Manoel Luiz Reefs morphology unveiled by high resolution satellite images (North Brazilian Continental Shelf)

Morfologia dos recifes de Manoel Luiz revelada por imagens de satélite de alta resolução WorldView-3 (Plataforma Continental Norte Brasileira)

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Abstract

The reefs of Manoel Luiz are located 100 nautical miles N from the city of São Luís, capital of the State of Maranhão - Brazil. The region is practically unconquerable, due to the great concentration of shallow reef pinnacles; it has never been possible to map the area by traditional methods, due to the dangers to navigate. The images acquired in June 2018, by programmed WorldView-3 satellite (30 cm resolution), revealed for the first time the real and exuberant reef formation with innumerable constructions, predominantly individual with circular, or linear and coalescent format. The reefs of Manoel Luiz are not constructed by corals. Drop-camera videos shows that sparse colonies of corals are fixed on hard structures formed (covered) by superimposed crusts of calcareous algae. The location of Manoel Luiz reefs remained almost 300 years unknown to navigators, since the year 1500, attributed to the discovery of Brazil, until 1820, when it was described by the French hydrographer Adm. Baron de Roussin, and another 198 years to be precisely georeferenced and mapped.

Key words: remote sensing; Manuel Luís Parcel's Marine State Park; Coralline algae; *Halimeda*; underwater images

Resumo

Os recifes de Manoel Luiz estão localizados 100 milhas náuticas a Norte da cidade de São Luís, capital do estado do Maranhão - Brasil. A região é praticamente inacessível, devido à grande concentração de pináculos recifais rasos; nunca foi possível mapear a área por métodos tradicionais devido aos perigos de navegação. Imagens adquiridas em junho de 2018, programadas através do satélite WorldView-3 (30 cm de resolução), revelaram pela primeira vez a real e exuberante formação recifal com inumeráveis construções, predominantemente individuais com formato circular, ou linear e coalescente. Os recifes de Manoel Luiz não são construídos por corais. Vídeos obtidos por *drop-camera* mostram colônias esparsas de corais fixos sobre estruturas rígidas formadas (cobertas) por incrustações de algas calcárias sobrepostas. A localização dos recifes de Manoel Luiz permaneceu desconhecida dos navegadores por quase 300 anos, desde o ano 1500, atribuído ao descobrimento do Brasil, até 1820, quando foram descritos pelo hidrógrafo francês Alte. Barão de Roussin, e outros 198 anos para serem precisamente georreferenciados e mapeados.

Palavras-chave: sensoriamento remoto; Parque Estadual Marinho do Parcel de Manuel Luís; algas calcárias; *Halimeda*; imagens subaquáticas

1. Introduction

The reefs of Manoel Luiz (ML) are located about 86 km (45 nm), NE from the nearest coast (Lençóis Island) and 100 nautical miles N from the city of São Luís, capital of the State of Maranhão (Figure 1). It is an environmental protected area called "Manoel Luiz Parcel's Marine State Park", created in 1991, with an area of 45,937.9 hectares, with the objective of preserving the marine fauna and flora, and their "coral reefs".

The region is practically unconquerable, due to the great concentration of shallow reef pinnacles, and it has never been possible to map the area by traditional methods, due to the great danger to navigate throughout it. In addition to these limitations, the region is affected by intense tidal currents related to the macro-tidal regime and the exploratory dives are limited to the time of the tidal slack water and performed only at the periphery of the reef area.

Because of the absence of significant emersion, there is no possibility to see abrupt reef pinnacles in time, causing many shipwrecks. The reason for the wrecks was the lack of knowledge of the reef's location for a long time. It was only in 1820 that the reefs were mapped by the French hydrographer Baron de Roussin. Manoel Luiz was the first navigator to report the existence of these dangerous reefs.

According to Roussin (1845), as translated by the authors: *"At the distance of seventy-seven miles in a North 8° East direction, from Morro Itacolomi, is one of the most dreadful shoals that can be encountered at sea: it is the vigie Manoel-Luiz"*. The term vigie means a dangerous

place that must be watched for a safe navigation route. It has relation with the portuguese term Abrolhos (open the eyes).

Roussin´s description of the reef continues: "When the sky is clear, we can see the rocks under the waters, where they show large black spots, but these spots are only seen very close. So, it is wise to follow the warning: after two hours of high tide, it is likely that no trace of the trap will be seen less than half a mile away if the sea is calm" (seen from the Gávea at the top of the mast). "Our observations, made at the anchor point at 400 Toises (800 m) of the rocks and under circumstances that authorize us to ensure accuracy, position these rocks as follows: LATITUDE 0° 51' 25''S, LONGITUDE 46° 34' 59''W. Declination of the magnetized needle observed on January 29th, 1820, at the anchoring site: 0° 57' Northeast".

In a quick confirmation, the absolute values of the anchor point coordinates provided by Roussin were positioned on Google Earth's map and caused initial disappointment because the point was plotted ~ 260 km west of the true reef location, but in latitude the value was correct. It was then found that this difference in longitude simply corresponds to the distance among the Meridians of Paris Observatory, in France, and Greenwich Observatory, in London (2 degrees and 20 seconds). Until 1911, the French navigators used the Meridian of Paris as reference. In addition, the position of Roussin's anchorage was not only correct but also its calculated distance of 800 m to the shallower reefs to the west.

The scarce studies of the region mainly consider the occurrences of coral species in the reefs. Corals, however, are not the true formers of these imposing columnar reef constructions that are more than 25 m high above the bottom, and may even show exposed relief (< 1 m) at low tide. Moura et al. (1999) described the approximately circular pinnacles, ranging from 50 to 300 m in diameter, raised from 25 to 30 m: "Superimposed coralline algal crusts constitute the framework of the reefs, which is sparsely covered with colonies of coral", identified as *Agaricia fragilis*, *Favia gravida*, *Madracis decactis*, *Meandrina braziliensis*, *Montastraea cavernosa*, *Mussismilia hispida*, *Porites* cf. *astreoides*, *Scolymia wellsi*, *Siderastrea stellata*, and *Millepora alcicornis*. The presence and great abundance of Caribbean reef organisms which do not occur along the eastern coast of South America, such as the purple reef fish *Chromis scotti*, provide additional evidence that the Manoel Luiz Reefs may be one of the main faunal stepping stones between the Caribbean and the Brazilian coast (Collette & Rützler 1977).

Amaral et al. (2007) identified in ML a rich coral fauna in relation to other parts of Brazil and comparable in diversity to the Abrolhos Islands (Bahia State). A total of 21 cnidarian species were identified, of which 16 were corals and calcifed hydroids.

The objectives of the present work are: (i) to present for the first time the real high-resolution images of ML reefs and their morphological aspects; (ii) to validate *in situ* the georeferenced satellite images after the final processing; and (iii) describe drop-camera video images obtained around the main reef structures.

2. The Manoel Luiz – Study Area

The bathymetric map, shown in Figure 1, indicates the location of the most northern coral communities known in Brazil, corresponding to the reefs of Manoel Luiz (1) and Banco do Álvaro (2), approximately aligned at the same depths in the middle shelf. Towards the coast is the Tarol Bank (3) consisting of calcareous algae deposits of *maerl* over quartzose sand and undetermined bed rocky relief (personal observations by the first author). In coastal areas less than 10 m depth, occurs a large sand waves field, formed by fine quartzose sand, known as Cururupu Banks (Palma 1979) (polygon 4 in the Figure 1).

According to Castro & Pires (2001): "ML reefs are constituted by a concentration of isolated pinnacles, each up to 300 m in diameter. These pinnacles may reach the low tide level, but the top of most of them are in depths up to 14 m. In the southwestern part, Coura (1994) described a predominance of the gorgonia *Phyllogorgia dilatata* on top and walls, in depths of up to 15 m, with corals, sponges, and algae dominating the slopes below this depth. The main absence seems to be the coral *Mussismilia harttii*, which may form large colonies in reefs in northeastern and eastern Brazil (Abrolhos)".

3. Materials and Methods

The satellite images processed in this work are from WorldView-3 (WV3) satellite and were programmed and obtained on 06/09/2018 in Bundle Mode (PAN + 8 MS), Standard Mode, with RPC / RPB data PAN, R, G, B, NIR1, NIR2, Red Edge, Yellow, and Coastal. Radiometric resolution was 11 bits and the angle of acquisition was between Nadir and 35º off-nadir. Images Datum is WGS84. The spatial resolution of the raw image in the panchromatic mode is 0.3 m and in the spectral mode is 1.2 m (PAN 30 cm and MS 120 cm).

The fusion procedure was performed by the imagery provider company, with the unification of multispectral and panchromatic images in a single-color image with a resolution of 30 cm. Then, an orthorectification was performed to correct the geometric deformations due to the sensor platform, the angle of acquisition, the relief, the curvature, and the rotation of the Earth. The orthorectification was performed based on SRTM 30 m local data. According to company information, the accuracy of WorldView satellites will not exceed 5 meters average error in 90% of cases.

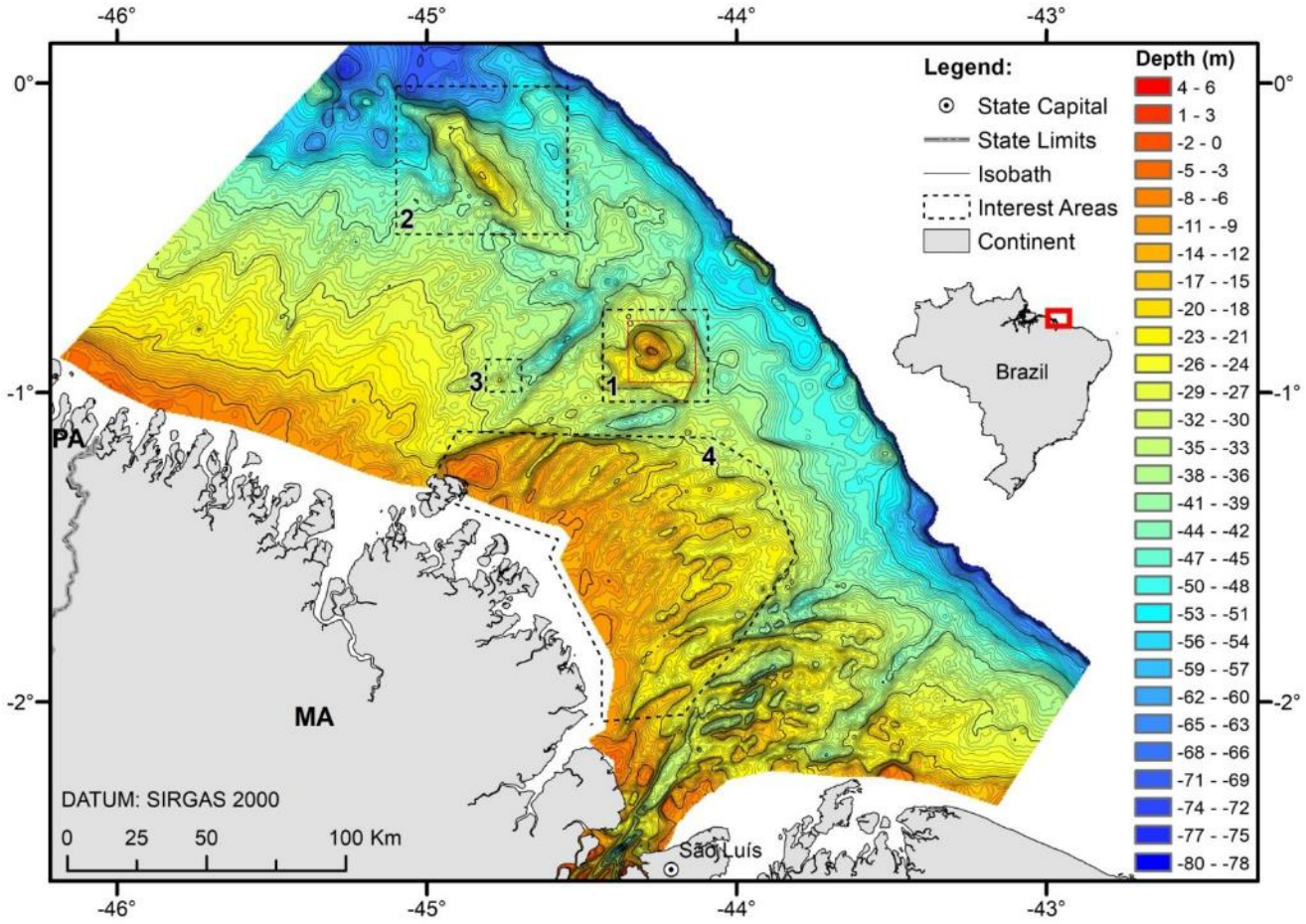

Figure 1: Bathymetric map showing the location of regional reefs Manoel Luiz-1 and Alvaro Bank-2 (coral occurrences), the Tarol Bank-3 (calcareous algae *maerl* type) and the Banks of Cururupu-4 (quartzose sand waves) adjacent to the coast. The study area is represented by the red square inside the polygon 1 (see Figure 3).

The satellite images were processed in ArcGIS and Geosoft systems. The elaborated maps were exported in GeoTiff format. To validate the georeferencing precision and also perform a drop camera survey in the area, a GeoTiff image was imported and visualized, in real time, with a navigation software (Hypack 2014).

Video images of the bottom and controlled navigation drift track were recorded around the main reef, but out of the GeoTiff image area because of the poor visibility conditions of the water (explanation in the Results section) (see location in Figure 3). The underwater images were acquired by the drop-camera system composed of a GoPro5 camera with a Qudos lighting system. A manual diving depth gauge and a compass were installed at the base of the frame.

4. Results

To specifically validate the georeferencing, we programmed to pass over an isolated pinnacle, showed in the satellite image (arrow and insert in the Figure 2). The peak of the structure was registered in sonar instruments (depth recorder and side scan sonar) and precisely coincident with the predicted pinnacle position, in a GPS navigation system (581400E, 9903150N; UTM 23S-WGS84).

The images obtained by the satellite WV3 in June 2018 revealed an exuberant formation with countless reef constructions, predominantly individual, with circular forms, besides linear and coalescent. The clearest large area in the image (Figures 2 and 4) delimits the shallowest Manoel Luiz reefs. The most concentrated and near-surface reef area occurs to the right of the image. Only two spectral bands were represented in the composite image. The Band 1 (coastal blue) with the highest water penetration was related to the blue color, and the Band 3 (green) related to the green color.

The Figure 3 shows the georeferenced satellite image on the Nautical Chart of the Brazilian Navy (DHN 400-2). A fair correlation is observed between the shallow (clear) reef areas and the contour of the 10 m isobath of the Nautical Chart, represented by the white line.

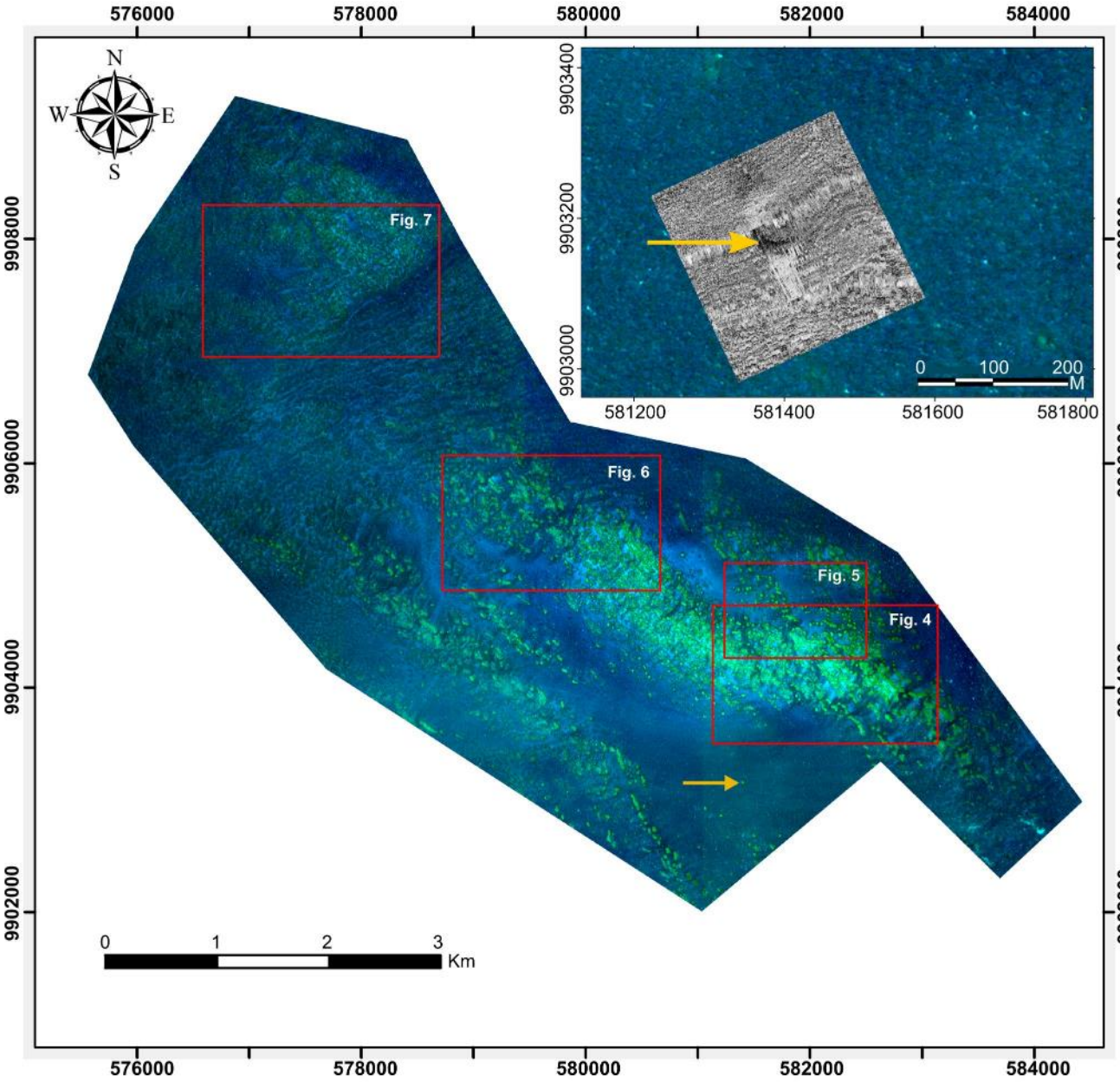

Figure 2: Image obtained by the satellite WV3 in June 2018, showing at the right the shallowest reef area of the Manoel Luiz reefs. Representation of Band 1 in blue color and Band 3 in green color. The delineated areas are described in detail in Figures 4, 5, 6, and 7. The isolated pinnacle indicated by the yellow arrow was used to validate the georeferencing by side scan survey (sonar image in the insert).

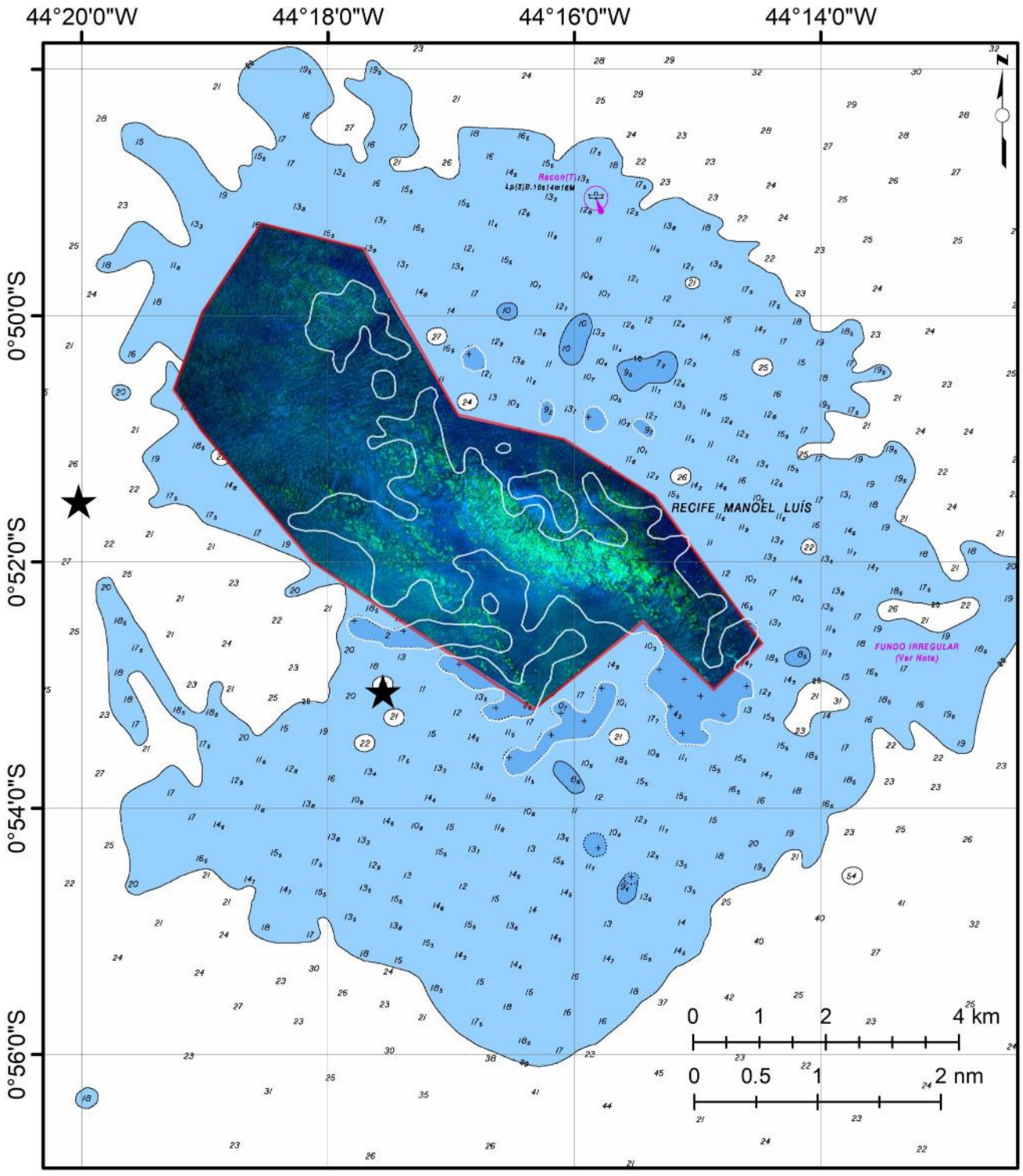

Figure 3: Representation of the georeferenced image over the Brazilian Nautical Chart DHN-400-2. In the adjustment of the image overlap, the errors related to differences in cartographic projections were not considered. The 10 m isobath is highlighted in white. The stars represent the position of the underwater video recordings obtained by drop-camera. See location on the regional map in the Figure 1.

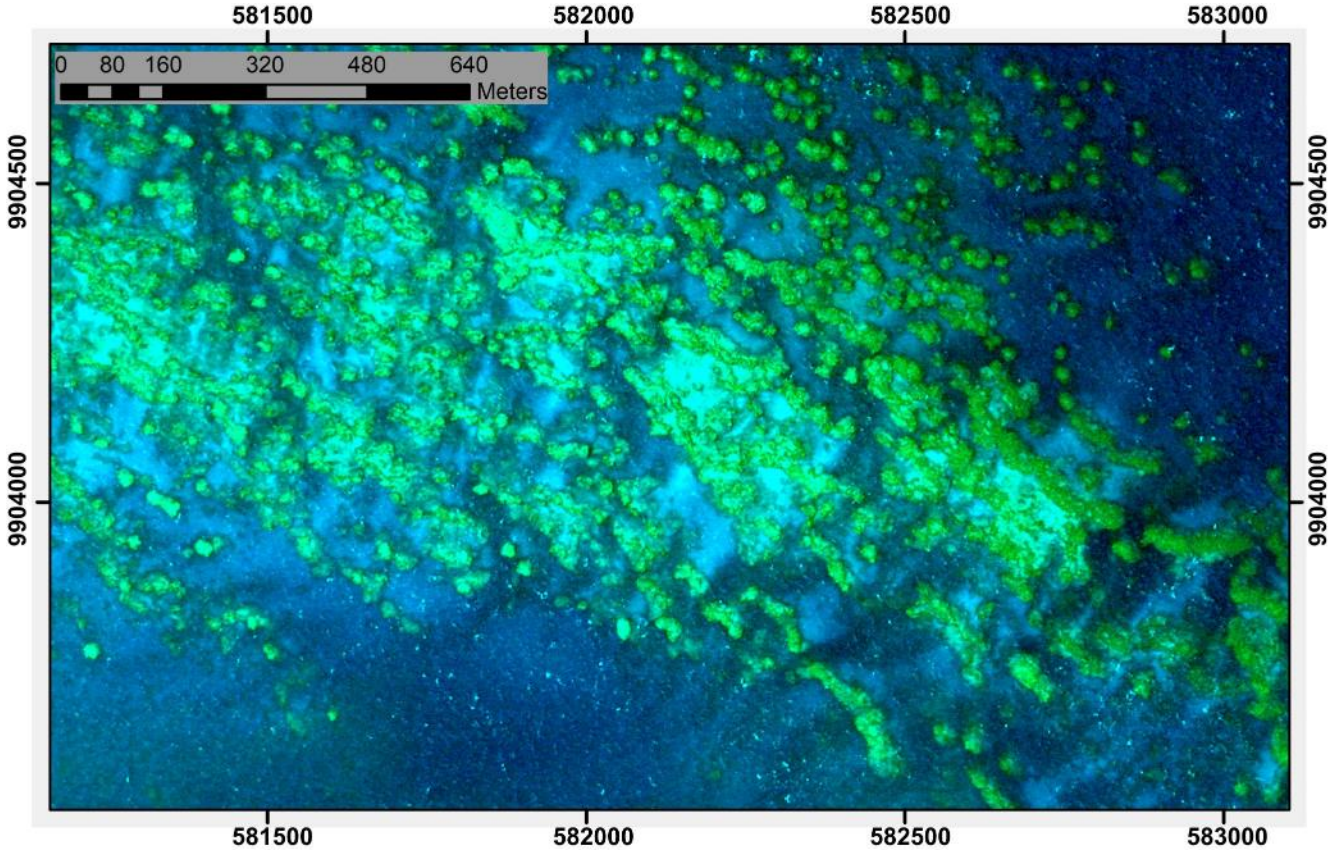

Figure 4: Detail of the shallowest reef area. The strong reflected white bottoms, inter reefs, are supposed to represent sediments composed by dead fragments of thallus of the green algae *Halimeda* sp. (see Figure 10).

Since the beginning of formation, the reefs have approximately circular shapes (patch reefs) and grow isolated, constructing vertical pinnacles. When they are close to the surface, they have a diameter varying between 20 and 30 m. The coalescence of the reefs occurs when they are aligned in the same direction and merge during the growth (Figure 5). The reefs grow mainly along NW-SE direction. In the shallower areas observed to the East of the image, linear coalescing reefs predominate, varying in length between 100 and 300 m, in the NW-SE direction.

Areas of greater depths (25 – 30 m) may occur abruptly, adjacent to the reef pinnacles. Apparently in some locals, channels similar to spurs and grooves are generated, possibly by the action of strong bottom currents that flow after high tidal damming (Figure 6).

To the NW of the regional image (see Figure 2), deeper reef formations occur, with predominant alignment in the NE-SW direction (Figure 7). These reefs are delimited by long channels, narrows and flats, some with more than 800 m in length, and only 20 to 30 m wide, apparently on a sandy bottom (*Halimeda* sand).

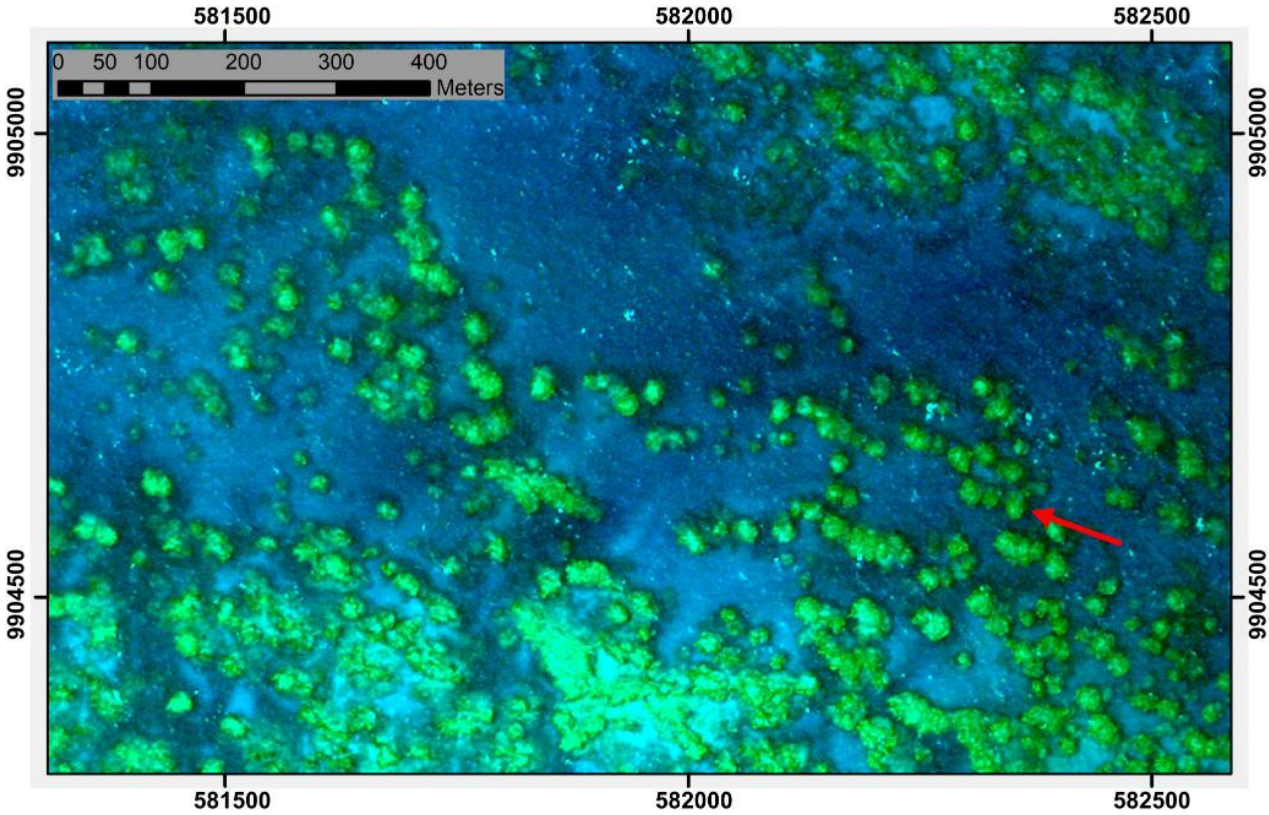

Figure 5: Growth of individual reefs colonizing a flat bottom area at depths greater than 25 m. Note the alignment of the reefs (red arrow). The second direction of growth is perpendicular to the first. See location in Figure 2. The areas of greater depth (25 – 30 m) may occur abruptly, adjacent to the reef pinnacles.

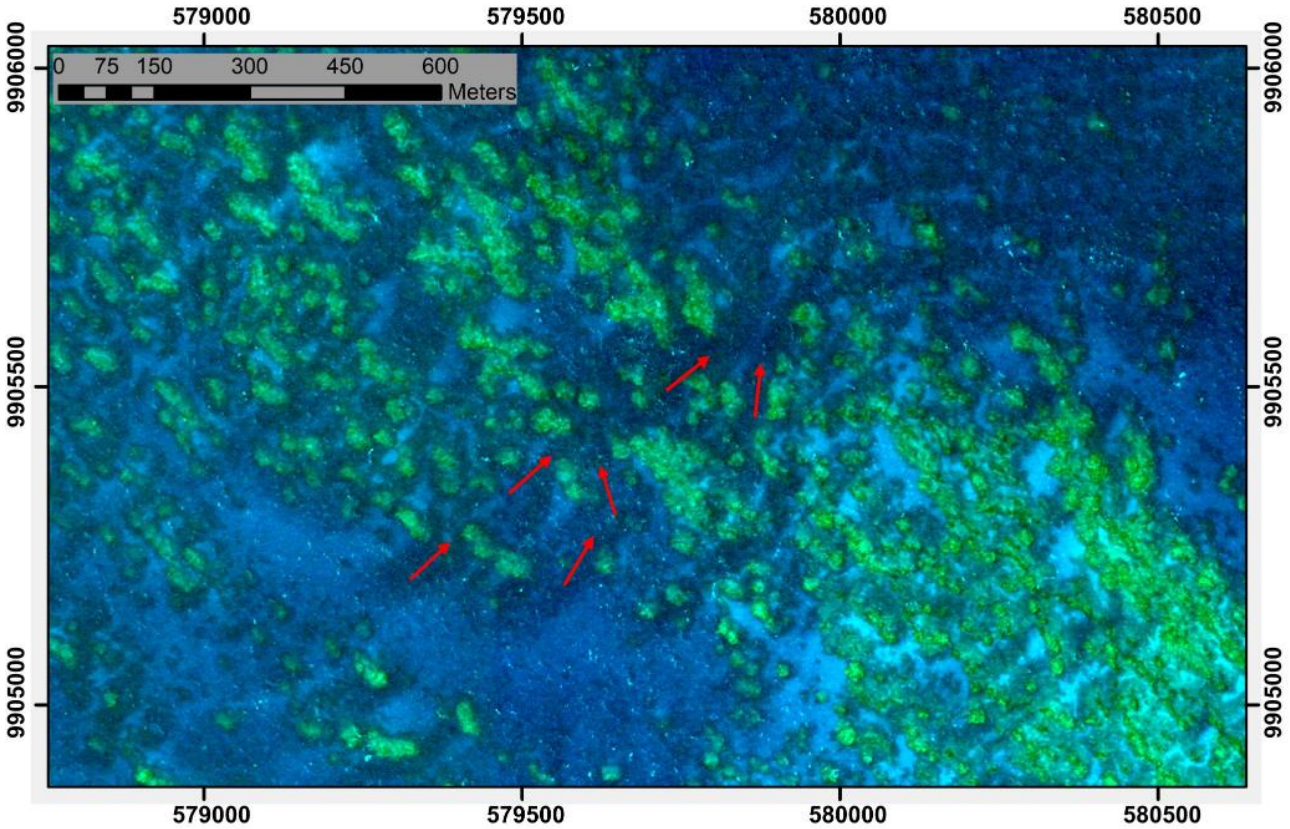

Figure 6: Bottom channels indicated by red arrows, possibly generated by amplified ebb tidal currents, apparent due to damming in the shallow area and reef constrictions. Form features similar to spurs and grooves.

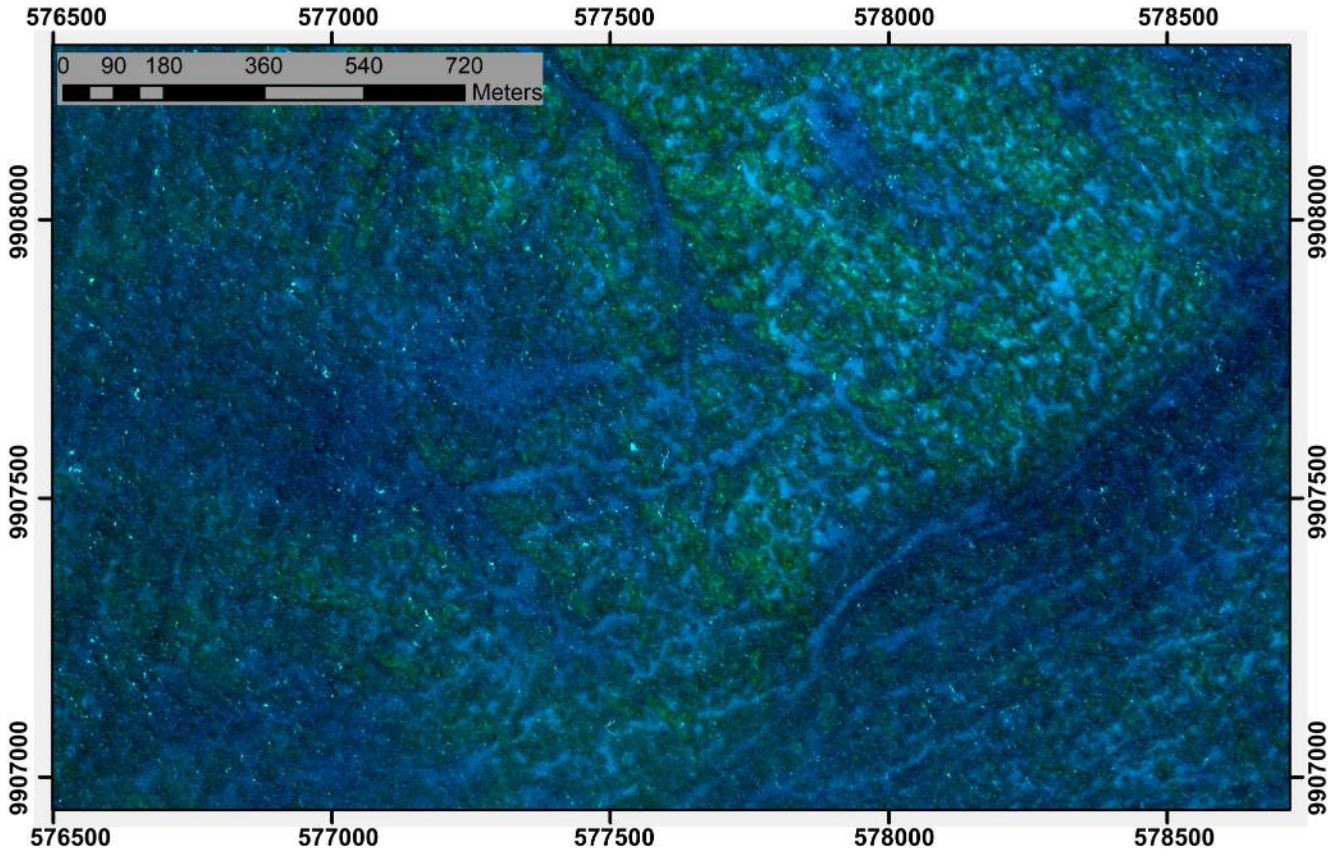

Figure 7: Larger and deepest reef area at NW of the Figure 2 image. The reefs have comparatively different alignments (NE-SW) cut by long and narrow channels, 800 m in length, and 20 to 30 m wide.

4.1. Submarine Video Images

The video images were taken through a system (drop-camera) towed close to the bottom in areas of depths greater than 20 m, with the vessel adrift, in stretches adjacent to the shallower reef massifs (see location in Figure 3). We did not navigate in shallower areas during the survey (March 2019), because the water visibility conditions were severely impaired due to the presence of "black waters", as regionally known. According to Cavalcante (2007), the "black waters" is a phenomenon that occurs sporadically, bringing continental water (salinity 12), apparently from Amazonas and/or Pará rivers, flowing towards the SE with ~0.78 ms^{-1}, in opposition to the typical coastal drift. Figure 8 illustrates the contrast between normal conditions and "black waters" conditions. Time series observations from Modis satellite (https://zoom.earth) allow assuming that they are continental waters rich in humic acids, without particulate inorganic mud, and coming from the coastal estuaries and the Pará river, at the peak of the rainy season. The brown color waters of the Amazon River, rich in suspended mud, flow to the NW, not reaching the ML region.

The photos shown below (Figures 9, 10, 11, 12, and 13) represent screen shots of the video, in moments when the system touched the sea bottom and the image remained stabilized, at a distance of ~50 cm from the focused ground. The scale of the photos can be evaluated by the base of the metal frame of the drop-camera, which is 4 cm wide. The images present in detail the characteristics of the reef surface, composed of crusts of coralline algae (red calcareous algae), green calcareous algae (*Halimeda* sp.), several species of sponges and sparsely patches of non-reef coral species. Although algae of the genus *Halimeda* do not constitute the reef framework, it forms a thin crust over much of the reef's surface, including covering certain parts of corals and coralline algae. Apparently, the dead crusts of coralline algae are covered entirely by *Halimeda* algae.

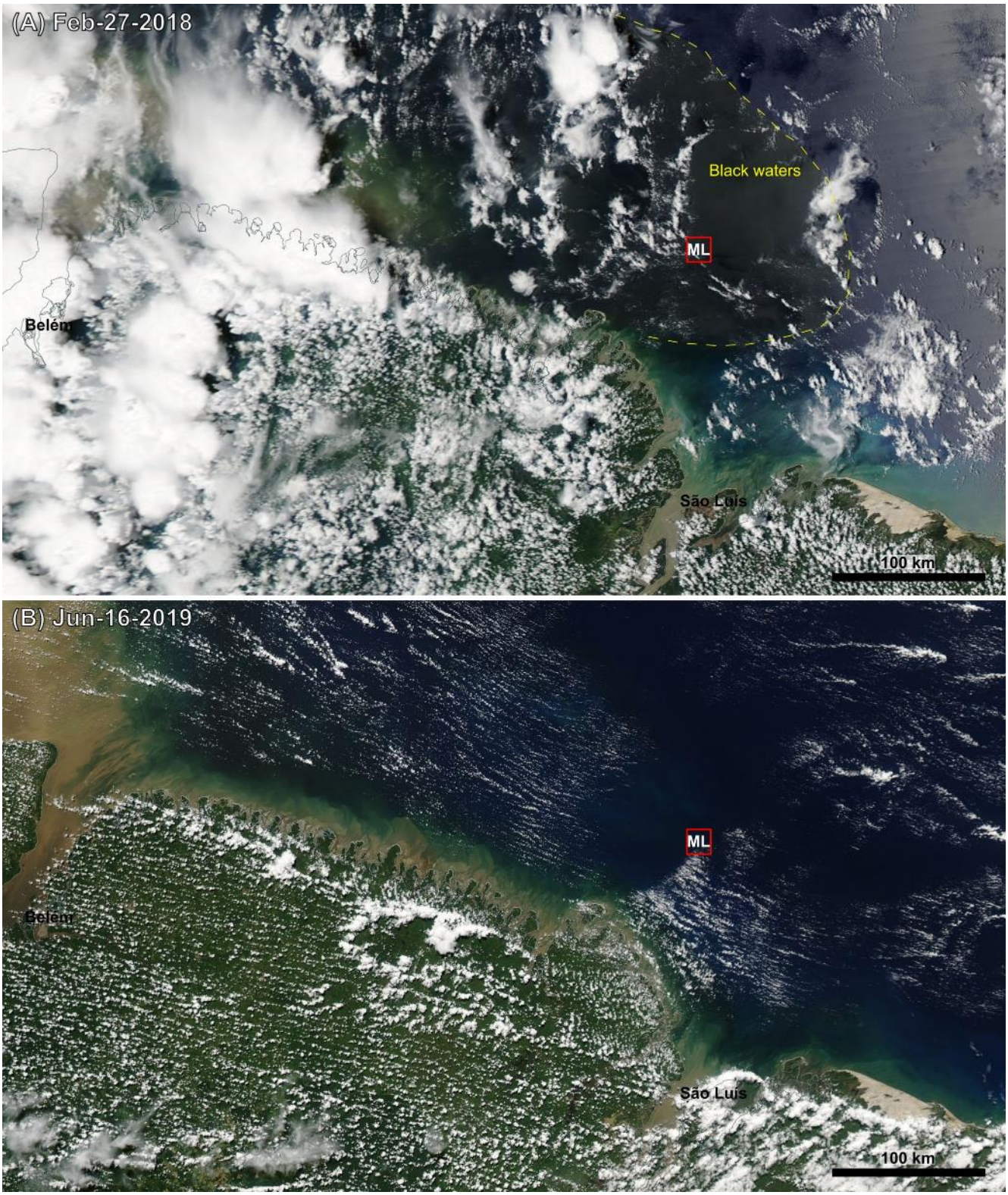

Figure 8: MODIS satellite images (Moderate Resolution Imaging Spectroradiometer), on different dates, showing very contrasting conditions of water quality. (A) represents the "black waters" season and (B) shows normal conditions with blue oceanic water. Source: https://worldview.earthdata.nasa.gov, accessed on September 2020.

Figure 9: A, B. 24 m depth. Color contrast between a sponge specimen (red color) and the living surface of a calcareous algae crust (purple color).

Figure 10: 28 m depth. Flat bottom covered entirely by dead thallus of green *Halimeda* algae, detached from the reef.

Figure 11: Depth 35m. Sponge in the foreground. The surface of the reef is almost entirely covered by a thin crust of *Halimeda*, except for a small patch of coral (in the center of the photo).

Figure 12: Depth 35 m. Thin crust of *Halimeda* covering coralline algae. *Halimeda*'s crust has apparently been eroded, as it has almost no live thallus. To the right of the photo is a sponge specimen.

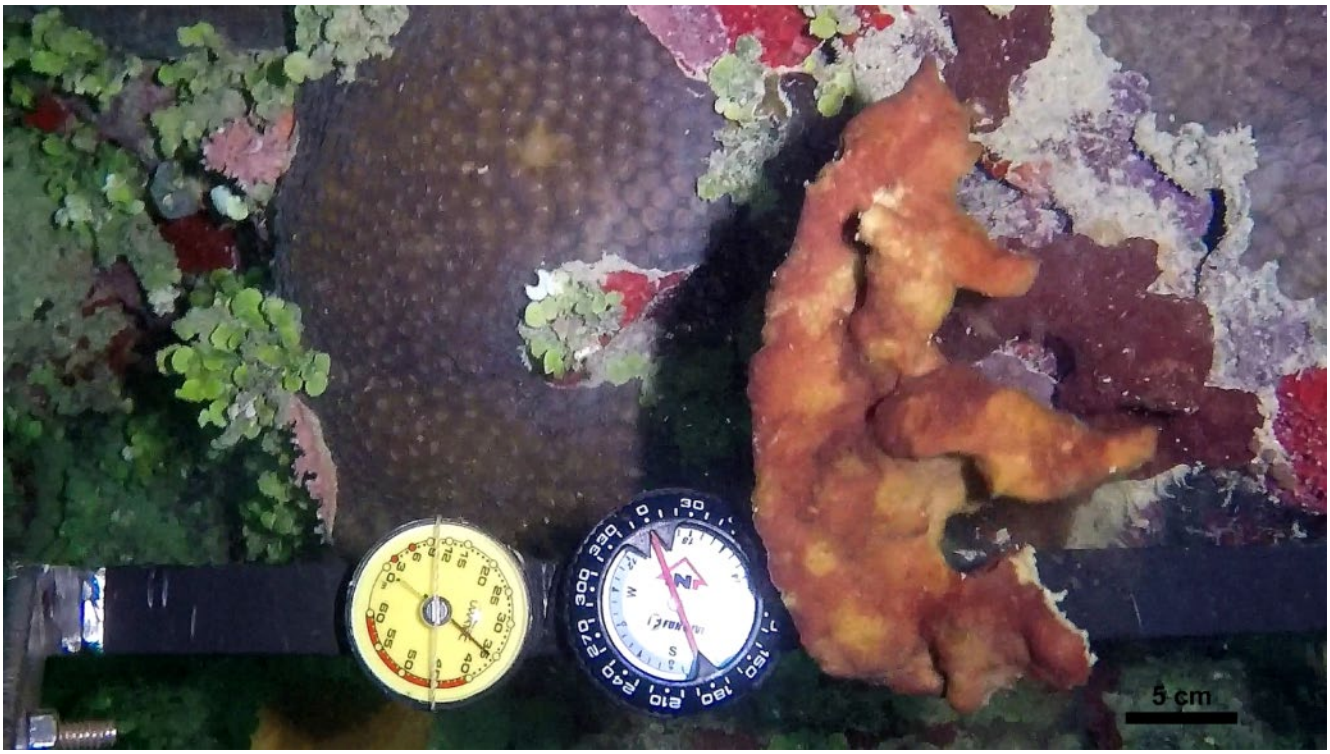

Figure 13: Depth 35 m. Coral patch, sponges and *Halimeda*.

5. Discussion and conclusions

There seems to be a structural conditioning of the underlying rocks, in the formation of the ML reefs and Alvaro Bank as both have a well-defined NW-SE orientation. This direction is the same as the faults direction of the Pará-Maranhão Basin.

Calcareous algae in the North - Northeastern Brazilian continental shelf present a wide variety of forms and species. In Manoel Luiz, in addition to the coralline algae that encrust (form?) the reef, there is also a wide coverage

of green calcareous algae (*Halimeda* sp.) on the surface of the reef. The reproduction of these green algae is intense, explaining the presence of large deposits of fragments on the bottom, adjacent to the reefs. The white areas of the image (see Figures 2, 4, 5, and 6), seen deep within the reefs, correspond to the concentrations of dead *Halimeda* thallus (*Halimeda* sands), reworked by marine currents (see Figure 10).

There are large areas of *Halimeda incrassata* on the bottom of the continental shelf off the coast of Ceará State (Monteiro 2011). In ML reefs however, the *Halimeda* species seems to be different, and it was to be expected, because in Ceará shelf these *Halimeda* algae are fixed in quartzose sand (Monteiro 2011), while in ML they are attached to rigid reefs.

There is a similarity between the *Halimeda* species encrusted in the Manoel Luiz reefs and those found in the Gulf of Mexico (Figure 14). If they are the same species, these algae could also attest that ML reefs represent stepping stones between the Caribbean and Brazil, as stated by Collette & Rützler (1977).

Figure 14: "Live rocks" for aquariums grown up in man-made carbonate blocks and harvest in Gulf of Mexico, in permitted areas by Federal government and by the state government of Florida (source: https://gulfliverock.com/premium-deco-live-rock, accessed on August 21, 2020). The green algae *Halimeda* naturally developed over the blocks are very similar to those encrusted in Manoel Luiz reefs.

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In Manoel Luiz, there are no deposits of free maerl type calcareous algae, which are, however, the only constituents of the Tarol Bank, close westward, as personally observed by the first author. Alvaro Bank apparently has its own encrusting coralline algae characteristics, but with absence of reef pinnacles. Spherical rhodoliths do not occur in these reef areas of the shelf, but are very abundant in the outer shelf, where together with sponges and octocorals form natural attractors that are also called "reefs" in descriptions of biological studies (Moura et al. 2016, Francini-Filho et al. 2019). According to Collette & Rützler (1977): "these environments have similar configurations with comparable, although less diverse associated flora and fauna are also known as 'reefs'. They can be created by sessile organisms (sponges, coralline algae, gorgonians, polychaete worms, vermetid mollusks, bryozoans". Future studies should be done to explain this diversity of occurrence of types of calcareous algae in areas close to each other.

Reefs themselves are formed by rigid constructions of biogenic origin (corals, calcareous algae and bryozoans) and / or rocky (diverse rocks, lateritic concretions, beach rocks). Reefs can be even constructed by man's activity (breakwaters, artificial reefs composed of automobiles, tires, or concrete blocks). Reef fishes and invertebrates are known to associate with a variety of substrates that provide hiding places as long as their other ecological requirements are met (Collette & Rützler 1977).

Generally, the Brazilian reef coral communities do not form true coral reefs, but just coral communities flourishing on hard bottoms (Castro & Pires 2001). Abrolhos reefs have been considered the only true coral reefs known in the South Atlantic (Paulay 1997). However, recent studies have shown that there are no exclusively coral reefs in Brazil, not even those called *coralgal* reefs, formed by joint constructions of calcareous algae and corals. The results of rotary drillings surveys on Abrolhos' corals (Bastos et al. 2018) revealed that they are in fact formed by bryozoans (44%), calcareous algae (28%) and corals (23%).

Moura et al. (2016) confirmed the results of the research initiated by Collette & Rützler (1977), and mapped a huge area (~9500 km²) of carbonate "reef" system between French Guiana and Maranhão, where benthic and demersal assemblages, including rhodoliths and sponge dominate the bottom. However, these "reefs" occur not only in the Brazilian Northern region, but also along extensive areas of the outer continental shelf, from the North down to the Rio de Janeiro shelf, at depths greater than 50 m (Milliman 1977, Amaral 1979). The rhodoliths banks found in these mesophotic areas are relict shallow deposits, that evolved and had transformed in stabilized forms, now developed on these mesophotic region.

The various definitions of reefs gave rise to misinterpretations. The pioneering studies by Collette & Rützler (1977) was entitled "Reef fishes over sponge bottoms off the mouth of the Amazon river", and by Moura

et al. (2016), was entitled "An extensive reef system at the Amazon River mouth". This latest scientific work was intensely publicized in the media and miscounted described as being the discovery of coral reefs at the mouth of the Amazon river, instead of reefs in general. The news caused widespread popular repercussions and widespread pressure from environmentalists, leading to the cancellation of a company's environmental license for oil exploration on the adjacent continental slope.

The reefs of Manoel Luiz are Holocene shallow reefs, that similarly to Brazilian Abrolhos reefs, followed the sea level rise during the last marine transgression. Just like Abrolhos, they are not constructed exclusively by corals; the existing sparse colonies of corals are fixed on structures formed by crusts of calcareous coralline algae (Moura et al. 2016). Two hypotheses can be formulated to explain the formation of ML reefs: (i) Calcareous coralline algae grow vertically by superimposed encrustation and are the only formers of reef pinnacles; or (ii) There is a rigid rocky substrate on which the calcareous algae are fixed.

The processed images of the WV3 satellite allowed revealing for the first time the true morphology of Manoel Luiz reefs. There has been an exuberant reef formation, with thousands of areas of attraction and shelter that enable the existence of a very high diversity of marine species. The valuable data obtained will serve as the basis for future integrated studies of this ecosystem (GeoHabitats).

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