (Cartagena, Colombia)

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ARTICLE INFO

Keywords:
Enrichment factor
Estuarine/marine sediments
Land-based sediments
Magdalena River
Magnetic properties
Trace elements

ABSTRACT

We used environmental magnetism methods to study recently deposited marine sediments from the estuarine ecosystems on the Caribbean coast of Colombia. Cartagena region has undergone an increasing sediment load during the last decades via sediment plumes from Magdalena River and its distributary man-made channel. Concentration dependent magnetic parameters show an increasing abundance of ferrimagnetic minerals on the uppermost sediments on sites located close to the continent (remanent magnetization SIRM = 5.4–9.5 × 10^{-3}Am^2 kg^{-1}) as well as faraway sites (SIRM = 0.5–1.7 × 10^{-3}Am^2 kg^{-1} near Rosario Islands coral reef complex). The magnetic grain size and mineralogy along the cores are variable, showing the dominance of the magnetite-like minerals (remanent coercivity H_{cr} = 34.3–45.3 mT), with a minor contribution of high-coercivity minerals (H_{cr} = 472–588 mT). In addition, there is a moderate enrichment of elements Cu, Mo, and Zn (enrichment factor EF = 1.5–3.8) that indicates the additional land-derived contribution on sediments. The environmental magnetism approach, which shows significant signals of magnetic minerals and trace elements, is a reliable tool to prove the presence of continental sediment supply in coral reef ecosystems.

1. Introduction

Natural systems such as coral reefs are complex and highly susceptible to environmental changes. Their behavior depends on the interaction of several independent forcing factors like climate variations and human activity affecting the environment. Fluvial sediment inputs in coral reefs have direct influence on coral health and diversity, affecting the distribution of coral communities (Hughes et al., 2003; Wolanski et al., 2005; Victor et al., 2006; Fabricius et al., 2013; McLaughlin et al., 2003). Sediment has been shown to be a major stressor to coral reefs globally. Storlazzi et al. (2015) showed that finer-grained and darker-colored sediments at higher suspended-sediment concentrations attenuate photosynthetically active radiation (PAR), significantly more than coarser, lighter-colored sediment at lower concentrations, and provide PAR attenuation coefficients for various grain sizes, colors, and suspended-sediment concentrations. Because fine-grained sediment particles settle-down slowly and are highly susceptible to resuspension, they remain in the water column longer, causing greater net impact by reducing light, essential for photosynthesis. Coral reef monitoring studies assessing the impacts of land-based sediment loads should concentrate on measuring fine grained lateritic and volcanic soils, as opposed to coarser grained siliceous and carbonate sediments (Storlazzi et al., 2015). In the Caribbean, water transparency has steeply declined over the last 20 years at different locations from Guatemala to Honduras, and also at La Parguera in Puerto Rico (Jackson et al., 2014).

Environmental magnetism involves the use of magnetic techniques in situations in which the transport, deposition, or transformation of magnetic grains is influenced by environmental processes in the atmosphere, lithosphere, and hydrosphere. Environmental magnetism methods have been used in diverse fields, including land-use studies, limnology, oceanography, sedimentology, and soil science, among others (Verosub and Roberts, 1995). Magnetic proxies have the advantage of being determined with high sensitivity combined with fast laboratory processing; sample preparation is easy, laboratory instruments are relatively low cost, and most measurements are non-destructive (Chaparro et al., 2006; Gubbins and Herrero-Bervera, 2007). Magnetic measurements are being used as a rapid and useful tool to appraise heavy metal contamination in soils and sediments (Thompson and Oldfield, 1986; Evans and Heller, 2003). Thus, magnetic measurements provide new tools, in addition to traditional ones, to investigate the natural processes and anthropogenic influences in ecosystems such as soils (Petrovský et al., 2001; Blundell et al., 2009; Quijano et al., 2014), estuaries (Prajith et al., 2015; Chaparro et al.,

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https://doi.org/10.1016/j.marpolbul.2018.04.030
Received 20 September 2017; Received in revised form 16 March 2018; Accepted 11 April 2018

2017a), lakes (Yang et al., 2007; Chaparro et al., 2017b), and rivers (Zhang et al., 2011; Krishnamoorthy et al., 2014).

The environmental magnetism method on marine sediment has not only been applied to investigate the recent influence of continental/anthropogenic sediments (e.g., Scoullos et al., 1979; Chan et al., 2001; Horng and Huh, 2011; Gwizdała et al., 2018), but also to investigate pollution records over decadal to centennial timescales (Locke and Bertine, 1986; Horng et al., 2009) and paleoclimate/paleoenvironmental records for longer periods (Bloemendal and deMenocal, 1989; Reinholdsson et al., 2013). Environmental magnetism studies on coral ecosystems are scarce around the world and absent in the Caribbean region. Among reported studies, Bothner et al. (2006) used sediment traps to evaluate the frequency, cause, and relative intensity of sediment mobility/resuspension along the fringing coral reef off of southern Molokai (Hawaii Island). Magnetic properties (e.g., isothermal and anhysteretic remanent magnetization, IRM and ARM, respectively, and ARM/IRM ratio) in those coastal sediments are a specific indicator of the land-derived component because the biogenic carbonate has non-magnetic properties. Land-derived particles carry their magnetic signature (volcanic rocks containing magnetite) potentially altered by weathering processes, as they are transported to and within the coastal ocean by streams, wind, and currents. Land-derived sediment, identified by the non-carbonate fraction and the presence of magnetite, is a ubiquitous component of sediment trap material, which indicates that fine-grained terrestrial sediment is constantly moving through reef ecosystems. Takesue et al. (2009) used geochemical tracers and magnetic properties (e.g., mass-specific magnetic susceptibility χ, IRM, and S-ratio) to assess the influence of terrestrial runoff on a coral reef-fringed embayment in Kauai (Hawaiian island). They found that trace element ratios, magnetic domain size, and relative magnetite-hematite concentrations, should reflect sediment provenance. They also identified non-point source runoff from roads reported as the main contributor to elevated levels of Ni, Cu, Zn, and Pb in flood sediments, which may pose a greater threat to coral reef communities.

The Magdalena River, the main contributor of fluvial fluxes to the Caribbean Sea (Restrepo and Kjerfve, 2000; Restrepo et al., 2015), is probably the largest fluvial system worldwide, delivering continental sediments to coral reef ecosystems (Restrepo and Alvarado, 2011; Restrepo et al., 2016a). The coastal region of Cartagena, characterized by the Barbacoas and Cartagena bays, as well as by the presence of the largest coastal coral reef ecosystem in Colombia – the Rosario Island National Park – receives the Magdalena fluvial plumes via the Canal del Dique, a 114 km man-made channel (Fig. 1).

In the Cartagena region, previous studies (e.g., Moreno-Madriñán et al., 2015; Restrepo et al., 2016a) have analyzed the distribution of suspended sediment over coral reefs by using in-situ calibrated MODIS satellite images, demonstrating that corals have been strongly exposed to sediment plumes specially during the last decade. Nevertheless, some debate about the source of these sediments is still remaining, especially because the semi-open character of the Cartagena and Barbacoas bays allow the resuspension of bottom sediments to the near shore reefs (Restrepo et al., 2016a). In this area, other sources of sediments (e.g. eolian) are considered negligible versus fluvial sediments discharged by systems as the Magdalena River and associated Canal del Dique.

The proposed approach of environmental magnetism in coral reefs is an additional, reliable, and low-cost proxy to confirm the presence of land-derived sediments in coastal ecosystems, especially in a coastal region influenced by the continental fluxes of many rivers. The aim of this study is to determine: a) the magnetic properties of marine sediments for understanding the recent depositional processes in the Cartagena and Barbacoas bays; b) the presence of some trace elements, their enrichment and potential impact on different sites along the bays; c) the horizontal and in-depth parameter variation of bottom marine sediments; and d) the influence of continental sediment supply from the Magdalena River to the reef zones of the Rosario Islands, where the presence of ferrimagnetic and antiferromagnetic minerals may be related to continental-source contribution.

2. Study area

The Cartagena Bay is located in northwest Colombia, on the Caribbean coast (Fig. 1). The Tierrabomba Island separates the bay from the open sea, leaving two sea inlets: Bocagrande in the north, and Bocachica in the south. The Bocachica inlet (15 m depth), the gap between Tierrabomba and Barú Peninsula, connects the bay with the major coral reef system in Colombia, the Rosario Island Coral Reef Natural Park, a 145 km^2 offshore coral reef (Restrepo et al., 2006).

Geologically, the Cartagena Bay area is located in the outer part of the Sinú fold belt, which is formed by Miocene to Pliocene marine sedimentary rocks deposited in turbiditic to coastal environments, like claystones, sandstones, gravels and calcareous sandstones, claystones and reef limestones (Duque-Caro, 1980). Locally, the hills and terraces in the bay (as La Popa Hill and Tierrabomba and Barú islands) are covered by a sequence of the Pleistocene Rotinet quartz-gravels over which is seated the La Popa Formation, a Pleistocene aged coral reef (Reyes et al., 2001). The observed rising of these coastal terraces at different levels (from ~20 to 3 m high) seems to be the response of active tectonics present along the bay which is expressed as faults and mud diapirism (Duque-Caro, 1980; Vernette, 1989).

The main freshwater source in the Cartagena Bay is the Canal del Dique, a 114 km long man-made distributary channel that connects the Magdalena River at Calamar with the Cartagena and Barbacoas bays (Fig. 1). The Canal del Dique has a great influence on the hydrology and sediment dynamics of these bays (Andrade et al., 2004; Restrepo et al., 2016a). The Canal has a high interannual river discharge variability, carrying most of its sediment load during short periods of time, being more pronounced during La Niña wet events. Between 1984 and 1998, the Canal transported 50% of its sediment load in seven extreme events (Restrepo et al., 2005). The highest sediment and water discharge rates occur during November, reaching 31×10^3 t/d and 800 m^3/s, respectively. Between 2000 and 2011, water and sediment fluxes have increased about 28% and 48% respectively, with interannual means of 397 m^3/s of water discharge and 5.9×10^6 t/y of sediment load (Restrepo and Correa, 2014; Restrepo et al., 2016a).

Sedimentation rates in the Cartagena and Barbacoas bays were obtained from the ^{210}Pb activity. Two cores were studied by Restrepo et al. (2016a) in order to assess sedimentation rates for the lower Magdalena River: one in the Pasacaballos delta, an outlet of El Dique into Cartagena Bay, and the other in the Barbacoas Bay, an area fed by a secondary delta system sourced by the Canal del Dique. No sedimentary discontinuities or changes in grain size were observed in the cores, which are absolutely dominated by silty sedimentation. For that reason, the interpretation of the ^{210}Pb results was based on the Constant Rate of Supply (CRS) model. The average accumulation rate for 10 samples in the core at the Barbacoas Bay is 0.75 cm per year and a similar value of 0.75 cm per year was estimated in the Pasacaballos Delta (25 samples). These fluvial-source sediments currently blanket the carbonate shelf and some are further transported reaching the more distal coral reefs of the Rosario Islands (Fig. 1). Along with the continental-bearing sediments, heavy metals, also detected, have been proved to come from the Magdalena basin and being flushed away to the bays and the Rosario Islands coral reef (Restrepo et al., 2016a).

The Rosario Islands coral reef, located in front of the Barbacoas Bay (Fig. 1), constitutes the major continental coral reef ecosystem in Colombia. In recent decades, the live coral cover has been reduced dramatically down to 22%, being replaced by the macroalgae cover (67%), which nowadays constitute the dominant feature in the reef (Restrepo and Alvarado, 2011). These authors discuss that the main causes of coral reef decline are the water quality in terms of turbidity, high sea surface temperature, and the use of dynamite and uncontrolled tourism in the Rosario Islands.