Geomorphological Map of the Rio de Janeiro city (Scale 1:25,000): The Challenge of Mapping the Technogen

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Abstract The geomorphology of the Rio de Janeiro city reveals a mosaic of landscapes conditioned by the Cenozoic tectonics and by the variation of the relative sea level, where coastal massifs surrounded by fluviomarine lowlands and marine plains near the coast stand out. The methodological assumptions for the elaboration of the geomorphological map are described in Dantas (Geodiversity of the state of Maranhão. CPRM, Teresina, pp. 133–140), based on the use of the Relief Patterns Library (Dantas in Library of relief patterns: susceptibility chart to gravitational mass movements and flooding. CPRM, Rio de Janeiro, 2016. http://rigeo.cprm.gov.br/jspui/handle/doc/16589). For the definition of relief patterns, the 3rd and 4th taxons of the methodology of Ross (Rev Dep Geogr 6:17–29, 1992) were adopted, based on interpretation of digital orthophoto mosaic coupled with digital terrain model at scale 1:25,000. The morphostructural and morphosculptural units were also individualized. Finally, it is necessary to map the changes printed on the physical landscape, "creating" favorable space for urban expansion. In synthesis, the mapping of the Technogen is of utmost importance for the geomorphological mapping of the Rio de Janeiro city.

1 Introduction

The city of Rio de Janeiro occupies a peculiar urban site "squeezed" between sea and mountain (Bernardes and Segadas-Soares 1987), presenting a remarkable geological-geomorphological diversity (Guerra 1965; Pinto 1965). However, the flat and well-drained spaces are relatively scarce. Since the mid-nineteenth century and throughout

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practically the entire twentieth century, when the city experienced a vertiginous population growth, excluded sectors of society were forced to occupy the steep slopes of the foothills of the coastal massifs or the swampy terrains of the alluvial and fluviomarine lowlands (Segadas-Soares 1965). The occurrence of socio-environmental disasters (not natural) resulting from intense rainfall has been recorded in the Rio de Janeiro city since the beginning of the twentieth century (Brandão 1992).

Historically, the process of growth of the urban network involved works of conquest of the urban space via rectification and channelization of rivers, filling of mangroves and lagoons; cutting of slopes and opening of tunnels; and even more radical changes such as removal and razing of hills and large embankments over the Guanabara Bay. However, the geomorphology of the city of Rio de Janeiro has such a relevant importance in the configuration of the Carioca society that, in a certain way, influenced the socio-spatial segregation of the city since the end of the XIX century, where the wealthier layers of the population followed the tram lines toward the South Zone and the more humble population and the excluded sectors of society followed the train tracks, toward the North Zone (Abreu 1987). The Tijuca Massif imposed itself as a great natural boundary between the two distinct urban expansion fronts and as an important obstacle for the expansion of the metropolis toward the Jacarepaguá lowlands until the 1970s.

Thus, in a scenario of a territory drastically changed for the implementation of the metropolis of Rio de Janeiro, there is the need to highlight and map the deep anthropogenic changes printed on the physical landscape that produced the urban site conducive to the expansion of the city. In synthesis, the mapping of the Technogen is of utmost importance for the geomorphological mapping of the Rio de Janeiro city, with emphasis on the mapping of the embankments on the Guanabara Bay; of the sanitary landfills; of the mining fronts (mainly quarries and gravel pits for the supply of aggregates for civil construction) and terraces of the hillside dismounting (highlighting the Castelo, Santo Antônio and Cruz Vermelha terraces, located in the central area of the city and Inhangá, the latter, in Copacabana).

The geomorphological map of the Rio de Janeiro city (Mello and Dantas 2019), which covers an area of 1255 km^2, was mapped on a scale of 1:10,000 and presented on a scale of 1:25,000 to meet the demands of mapping the mass movement and flooding susceptibility with a cartographic level precision of great detail that was compatible with the great accumulation of knowledge generated by reputable municipal institutions as Geo-Rio and Rio Águas and by several public universities, UFRJ, UERJ, UFF, and the Rural University. Therefore, this mapping was developed to be the most detailed geomorphological cartography product of the municipality of Rio de Janeiro, in order to be applicable for the most diverse environmental management and territorial planning studies.

2 Study Area

The geomorphology of the municipality of Rio de Janeiro, as well as that of its hinterland, presents a notable inheritance coming from a Cenozoic tectonics, a fact already observed since the studies of Ruellan (1944). This famous french professor previously pointed out, with the rudimentary cartographic resources of his time, the significant topographic unevenness existing between the coastal massifs, the Baixada Fluminense and the Serra do Mar, besides the indentations represented by the Guanabara and Sepetiba bays. Ruellan affirmed then that the Serra do Mar consisted a dissected front of fault block.

Later, reports of structural geology and geotectonics executed in the scope of the Remac Project (Asmus and Ferrari 1978), as well as in-depth studies on the geological and tectonic evolution during the Cenozoic carried out by Almeida (1976), Riccomini et al. (1989) and Riccomini, Sant'Anna and Ferrari (2004), contextualized the relief of the Atlantic seaboard of the Rio de Janeiro metropolitan region as a system of *horst* and *grabens* fault blocks of a passive margin of the South American Plate. Ferrari (1990, 2001) refines this tectonic contextualization and enframe a large part of the metropolitan region of Rio de Janeiro in the so-called Guanabara Graben, embedded between the coastal massifs and the Serra do Mar front (Silva et al. 2015). In the Rio de Janeiro city, the coastal massifs of Tijuca and Pedra Branca, supported by igneo-metamorphic rocks of Neoproterozoic age of the Ribeira Belt; the Mendanha-Gericinó massif, constituted by a cretaceous pluton of alkaline rocks, stand out; and, from these mountainous terrains, spread out the fluviomarine lowlands (*baixadas*) of Guanabara, Jacarepaguá, and Sepetiba, all dotted with residual reliefs, such as hills (*morros*) and small isolated ridges (*serras*); and finally, the marine plains and beaches that border all the coastline, from Leme to the Marambaia sandy barrier. The filling processes of these fluviomarine lowlands, as well as the formation of the marine terraces are closely associated with the hydroeustatic fluctuations of the relative sea level during the Upper Quaternary (Amador 1997; Muehe and Valentini 1998; Fernandez and Rocha 2015; Muehe and Lins de Barros 2016).

3 Methodology

The geomorphological map of the Rio de Janeiro city was produced on semi-detail scale (1:25,000) (Fig. 1) based on the identification and compartmentalization of the Rio de Janeiro municipality in morphostructural units, morphosculptural units, and geomorphological units, following the methodology recommended by Ross (1992). The geomorphological cartography is, in turn, based on a morphological and morphometric compartmentalization of homologous units, with Relief Pattern Library employment, emphasizing a systematic relief amplitudes measurement, slope gradients, and drainage density (Dantas 2013, 2016). The morphological analysis was obtained from the empirical evaluation of the various sets of shapes and patterns of relief positioned at different topographic levels, through field observations and analysis of remote sensors (Orthophotos and MDE with spatial resolution of 5 m—IBGE 2010).

In order to improve the visualization of the terrain, was sought to highlight the areas of plains, as well as the areas on top of the elevations. Through the GlobalMapper 7.0 *software* tools, it was applied an overlay of the Digital Elevation Model

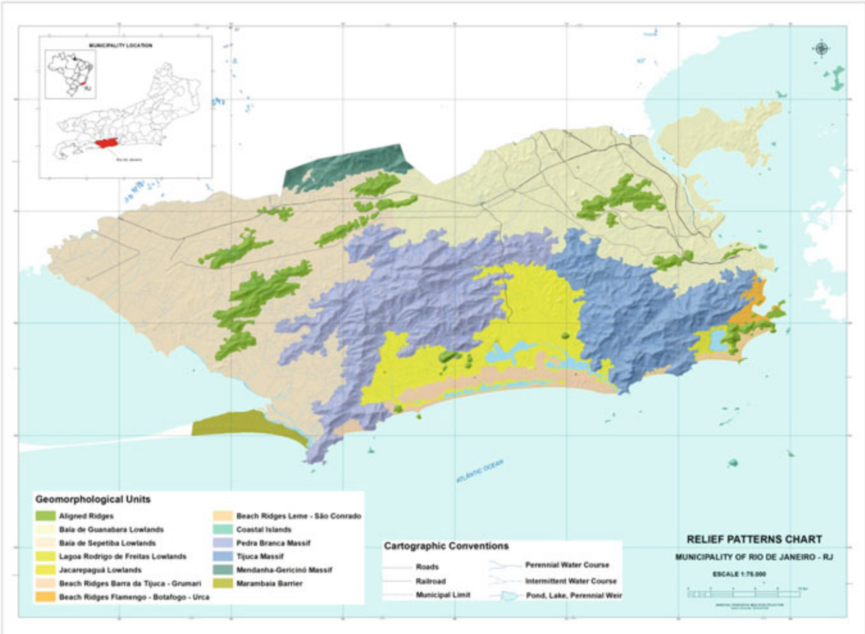

Fig. 1 Map of geomorphological units of the Rio de Janeiro city

(DEM), pseudo illuminated (*slope shader*), with the orthophotos generating greater contrasts between these two areas of the relief, resulting in an easier separation of these units, especially in the lowlands and valley bottoms domains (Shinzato et al. 2012). The geomorphological units were digitized on canvas, using the ArcGis 10.2 *software*. The products generated from the digital treatment of images and DEM were: slope; hydrography; contour lines with equidistance of 5 m; shaded relief with two directions of view—NE and NW; and hypsometry, as already proposed by Dantas et al. 2014.

Finally, highlights a peculiar methodological approach to proceed with the historical reconstitution of the Rio de Janeiro physical space transformation resulting from successive and cumulative human interventions carried out due to the metropolis expansion. Thus, the mapping of a densely urbanized area extreme transformed by human action over five centuries requires new approaches, which were introduced for the preparation of this geomorphological map, highlighting:

(a) the intensive use of Google Earth, Google Maps, and Street View.
(b) the use of a thorough bibliographic and cartographic research about the municipality of Rio de Janeiro, with emphasis on the following authors: Maia et al. (1984), Amador (1997), Abreu (1987), Roncarati and Neves (1976), Roncarati and Barrocas (1978), IPP (2008), Pereira et al. (2012) and the Embrapa pedogeotechnical map (Mendonça-Santos et al. 2009).

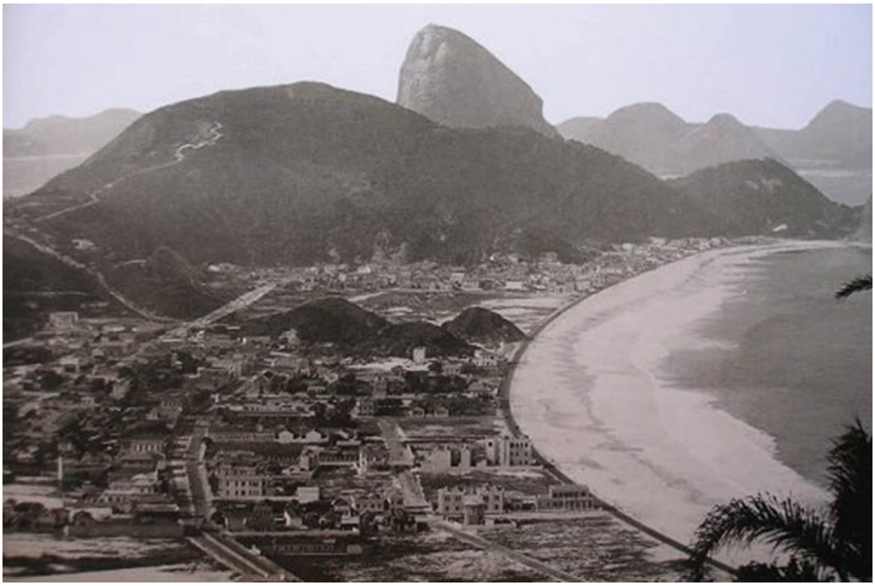

Fig. 2 Photograph of the Copacabana neighborhood, in the year 1920, highlighting the former low elevations location of the Morro do Inhangá, in the beach arc central portion. These elevations were razed throughout the twentieth century. *Source* Morro do Inhangá (2010)

Fig. 3 Photograph of Praça da Bandeira, in 1940, showing the occurrence of floods that periodically reach a consisting mangrove embankments area in a confluence of rivers that flowed into the Saco de São Diogo in the past. *Source* Malta, 29 Jan. (1940)

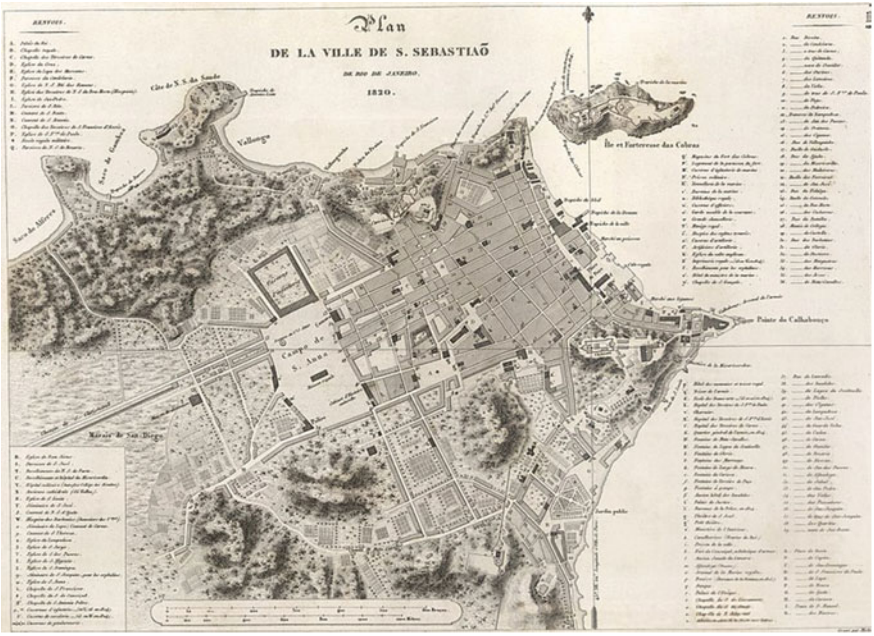

Fig. 4 Topographic plan of São Sebastião village of Rio de Janeiro, drawn up in the year 1820 and showing, with rich detail, the original coastline contour and the location of all hills, at a time before the embankments and razing of hills, throughout the twentieth century. *Source* Freycinet [ca. 1824]

(c) the use of photographs (Figs. 2 and 3), images, and historical maps (Fig. 4) to reconstitute the natural environments, before the radical transformations undertaken by successive urbanization events.

(d) the use of historical map platforms and graphic animations (ImagineRio 2021) that allow reconstituting the urban site's historical evolution and the environmental transformations resulting from the urbanization process of the Rio de Janeiro city.

4 Results and Discussions

The Rio de Janeiro city is compartmentalized into seven geomorphological units that will be systematically described below, emphasizing dominant relief patterns, their genesis and morphogenetic evolution, and technogenic transformations:

4.1 Tijuca Massif

The Tijuca Massif occupies the central-eastern portion of the city and consists of an imposing mountainous massif, surrounded by the Guanabara, Jacarepaguá, and South Zone lowlands. It is supported by a diverse geological substrate composed of paragneisses, orthogneisses, and granitoid rocks of Neoproterozoic age (Heilbron et al. 2016, 2020). The highest peaks, (Pico da Tijuca, 1021 m; Pico do Papagaio, 989 m; Pedra da Gávea, 842 m) are constituted by granite dome-shaped elevations or laccoliths that stand out amidst the rugged and forested relief of steep slopes, often covered by deposits of colluvium and talus (Fig. 5). A network of channels with high drainage density and marked structural control stands out, as observed along the valleys of the Cachoeira and Maracanã rivers, both conditioned by a lineament of NE-SW direction.

This massif divides the southern, northern, and western zones, acting as a water dispersion zone between the Guanabara and Jacarepaguá lowlands and is characterized by alignments of WSW-ENE direction ridges, including the Serra da Carioca where the peak of Corcovado (704 m) is located. Small associated mountain alignments are also remarkable, such as the alignment Morro dos Cabritos (379 m)—Pão de Açúcar (395 m), disposed of parallel to Serra da Carioca (Motta 2017) (Fig. 6). Extensions in NE direction, near Santa Teresa and Glória neighborhoods, emphasize the very dissected aspect of this massif, already undone in a relief of aligned hills (Dantas 2000).

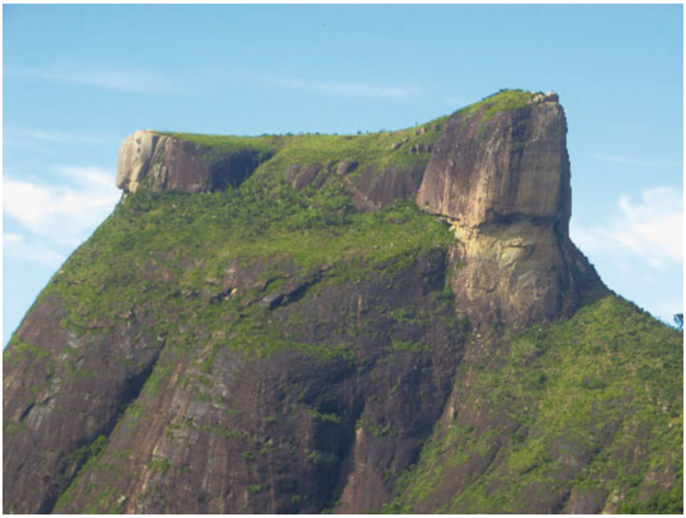

Fig. 5 Detail view of the Gávea summit (842 m high), which presents a relatively flat top due to the granitic laccolith intrusion more resistant to weathering than the underlying gneissic rock. *Photograph* Marcelo Ambrosio Ferrassoli

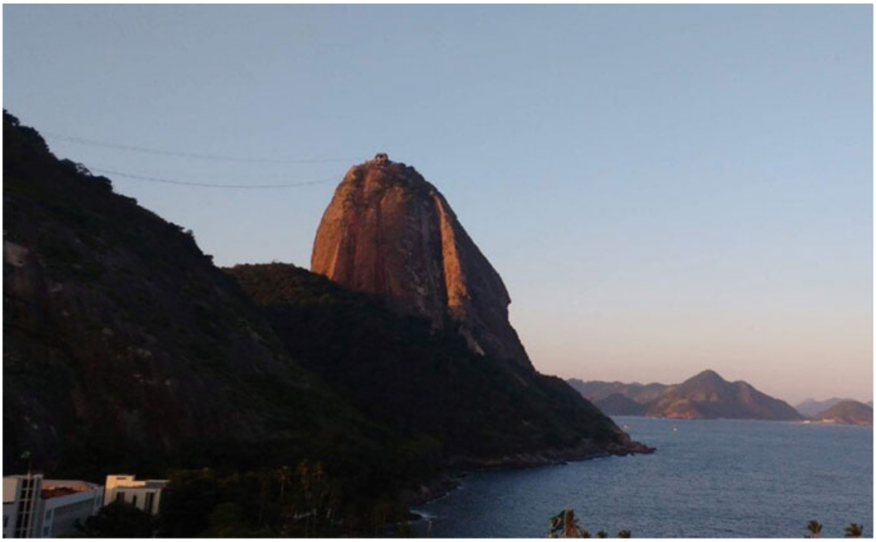

Fig. 6 Panoramic view of the Sugar Loaf (395 m high), the iconic rocky elevation, of peculiar and slender rounded shape that guards the entrance to the Guanabara Bay, as a historic sentinel of the Rio de Janeiro city. *Photograph* Loury Bastos Mello

Virtually the entire area of the Tijuca Massif was devastated in the early nineteenth century, for planting coffee plantations, and reforested around 1860, due to serious environmental problems arising from deforestation. Noteworthy in this context: the erosion of slopes, silting up of rivers, and the subsequent scarcity of water for urban supply. This secondary forest of 150 years of existence is the scene of many geomorphological and geoecological studies, which demonstrate the importance of the structure and functionality of the forest cover in regularizing the slopes hydrology and controlling mass movements (Coelho Netto 1992, 2005, 2007; Rocha Leão 1997; Fernandes et al. 2006; Negreiros et al. 2006, among others).

Like the other coastal massifs, the Tijuca Massif presents a high potential of vulnerability to erosion events and mass movements. During the extreme events of 1966/1967 and 1988, were recorded in Carioca and Maracanã river basins (Mousinho and Silva 1968); in 1996, were recorded in Quitite and Papagaio river basins, in Jacarepaguá (Cruz et al. 1998; Fernandes et al. 2001, 2004; Vieira and Fernandes 2004); and in 2010, the slopes of Santa Teresa were the most affected (Coelho Netto et al. 2012). Thus, neighborhoods located at the foothills of steep slopes, including Jardim Botânico, Humaitá, Cosme Velho, Santa Teresa, Tijuca, Grajaú, and Freguesia, as well as communities like Rocinha and Vidigal are subject to suffer the impact of torrential rains, landslides and mass runs of great magnitude from the slopes of the mountain massif.

Due to the fact that the massif is close to the historic core of the metropolis of Rio de Janeiro, it suffers an intense urban pressure from all sectors, resulting in the vegetation cover degradation. This process is developed through deforestation, fires, or slums, with greater intensity on the northern slope (urban network expansion around the Tijuca and Méier neighborhoods) and, more recently, in the western slope (urban network expansion of Jacarepaguá) (Fernandes et al. 1998; Zaú et al. 2007).

Despite the significant human transformation of the natural landscape of the Tijuca Massif, such changes were not sufficient to generate technogenic formations.

4.2 Pedra Branca Massif

The Pedra Branca Massif is located in the western part of the city and, like the Tijuca Massif, consists of an imposing mountainous massif, surrounded by the Sepetiba and Jacarepaguá lowlands. It is supported predominantly by tarditectonic granitoid rocks of Cambrian age (Heilbron et al. 2016, 2020). In this massif, the highest point of the municipality of Rio de Janeiro (Pico da Pedra Branca, 1024 m) stands out like a granite dome-shaped elevation amidst steep and forested slopes. Its southwestern extension consists of an extensive alignment of SW-NE direction that directly reaches the ocean, close to the Grumari and Barra de Guaratiba beaches. The isolated mountain ranges of Serra do Cantagalo (254 m) and Serra da Paciência (202 m), in WSW-ENE direction, are also remarkable, being detached elevations of the Pedra Branca Massif within the Sepetiba lowlands (Dantas 2000).

Extensive Pedra Branca Massif areas were deforested in favor of the coal cycle during the nineteenth century, intended to provide the city with charcoal (Oliveira and Fraga 2011). From 1960, the Pedra Branca Massif began to suffer the increase of urban pressure in its lower hills, with high susceptibility to mass movements and floods, especially in its eastern (Jacarepaguá) and northern (Realengo, Bangu and Campo Grande) slopes. On the northern slope, the forest has been completely replaced by grass vegetation.

Quarries for gravel supply are registered at the foothills of the Pedra Branca Massif steep slopes, which denotes, locally, a radical alteration of the natural landscape, representing technogenic formations mappable on a scale of 1:25,000. These quarries, active or abandoned, also occur to a lesser extent in the Tijuca Massif and other small hills and mountains. The virtual urban expansion toward abandoned quarry terraces may result in the generation of new risk areas. However, old quarries deactivated many decades ago, are now fully incorporated into the urban fabric of Rio de Janeiro. Many imposing historic buildings erected using ashlar elements between the nineteenth century and the first half of the twentieth century were built from material extracted from these old quarries, mainly using the iconic Facoidal Gneiss, “the most Carioca of rocks” (Castro et al. 2021).

4.3 Mendanha-Gericinó Massif

The Mendanha-Gericinó massif occupies a northern portion of the city, bordering Mesquita and Nova Iguaçu municipalities (Motta, 2017). It consists of an intrusive and isolated mountainous massif, with dome shape, elongated in the WSW-ENE direction, reaching 940 m high, and is abruptly delimited by the surrounding fluviomarine lowlands, dotted by isolated hills (Dantas 2000). It is supported by an igneous rock pluton of alkaline composition from Neocretaceous age (Heilbron et al. 2016). The Marapicu hill (620 m) integrates this unit and consists of an intrusion located slightly southwest of the main intrusive body, presenting a morphology of a subvolcanic neck, preserving ring structures. The unit presents a high potential of vulnerability to erosion and mass movement events, which are often triggered by the degradation of the forest cover, initially as a result of agricultural exploitation and later due to the urban increasing pressure to which the massif is submitted. This process is verified in its southern slope (urban networks expansion of Bangu and Campo Grande), where the lower slopes deforestation has been increasing.

4.4 Sepetiba Lowlands and Marambaia Sandy Barrier

The Sepetiba lowlands are situated in the western part of the city, west of the Pedra Branca Massif, being generated by cumulative depositional events of Pleistocene and Holocene ages, which filled the inland Sepetiba lowlands. Such formation process of this vast lowland generated a complex mosaic of depositional environments that include tidal plains (mangroves); fluviomarine plains (marshes) and floodplains, besides the alluvial-colluvial lowlands of the Guandu, Prata, Guandu do Sena, Piraquê and Portinho river basins. The Sepetiba lowlands consist of an extensive flat surface with shallow to sub-flooding water tables, dotted with hills, aligned hills, and small mountain ridges between the neighborhoods of Pedra de Guaratiba and Sepetiba to Santa Cruz and Campo Grande.

The Sepetiba lowlands experiences, from the mid-twentieth century, an accelerated process of urban network expansion, resulting in the installation of neighborhoods in flood risk areas, being Jardim Maravilha the most emblematic example. Despite this urbanization process, extensive mangroves and apicuns remain at the bottom of Sepetiba Bay, between Pedra and Barra de Guaratiba, and the inner portion of the Marambaia sandy barrier. This extensive beach-ridge, which is a unique geomorphological unit, is characterized by an extensive coastal sandy marine deposit that separates Sepetiba Bay from the ocean, with areas with dune fields resulting from the aeolian remobilization of the sand barrier.

4.5 Jacarepaguá Lowlands

The Jacarepaguá lowlands occupy the southern portion of the West Zone of the municipality, between the Tijuca and Pedra Branca massifs (Fig. 7). Just like the other fluviomarine plains, the events of regression and transgression of the relative sea level are determinants of its original morphological configuration. Thus, the Jacarepaguá lowlands display a diverse mosaic of depositional environments where it stands out, near the coastline, corresponding to Barra da Tijuca, a lagoon system with two sandy barriers anchored between the Joá and Prainha promontories, interspersed with lagoon plains (marshes) that represent floodable lowlands resulting from the filling of part of the current lagoons. Behind it, in Jacarepaguá, there is a floodplain composed of the Camorim, Grande, Anil, Arroio Pavuna, and Arroio Fundo river basins, dotted with hills and isolated rocky elevations.

The Jacarepaguá lowlands experienced, as of 1970, an accelerated process of the urban network expansion, being characterized as the main growth vector of the Rio de Janeiro city (Dantas 2000). The disorderly urban expansion generated serious socio-environmental problems in communities such as Cidade de Deus and Rio das Pedras, located in areas susceptible to flooding. Serious geotechnical problems have also arisen in the construction of buildings groups over the "soft soils" on lagoon plain, expressed by means of sinking. However, it is the lagoon bodies that suffer the most intense degradation process in the region, as a result of the large amounts of sewage and waste discharge, associated with the low renewal capacity of their waters.

Fig. 7 Overall view of the Jacarepaguá alluvial-colluvial plain. In the background, the beauty silhouette of the Tijuca Massif west flank. *Photograph* Marcelo Ambrosio Ferrassoli

4.6 Guanabara Lowlands

The Guanabara lowlands, located in the northern part of the city, cover its eastern portion north of the Tijuca Massif, being also generated by Quaternary depositional events that filled the Guanabara Bay recess. The depositional environments that model the Guanabara lowlands are represented by tidal plains (mangroves); fluviomarine plains (marshes) and floodplains of Sarapuí, Pavuna, Acari, Irajá, Faria-Timbó, and Maracanã river basins. However, it is emphasized as the dominant morphological feature, the extensive areas covered by alluvial-colluvial lowlands. These terrains consist of depositional surfaces of mixed origin that fill the lowered sectors of the Guanabara Graben (Ferrari 1990), in the Sepetiba and Guanabara lowlands and that extends throughout the Baixada Fluminense (Dantas 2000) and can be correlated to the Caceribu Formation, described by Amador (1980). The Guanabara lowlands are dotted with isolated low hills, besides small ridges like the Engenho Novo hills (180–210 m) that divide the Maracanã and Faria-Timbó river basins and the Misericórdia hills (170–250 m), where the Alemão and Penha slum complexes are located.

Vast embankments over the Guanabara Bay were implanted since the beginning of the XX century, highlighting the disappearance of the old Inhaúma inlet, Maria Angu beach, and the creation of Fundão Island and the Galeão airport, representing technogenic deposits mappable on a scale of 1:25,000.

In general, all these fluviomarine lowlands present an advanced stage of socio-environmental degradation, presenting serious problems as result from the significant population growth verified throughout the twentieth century. The installed degradation comes from the bad disposal of solid waste, the lack of basic sanitation, the slope deforestation, the silting up of the channels, and the inadequate soil occupation, among the main problems (Dantas 2000).

4.7 Downtown and South Zone Lowlands

The lowlands located in the Center and South Zone of the city, densely urbanized and object of greater real estate valuation, suffered the deepest changes in their geographic space. So, the geomorphological mapping of these terrains becomes very difficult in response to the extreme difficulty of reconstituting the past depositional environments. We highlight tidal plains (mangroves); fluviomarine plains (marshes); floodplains of Carioca and Macacos river basins; and marine plains of the Flamengo, Leme-Copacabana, and Ipanema-Leblon beach arcs.

Important embankments over the Guanabara Bay's water surface were implemented since the beginning of the twentieth century, highlighting the disappearance of Saco de São Diogo and the construction of Santos Dumont Airport, Aterro do Flamengo, Cais do Porto, Urca neighborhood (Fig. 8) and the surroundings of Rodrigo de Freitas lagoon (Fig. 9), in addition to the enlargement of the Copacabana beach. Such embankments were built from the dismantling of the past hills of

Fig. 8 Aerial view of the Urca neighborhood, built from embankment over the waters of Guanabara Bay. *Photograph* Marcelo Eduardo Dantas

Fig. 9 Panoramic view of the Rodrigo de Freitas lagoon, obtained from the Corcovado hill, where Christ the Redeemer statue was erected. Its water body has been successively reduced due to land reclamation works on its margins. *Photograph* Loury Bastos Mello

Fig. 10 Photograph of the esplanade of Castelo hill in 1930, a few years after its dismantlement, where the immense urban void stands out amidst the nineteenth- and early twentieth-century houses. This esplanade is positioned 5–8 m above the base level of the surrounding plains. It can be seen, on the left, an extensive area that has just been reclaimed along the Guanabara Bay. *Source* Holland (1930?)

the downtown consisting of thick regolith of weathered biotite-gneiss rock (Castelo, Santo Antônio, and Senado) (Fig. 10). These esplanades constituted excellent sites for urban expansion in the city center itself, being represented by the road axes of the Antônio Carlos and Chile avenues and by the Cruz Vermelha square. All these technogenic formations are also mappable at a scale of 1:25,000.

5 Conclusions

The Rio de Janeiro city presents a remarkable geomorphological diversity represented by imposing coastal massifs, with steep and predominantly forested slopes, supported by lithologies of distinct compositions, as well as by extensive fluviomarine and marine plains constituted by a complex mosaic of Quaternary depositional environments that may present gravitational, alluvial, marine or transitional genesis.

However, the execution of a geomorphological mapping in a densely urbanized metropolis that presents a secular accumulation of successive human interventions on the physical environment proves to be extremely difficult, requiring the use of new and some unusual analysis tools, such as: the use of programs and applications like

Google Earth and Street View; and the historical rescue of the natural space transformation process with the use of historical sources (cartographic or documentary), old photographs and, if possible, historical map platforms.

The reconstitution of the original physical environment of the Rio de Janeiro city and the determination and mapping of that technogenic formations are of great relevance to support studies of environmental management and territorial planning, including the Municipal Master Plan. From this reconstitution, it is possible to determine areas with higher susceptibility to flooding and mass movement events or areas of greater environmental fragility, as well as to provide subsidies for engineering geological studies aiming at the expansion or consolidation of the urban network.

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