Earth Science Research; Vol. 5, No. 2; 2016
ISSN 1927-0542 E-ISSN 1927-0550
Published by Canadian Center of Science and Education

Fluvial Erosion Characterisation in the Juqueriquerê River Channel, Caraguatatuba, Brazil

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Received: October 8, 2015 Accepted: February 5, 2016 Online Published: June 5, 2016

doi:10.5539/esr.v5n2p105 URL: http://dx.doi.org/10.5539/esr.v5n2p105

Abstract

The Juqueriquerê River channel was formed in a Precambrian crystalline basement. The lithological association is largely composed of ancient metamorphic and igneous rocks, with several overlapping tectonic episodes. Field surveys along the upper and middle course allowed for cataloguing a wide variety of fluvial erosion features. A sizable amount of morphological features have been sculpted on different types of rocks, including furrows, potholes, percussion marks, polishing and smoothing boulders as the most representative. The sizes and shapes of these scour marks are also diverse, and their study has provided important results for better understanding the erosive processes. Given their wide variety, the erosive morphological features offer an excellent opportunity to explore the mechanisms of fluvial erosion and evaluate their effective capacity to remove cobbles and boulders in bedrock river systems.

Keywords: Juqueriquerê River, bedrock channel, fluvial erosional features

1. Introduction

Regardless of size, the essential role of a river is to transport water and sediments from a higher altitude region to a lower altitude region, ending its course in an ocean or lake (Hogan & Luzi, 2010). Although sediment transport may seem like a simple process, the origin and evolution of the erosional features in bedrock river channels remain poorly understood. As a result, numerous studies have focused on the processes that involve the formation of those sculpted shapes (Barnes, 1956; Allen, 1971; Wohl, 1998; Johnson & Whipple, 2007; Cook, Turowski, & Hovius, 2013). Bedrock fluvial systems are essentially characterised by boulder deposits, which have been accumulated under conditions of high flow turbulence from upstream source areas (Goode & Wohl, 2010). The transfer of very coarse sediments into the channel occurs mostly through lateral hillslope links, debris flows and landslides (Whipple, 2004). Another important aspect that must be considered in bedrock systems is the channel morphology. According to Wohl (1998), there is a close connection between the erosional process and the resistance of the material that composes the channel substrate. Recent studies indicate that this interaction is controlled by other factors, such as climate, lithological heterogeneity, rock mineral composition, regional structural pattern, topographic gradient and turbulent fluctuation (Burbank & Anderson, 2001; Wohl & Achyuthan, 2002; Kobor & Roering, 2004; Hovius & Stark, 2006; Johnson & Whipple, 2010; Turowski, 2012; Cook et al., 2013; Wilson, Wilson, Hovius, & Turowski, 2013).

In light of the considerations made above, it is possible to assume that fluvial bedforms along the river channels are mainly due to the action of hydrodynamic power on the bedrock. Richardson and Carling (2005) proposed a detailed description and a systematic nomenclature for the typology of sculpted shapes in open bedrock channels. The sizes and shapes of such scour marks are diverse, and a wide range of approaches have been used to study them. In this context, Wohl and Merritt (2001) and Wohl and Achyuthan (2002) are among the studies that deserve special mention. These authors conducted exhaustive reviews with regard to the hydraulic driving forces, physical resistances of the substrate and morphological features. As previously noted by Wohl (1998) and

Whipple, DiBiase, & Crosby (2013), the natural occurrence of these sculpted forms is particularly interesting to illustrate the general implications of the fluvial erosion dynamic process on the river channel incision and landscape evolution.

A detailed characterisation of a large number of erosional features occurring along the upper and middle stream of Juqueriquere River is documented in this paper for the first time. The bedforms that have been sculpted in igneous and metamorphic rocks provide an excellent opportunity to explore the mechanisms of fluvial erosion and their effective capacity to remove cobbles and boulders in bedrock river systems.

2. Study Area Contextualisation

The Juqueriquerê River, which initiates at an altitude of 1100 m in the Lorenço Velho Plateau, on the western edge of the Caraguatatuba district, in the northern sector of Serra do Mar, has an extension of approximately 48 km to its outflow into the ocean. As a function of the topographical variation, the channel width, and the clastic sediments in transport, the Juqueriquerê River can be divided along a longitudinal profile into three main segments (Figure 1): a) The upper stream, which has an extension of 10 km from its source, flows in the NW-SE direction and is named the Pardo River. With a width ranging from 5 to 20 m, the channel displays a limited overbank deposition, consisting only of boulders and cobbles. b) The middle stream, named the Camburu River, presents a watercourse markedly influenced by the regional structural pattern, with a general E-W direction. With an altitude of 560 m and a width varying between 10 and 30 m, the channel mostly has a rectilinear form. Very poorly-sorted sediments of cobbles and gravels, with occasional blocks, are the most significant surface deposits. c) The lower stream begins at the boundary of escarpment erosion, and it extends toward the coastal plain. At this location, the course is referred to as the Juqueriquerê River, and the channel recovers its NW-SE initial direction. Throughout this final stretch, the river has a width ranging from 15 to 50 m, it meanders, and it drains into a floodplain of an altitude lower than 10 m. Heterogeneous deposits consisting of sand, silt and clay occur along the banks.

The present study focuses on the segment located between Lorenço Velho and Juqueriquerê plateaus. The region provides an excellent exposure of the bedrock channel, with numerous small waterfalls, in part, clearly influenced by the regional tectonic structure.

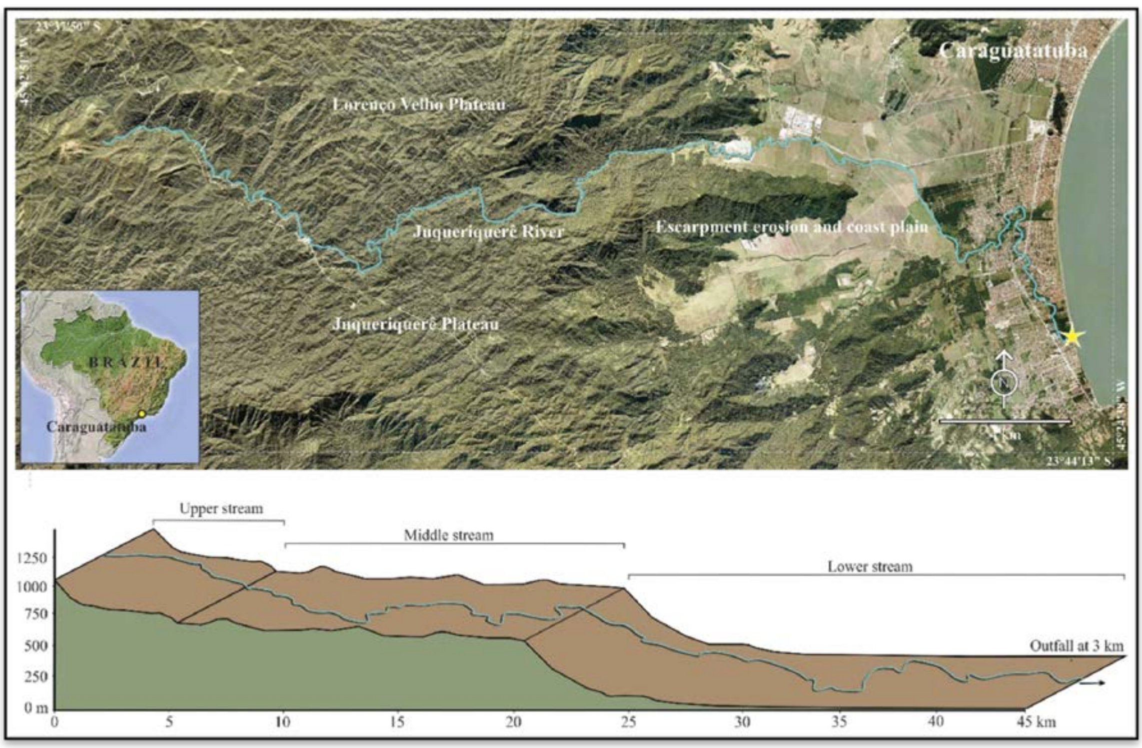

Figure 1. Geographical location of the Juqueriquerê River. Insets: Brazil in South America and stream gradient variation of the Juqueriquerê River along a longitudinal section. The yellow star indicates the location of the outfall

3. Geological Setting

The study area is inserted in the domain of the Ribeira Belt. This geological feature, with an extension of approximately 1500 km, surrounds the Atlantic coast of southeastern Brazil, and it represents an important episode of a complex long-term crustal evolution that occurred during the final accretion of the Western Gondwana supercontinent (Almeida, Amaral, Cordani, & Kawashita, 1973; Cordani, Brito-Neves, & D'Agrella, 2003; Heilbron et al., 2008). The Ribeira Belt is a very complex regional deformation zone that brings together various geological units and has received diverse proposals for its lithostratigraphical classification. According to Tassinari et al. (2006), the lithological association present in the central segment of the southeastern boundary of São Paulo State can be grouped into three main domains: São Roque, Embú and Costeiro.

The Juqueriquerê River is located in the northern sector of the central segment of the Ribeira Belt, in the Costeiro domain, and the lithologies are composed in large part of ancient metamorphic and igneous rocks (Morais, 1999) (Figure 2). In the upper stream gradient of the river, an extensive exposition of metamorphosed mafic bodies can be observed, including metagabbros, diorites, amphibolites, and, to a lesser extent, enderbites, quartz diorites, gneiss and migmatites (Campanha & Ens, 1996; Morais, 1999). The massive occurrence of heterogeneous structures, such as nebulitic, shlieren, and stromatitic structures, indicates that these rocks were generated under extreme conditions of metamorphism. Veins and segregations of light-coloured granitic composition and thin layers of amphibolites may be present (Fernandes, 1991; Silva, 1992). Along the middle stream gradient, an association of medium- to coarse-grained granitic rocks occurs, often with porphyroblasts and marked foliation, composed of microcline (such as megacrysts), quartz, plagioclase, amphibole and biotite (Silva, Chiodi Filho, Chiodi, & Pinho Filho, 1977; Campanha & Poçano, 1994; Campanha & Ens, 1996; Morais, 1999). Elongated bodies of biotite gneisses and migmatites are present in large quantities. Slightly farther south of this stretch, metabasic rocks outcrop in a small area. According to Dias Neto, Correia, Tassinari, & Munhá (2009), this occurrence represents a late- to post-orogenic intrusion, and it is mainly composed of metagabbros, metadiorites and diorite porphyry. In the lower stream gradient, detrital deposits are broadly distributed throughout the coastline and in the valleys. The thickness of these heterogeneous deposits of unconsolidated sediments is strongly controlled by the local variation of the topographic gradient, and the layers are usually formed, in varying proportions, by gravel, sand, silt and clay (Morais, 1999).

Proceeding farther south of the Juqueriquerê River, an extensive outcropping of granite gneiss, peraluminous gneiss, paragneiss, kinzigitic gneiss, migmatites, and minor tabular bodies of amphibolites is found (Campanha & Ens, 1996; Morais, 1999; Perrota et al. 2005). A penetrative planar fabric, marked banding and various other migmatitic structures (mainly nebulitic, shlieren and stromatitic structures) are often in those rocks. In terms of textural variation, layers of k-feldspar augen gneiss can occur locally (Maffra, 2000), revealing a mineralogical association of quartz, microcline, plagioclase, biotite and amphibole (Janassi & Ulbrich, 1992). All of these lithologies show several superimposed tectonic deformations, development of intense mylonitic foliation, and a pervasive segregation of light and dark minerals, resulting in a complex relationship between texture and structure (Campanha & Ens, 1996; Morais, 1999; Passarelli, 2001; Dias Neto, 2001). Smaller dykes that display a compositional variation from tholeiitic to alkaline are also common in this region.

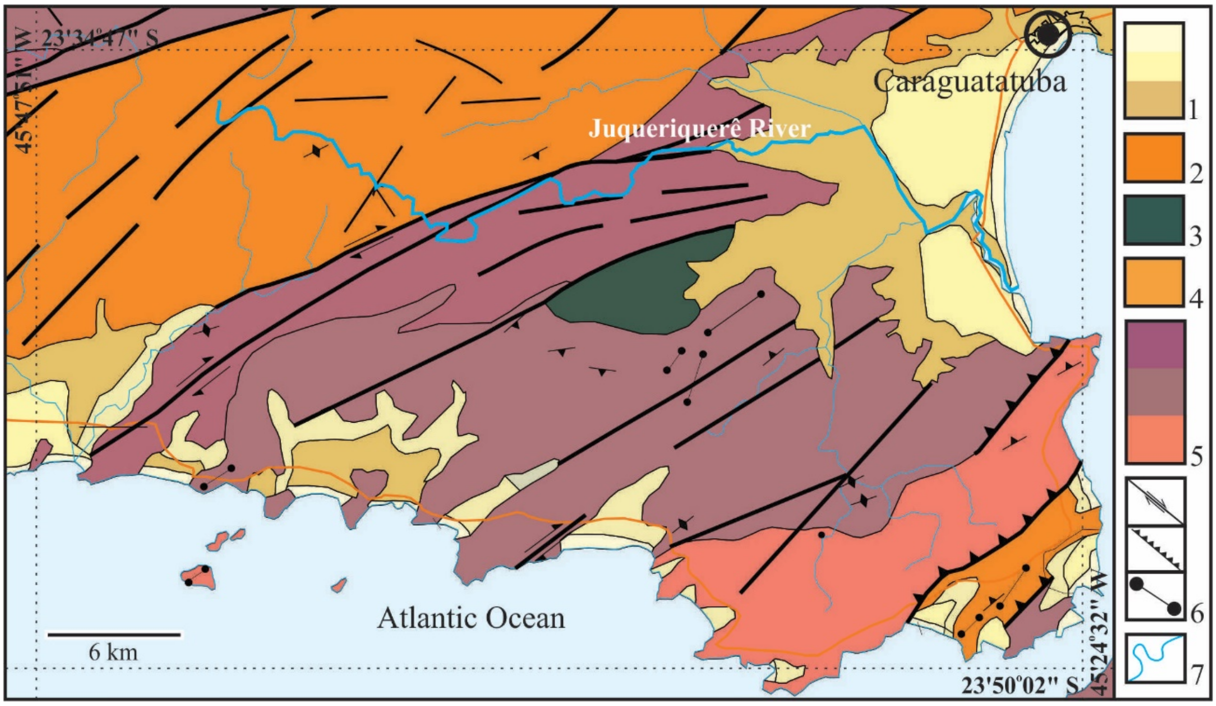

Figure 2. Simplified geological map of the Juqueriquerê River surrounding region (after Morais, 1999).

1- Beach sediments, shoreline deposit, and deposits of undifferentiated sandy-clay; 2- Metagabbros, diorites, quartz diorites gneissic, enderbites, amphibolites, and migmatites; 3- Metabasic body; 4- Migmatites, (Hornblende)-biotite migmatites and/or porphyroblastic granite-gneiss; 5- Biotite gneiss, feldspathic quartzites, peraluminous gneiss, quartzites, and amphibolites; 6- Fault and fracture, thrust fault, and dykes; 7- Surface drainage

4. Geomorphological aspects

The Juqueriquerê River basin (Figure 3) has an area of 710 km² and includes parts of the cities of Salesópolis, São Sebastião, Caraguatatuba, Paraibuna and Natividade da Serra. The highest area, located in the Serra do Mar escarpment, is locally denominated as the Juqueriquerê Plateau (Instituto de Pesquisas Tecnológicas [IPT], 1981). According to Ross and Moroz (1997), the Serra do Mar Morphostructural Unit and coastal hills are both characterised by the presence of steep slopes that outline the Atlantic Plateau.

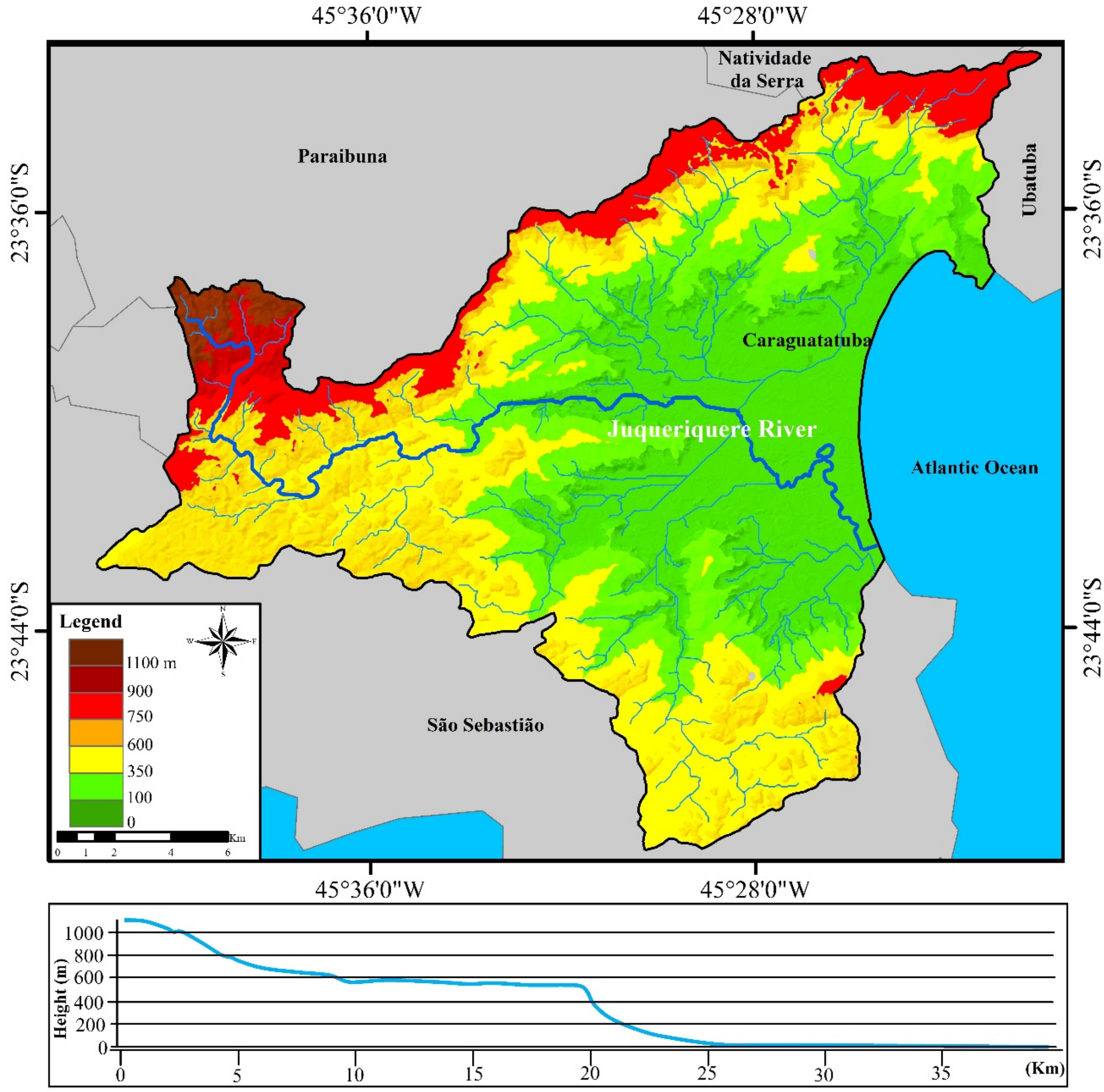

Figure 3. Hypsometric map and surface drainage of the Juqueriquerê River basin. Inset: longitudinal section showing the topographic variations

Individualised Amphitheatres by ridges branched in subparallel form, with marked topographic levels, angular tops, parallel drainage patterns and closed valleys are part of the relief of festooned escarpment (Companhia de Pesquisa de Recursos Minerais [CPRM], 1982). The parallel hills display rounded tops, rectilinear and convex slopes, trellis to sub-dendritic drainage pattern, and the restricted presence of alluvial plains. The mountains with deep valleys show both angular and rounded tops, rectilinear to convex slopes, and a predominantly dendritic drainage pattern. The low hills have rounded tops, with a predominance of convex to rectilinear slopes, closed valleys, and dendritic drainage. The coastal plain has a low drainage density, with patterns ranging from meandering to anastomosed (IPT, 1981; CPRM, 1982). In another sector of the Juqueriquerê Plateau, the festooned escarpments are segmented and engulfed in individualised amphitheatres by ridges that exhibit angular tops, rectilinear slopes, and subparallel to dendritic drainage.

From the source to the mouth, the Juqueriquerê River travels through different geomorphological compartments (CPRM, 1982). These compartments are associated with relief elevation changes (Figure 4). Except for the coastal plain, most of the course flows on a high slope surface.

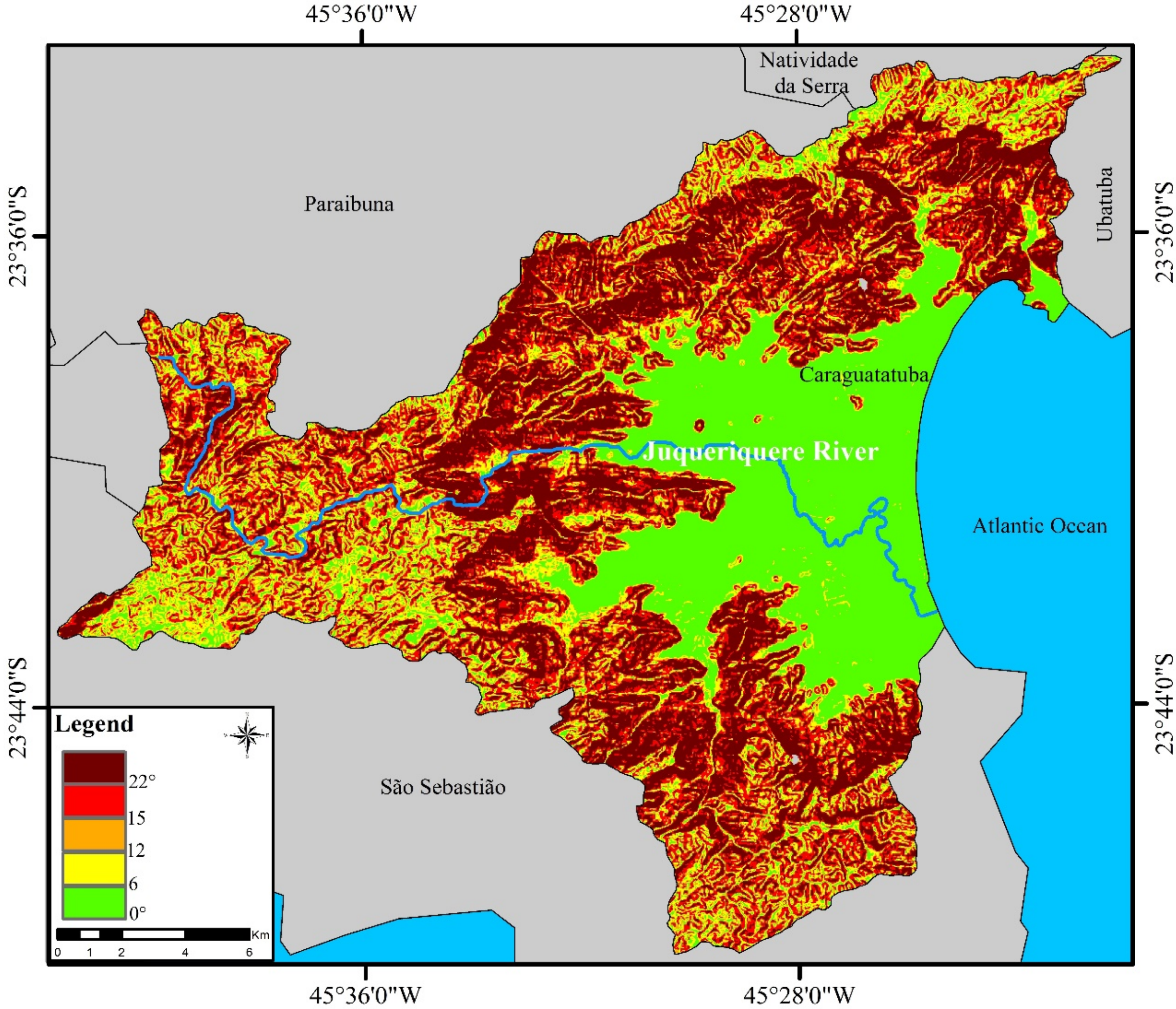

Figure 4. Topographic map of the Juqueriquerê River basin

Five geomorphological compartments may be identified throughout the Juqueriquerê River course (Figure 5). In the first stretch, the river is situated in a compartment of steep mountains and deep valleys (253). The relief has elongated ridges, angular tops, rectilinear slopes, and a dense network of dendritic drainage. In the region lying between the plateau and the Serra do Mar escarpment, the valleys have similar characteristics to a canyon (IPT, 1981). In the second stretch, the river briefly runs by small hills (231), with topographic amplitude of less than 50 m, rounded tops, and the slopes are commonly convex. The drainage network is dense and flows through closed valleys. When the river reaches the Parallel Hills (244), the course takes a parallel to rectangular tracing. In this sector, the topographic amplitudes vary between 100 and 300 m, the tops are rounded, and the slopes have rectilinear to convex profiles. In the escarpments with digitate ridges (522), the course is controlled by linear ridges that have angular tops and rectilinear slopes. The drainage network is dense and acquires a parallel pattern (CPRM, 1982). The last unit the river runs through is the coastal plain (121). In this area, the surface is slightly flat, the drainage density is low, and the river exhibits meandering behaviour.

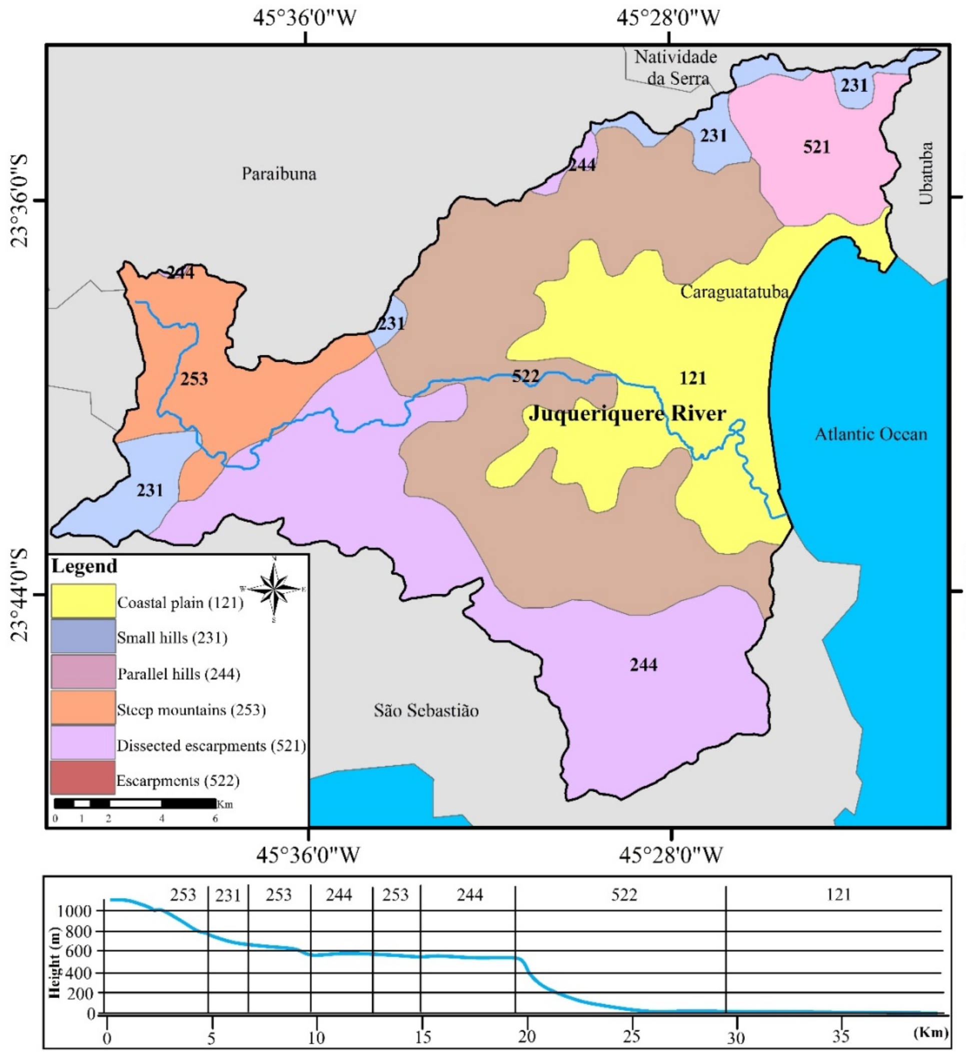

Figure 5. Geomorphological map of the Juqueriquerê River basin

5. Field Data Acquisition

The field survey was performed using a geological map and satellite images (IKONOS and ORTHOFOTOS), with resolution up to 1 m, provided by the Geological Institute-SMA/SP, under exclusive licence of The State of São Paulo Metropolitan Planning Public Company [EMPLASA] (2010). The integrated use of these cartographical products allowed for the identification of specific attributes of the dominant lithological units, the landscape relief, and the channel trajectory. To catalogue the most representative and easily recognisable sculpted forms that occur along the course, the data collection was performed after a long drought period, increasing the likelihood of access to the river bed. The accurate location of the outcrops was marked with GPS, Garmin 12XL, which operates with 12 parallel channels to compute the position. The description and characterisation of the erosional features were based on the nomenclature proposed by Richardson & Carling (2005) and Bourke & Viles (2007). For a more comprehensive view on the subject, please refer to these articles. Lastly, geological computational tools (Global Mapper 16, Golden Surfer 12 and CorelDraw Graphic Suite X7) were used to optimise the organisation, integration and final edition of the illustrations.

6. Bedform Characterisation

A wide range of bedforms is usual along the upper and middle course of the Juqueriqurê River. Field observations suggest that such forms have a specific morphology, which can be separately considered as natural printmaking of mechanical abrasion resistance of the bedrock surfaces. An important remark should be made before proceeding with the descriptions. Although the forms produced by erosion vary considerably from one location to another, this paper does not intend to characterise all of the fluvial features. Therefore, in the following excerpts, only the most frequent and exceptional bedforms that have been previously selected are reported.

6.1 Longitudinal Furrows

Furrows are hollows produced by abrasion of the bedrock. According to their position in relation to the local flow direction, Richardson and Carling (2005) distinguished two types: longitudinal and non-longitudinal furrows, which are respectively formed parallel and non-parallel to the watercourse. The first type is predominant in the upper stream of the Juqueriquerê River, which is flutes occurring in high frequency. Although the morphology of the flutes may vary widely, the U-shaped outer appearance prevails in the region. Following the recommendations of Richardson and Carling (2005), it is possible to group them into four categories: broad, shallow, spindle and paired (Figure 6). Broad flutes normally exhibit a curvilinear contour, similar to a parabola, with a smooth vertex, and the edges are rounded and display an open outline. Shallow flutes present a large external resemblance to those broad flutes, but with a much smaller depth than length. In some particular cases, shallow flutes may acquire a more oval appearance. Allen (1971) described spindle flutes as being a small shallow hollow, much longer than wide, and with sharp proximal ends. In the study area, the spindle flutes show a parallel arrangement and are separated from one another by a few centimetres. They are characterised by shallow bottoms, with lengths three or more times larger than widths, parallel lateral edges and smooth vertexes. Paired flutes were seldom observed compared to single flutes, but they were constituted by two depressions separated by a central ridge (Richardson & Carling, 2005). Sinuous contours with the deepest interior close to the vertex, which gradually decreases towards the lateral edges, are its distinctive morphological characteristics. It is noteworthy that the flutes described usually occur in areas of high incidence of brittle structures, mainly fractures.

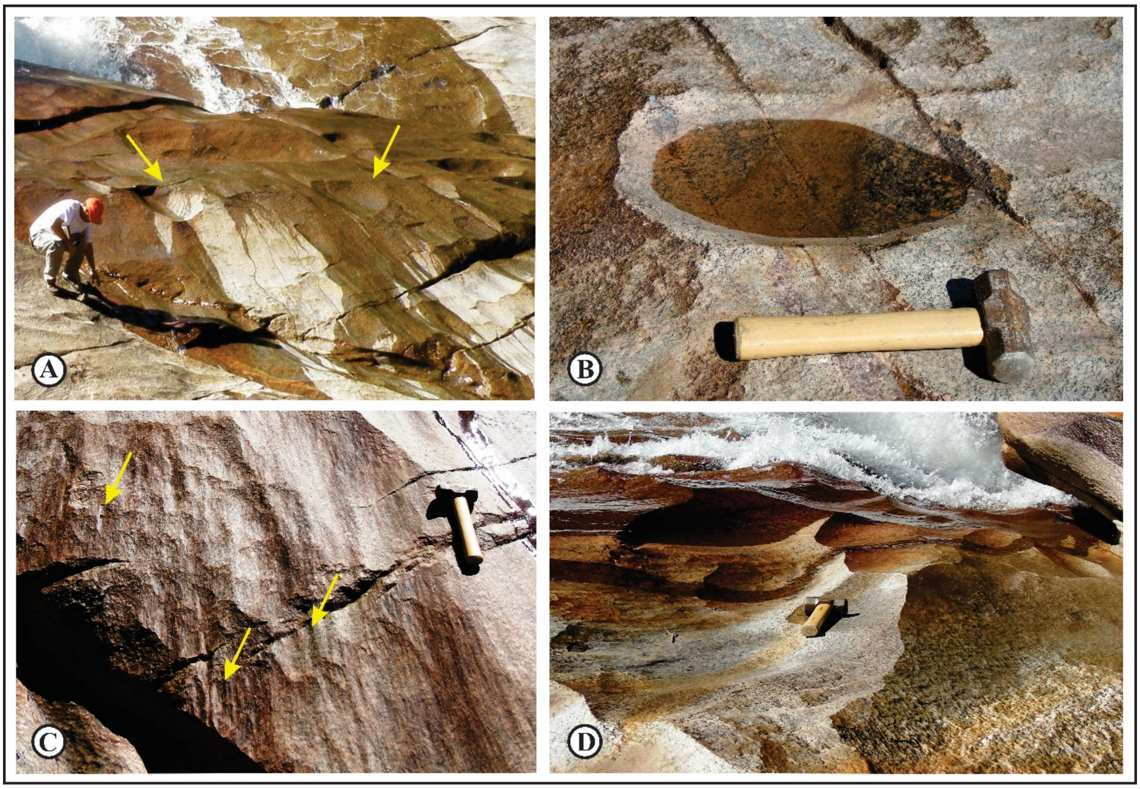

Figure 6. Longitudinal furrows: a) broad flute; b) shallow flute; c) spindle flute; d) paired flute. See text for further explanation

6.2 Potholes

Different denominations may be found in the literature for potholes. For this reason, it was thought appropriate to adopt the definition suggested by Richardson and Carling (2005) for potholes as being essentially round (in plan view), deep depressions, which are, or can be expected to be, eroded by vortices with approximately vertical axes by mechanisms other than plucking. Obviously, this is the most comprehensive definition because it takes into account both the process of formation and the morphological aspect.

Isolated potholes were observed in the upper course of the Juqueriquerê River (Figure 7). The depressions were formed on granitic rocks. In almost all cases, the cavities are well-developed and usually have an oval shape roughly 30 cm in diameter, a depth of less than 50 cm, and a vertical axis. Differential erosion provoked by stream power has led to the formation of small irregular channels on the upper part of potholes, which may occasionally extend through the walls of the cavities. Unfortunately, it has not been possible to establish a relation between the orientation pattern of these channels and the direction of stream flow. Likewise, and different from that which has been observed by Ortega, Gómez-Heras, Perez-López, & Ellen Wohl (2014) in the Tietar, Alberche and Manzanares regions of the Spanish Central System, no conclusive evidence that could suggest the influence of brittle structures on the origin of the potholes in granite was found. The granites outcropping along the Juqueriquerê River reveal abundant mafic minerals (biotite/amphibole) and a coarse-grained texture. In terms of chemical weathering, these mafic minerals disintegrate far faster than quartz and feldspar, leading to the formation of small hollow marks on the surface that can easily progress into a large hole by continuous vertical abrasion. This suggests that both the mineralogical assembly and the texture pattern played an important role in the initial formation of the potholes.

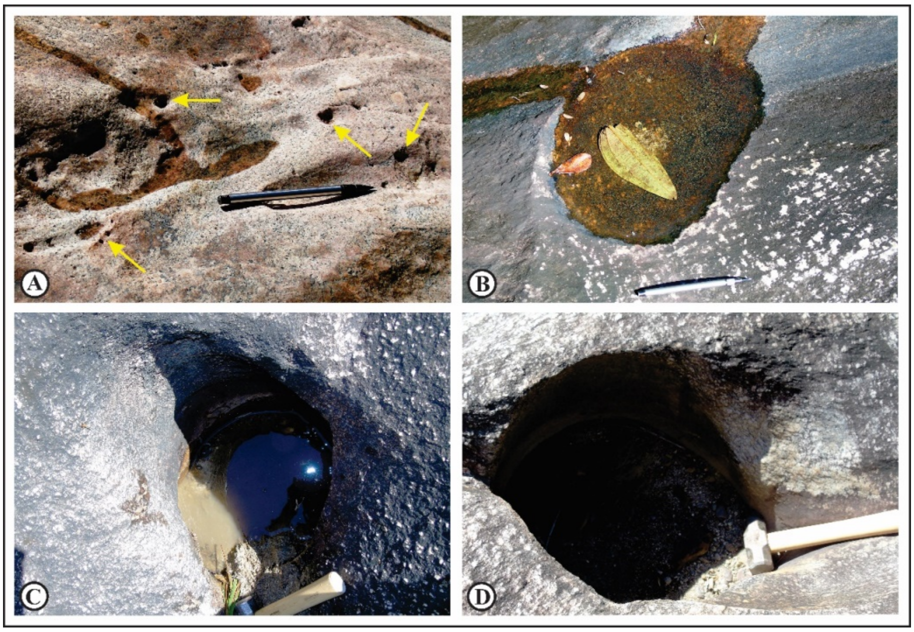

Figure 7. Concave features: a) incipient vertical eddies; b) oval shallow pothole; c) pothole with spiral furrows; d) pothole with an extended exit furrow

6.3 Percussion Marks

From the point of view of the geological processes that shape the Earth's surface, the mechanical action of rivers may seem proportionally smaller. However, unidirectional water flow and sediment gravity flow may be the most powerful agents of erosion, sediment transport, and deposition (Bridge & Domicco, 2008). In the upstream of a bedrock channel system, larger boulders usually enter through the canyon walls through toppling, avalanches or landslides, even though they may also be the remnant load of a palaeoflow of higher magnitude (Church, 2006; Bourke & Viles, 2007). Although the great size of the material could decrease the transport distance, the setting is highly favourable for a high-speed collision between great stones. The percussion marks on the polished surfaces of boulders are a direct outcome of those particular conditions.

Four different types of percussion marks (Figure 8), which are considered relevant by some authors in terms of geological processes, were identified on the surface of the boulders that outcrop along the Juqueriquerê River: a) edge percussion marks, b) conchoidal fractures, c) percussion pits and d) incipient cones (Cotterell & Kamminga, 1987; Richardson & Carling, 2005; Bourke & Viles, 2007). Edge percussion marks are the most frequent signature of successive collisions between boulders. Practically all boulders reveal percussion fractures, and sometimes, there are marks on the surface showing more than a collision. In three dimensions, the morphological appearance is very similar to a small round bowl, with a well-delineated distal ridge, and the internal part is defined by a negative curvilinear surface. Conchoidal fracture is a term used to characterise rupture of a rough surface that does not follow the natural weakness plane of propagation present in some minerals and rocks. In most favourable circumstances, a single curved undulation, called a bulb, aligned perpendicular to the impact direction (Bourke & Viles, 2007), may be observed on the fracture surface. The intrinsic physical properties of a rock, including the absence of a cleavage plane, homogeneous fine-grained texture, and internal random arrangement of the mineral grains, are determining factors for the propagation of such fractures. This combination of factors has been exhaustively examined during the fieldwork, and it was observed that the most obvious conchoidal fractures were developed on the surface of volcanic mafic metamorphic rocks and effusive acid igneous rocks. Percussion pits are small ellipsoidal-ovoidal depressions lower than 5 cm, which are formed on the surfaces of boulders through crushing (Richardson & Carling, 2005). There are rocks where, instead of cracking, the mineral grains tend to be removed from the surface completely, resulting in pits (Bourke & Viles, 2007). As a general rule, rocks with heterogeneous coarse granular texture (e.g., granite and gneiss rocks) are highly favourable for the formation of pits. However, field observations suggest that the boulders are relatively stable and exposed to continuous moderate collisions, regardless of texture, and can also develop percussion pits. Incipient cones, also referred to as subsurface hertzian cones, are fractures with circular to semi-circular patterns, which are formed in amorphous material by percussion wave deflections (Byous, 2013). In geological material, the incipient cone has a certain similarity with the crescent-shaped depression and can be found in volcanic glass (obsidian), quartzites and rhyolites (Bourke & Viles, 2007). This feature was only observed in boulders of quartz veins, revealing various other percussion marks on the surface. The cones have a diameter ranging from 3 to 5 cm, with the upper part eroded and the support partially exposed.

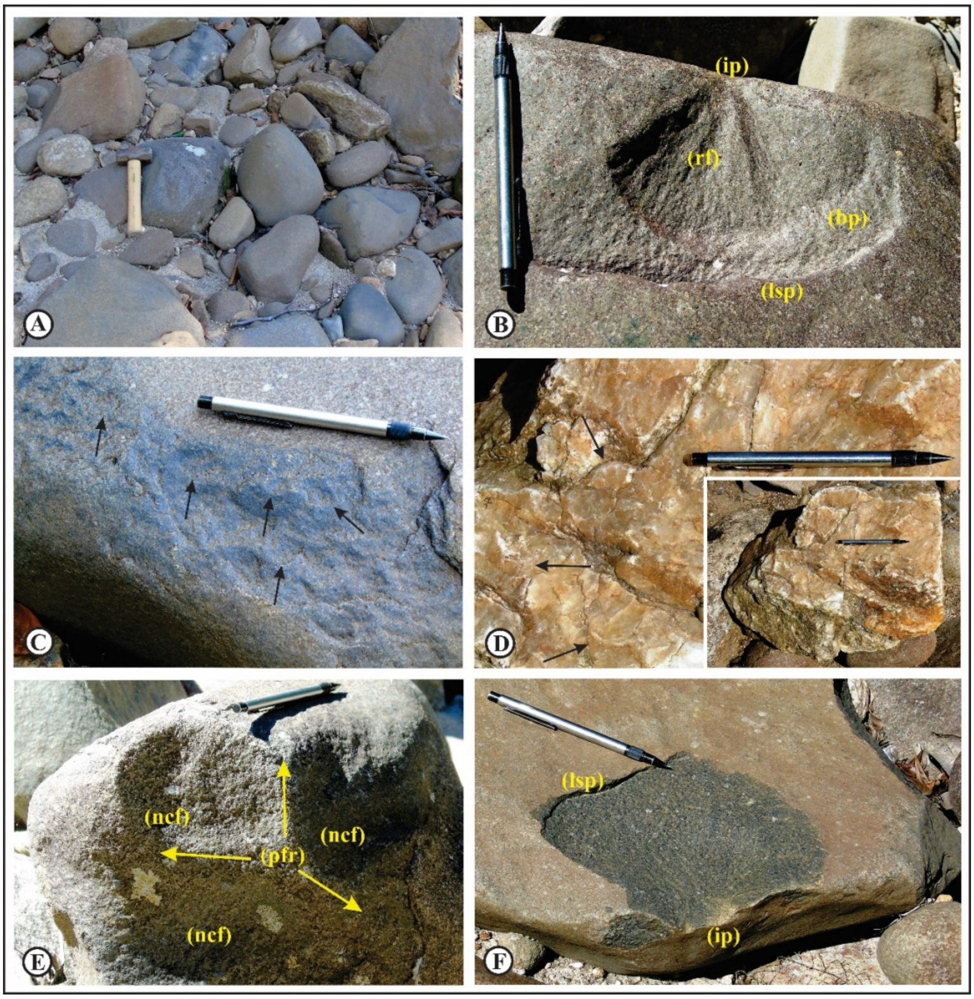

Figure 8. Percussion marks: a) rounded to sub-rounded blocks with diverse fluvial percussion fractures; b) conchoidal fracture in a metabasite volcanic block (ip - initial point, rf – radial fracture, bp – bulb of percussion, lsp – large step termination); c) metabasite volcanic block with various overprint percussion pits; d) incipient cones developed on the quartzite block surface; e) multiple percussion events on the granodiorite block surface (pfr – percussion fracture ridges, ncf- negative curvilinear face); f) percussion fracture on the metabasite volcanic block, with clear evidence of large step termination (lsp) and the impact point (ip)

6.4 Polishing and Smoothing Boulders

Boulders of igneous and metamorphic rocks of different sizes have been documented along the Juqueriquerê River (Figure 9). The analysis of natural entrainment mechanisms of boulders in the bedrock channel was conducted following the criteria established by Carling, Hoffmann, & Latter (2002), considering three main groups: a) isolated boulders, b) stacks of a few boulders of limited span, and c) stacks of many spanwise. Based on this distinction, large boulders clustered in small numbers and of limited distribution are frequently found in the upper course. Judging by the size and the partially worn corners, these very coarse clastic sediments were presumably incorporated into the channel by landslides. Along the middle course banks, an extensive deposit of poorly sorted cobbles and pebbles is exposed. As a result of the violent collision among the clasts during the transport, such materials reveal a wide range of surface textures. The abrasion mechanism caused substantial changes on the surface and corners of the boulders, making them polished and rounded. Despite the fact that these features occur in large quantities in the fluvial erosion system (Howard, 1998), the carved surface by hydraulic abrasion indicates that its formation depends on other factors. At a smaller scale, single mineral grains or aggregates of mineral grains, instead of being polished by friction, are plucked from the rock's surface because they are less efficient in terms of adherence than their nearest neighbours, yielding a slightly rough surface. This type of natural wear was mainly registered in granite and gneiss cobbles, which are characterised by heterogeneous mineralogical associations, coarse granular textures, and pervasive banding structures. However, the degree of rounding and polishing of boulder surfaces may be as variable as the texture and structure of a rock, and to understand the process entirely, these and other factors must be carefully examined.

Figure 9. Polishing and smoothing boulders: a) stacks of a few boulders of limited span; b) stacks of boulders spanning many sizes; c to f) difference degree of rounding and polishing. See text for explanation

7. Final Considerations

The region offers an excellent opportunity to exemplify the role of tectonic processes, lithology, climate and weathering in the context of landscape evolution (Velázquez, Sobrinho, Pletsch, Guedes, & Zobel, 2013). The geological setting, however, is particularly interesting to explore the relation between fluvial erosion and the sculpted forms in the bedrock channel.

The Juqueriquerê River is inserted at the northern end of the Serra do Mar, which is constituted by an enormous variety of granite and gneiss rocks of a Precambrian crystalline basement. In morphostructural terms, the area is characterised by the occurrence of expressive fault escarpment, major lineaments and curvilinear features (mainly topolineaments), with a preferential NE-SW direction. On a local scale, these structures exert an important control over the topographic variation and the surface drainage pattern.

Many studies have been conducted to examine the processes involving both chemical and physical weathering in fluvial erosion (Howard, Dietrich, & Seidl, 1994; Wohl, 1998; Hancock, Anderson, & Whipple, 1998; Whipple, Hancock, & Anderson, 2000). In bedrock channels, the erosive process and overland flow behaviour are markedly influenced by surface steepness (Hovius & Stark, 2006). A broad rectilinear surface, ranging from 250 to 750 m, with a significant variable gradient, has been observed in the upper and middle stream sections of the Juqueriquerê River. As a consequence of fluvial mechanical erosion, different bedforms were locally sculpted along those surfaces, and the largest rock fragments were progressively accumulated in the slope base. The morphological aspect of the sculpted forms, the poorly sorted very coarse lithic clast deposits, and the stones highlighting the well-polished and rounded edges are strongly indicative of a fairly efficient flow regime in terms of energy and transport of abrasive particles.

The flutes and potholes are concave features that resulted from the interaction between erosive processes and the physical resistance of the channel substrate (Tinkler, 1993; Hancock et al., 1998; Whipple et al., 2000). Allen (1971) proposed that the generation of flutes is caused by flow separation in the upstream. In practical terms, the phenomenon is an irregular fluctuation of the water flow velocity, creating eddies and vortices. Flow separation in bedrock channels may be influenced by the topographic irregularities of the substrate (Richardson & Carling, 2005). The most conclusive proof was registered along the discontinuous surfaces in the granite bed. In these locations, the arrangement of the brittle structures in an oblique or orthogonal direction to the main direction of the stream has been shown as highly favourable for flow separation. This condition plays a crucial role in flute formation, mainly when the fracture surfaces present a small step in the direction of the flow, inducing an early stage of mechanical abrasion. Potholes are considered as one of the most convincing features of fluvial erosion in bedrock channels (Wohl, 1998; Kale & Joshi, 2004; Sengupta & Kale, 2011). Different erosive processes have been postulated as being responsible for their formation, including abrasion, cavitation, corrosion and plucking (Hancock et al., 1998; Whipple et al., 2000). Richardson and Carling (2005) presented a comprehensive discussion of these processes. Alternative interpretations, however, were proposed by Lorenc, Barco, & Saavedra (1994), Springer, Tooth, & Wohl (2006), Sengupta and Kale (2011) and Ortega et al. (2014). These authors suggest that pothole formation is much more influenced by the substrate properties, especially the rock deformation pattern, than by mechanical abrasion of the material in transport. In our particular case, given the geological complexity and vast extension of the study area, it is difficult to completely neglect the influence of brittle structures on pothole formation. However, field observations indicate that corrosion and granular disintegration may have prevailed in the early phase of the erosive process. This interpretation is based on data of the mineralogical composition and textural features of granitic rocks. Chemical erosion (corrosion) is more efficient for mafic minerals (biotite/amphibole), modifying the internal structure and increasing the wear of the grains. However, granular disintegration proves to be an important process in coarse-grained rocks, where minerals are plucked from the substrate surface. Although in such cases the initial hole has a diameter of less than 4 cm (Figure 7A), this is still sufficiently large to allow vertical abrasion to continue increasing the cavity.

Depending on the mode in which particles travel in an aqueous medium, the fluvial sediment transport can occur as suspended load and bedload (Church, 2006). The fine sediments (clay and silt) may spend more time in the water column, travelling essentially in suspension. Bedload transport can occur by traction and saltation, or both, and plays a major role in the translation and deposition of very coarse sediments (McKnight & Hess, 2013). In this type of transport, the mechanical erosion is caused by the combined action of traction and percussion, and both the form and size of the sediments are deeply modified (Johnson, Whipple, Sklar, & Hanks, 2009; Hodge, Hoey, & Sklar, 2011). A wide variety of surface morphological features related to fluvial transport were documented by Howard (1998) and Bourke and Viles (2007), producing detailed descriptions concerning rounding, polishing, smoothing, and percussion fractures in gravel, cobbles and boulders. In the Juqueriquerê River, the best examples of these features were observed along the middle course. A remarkable variation in morphology and surface texture was found in boulders of igneous and metamorphic rocks. Unlike some models that follow the traditional interpretation, the degree of surface polishing of these rocks, under a similar condition of abrasion and on a centimetre scale, is strongly controlled by the intrinsic property of the material. Direct observations indicate that boulders of igneous and metamorphic rocks with coarse grain and heterogeneous texture are less appropriate to generate smooth surfaces and fine polishing. In a similar manner, relatively stable boulders displaying a homogeneous fine-grained texture are more favourable for developing percussion fractures, in particular, radial fractures, bulbs of percussion, and hertzian cones. It is worth reminding that, besides the factors cited, the visible morphological features in each fracture surface are a direct result of the magnitude and intensity of the stream power and the boulder collisions.

In a general way, the bedforms that have been characterised in the Juqueriquerê River resulted from the interaction between hydraulic force, mechanical erosion and lithology. Some of the erosive features identified, particularly the percussion marks, are interpreted as revealing indicators of the influence that the mineralogical assemblage and textural pattern have on the formation of those peculiar signatures in the boulders. However, the quantification of the practical implications of these factors for each of the sculpted shapes requires further research.

Acknowledgments

The authors express their sincere thanks to the IG-SMA for providing the digital images. Fruitful grammatical revision and helpful comments were given by Dr. Vagner Maringolo. We would like to extend our deep gratitude to the anonymous referees who substantially improved the quality of this manuscript. This study has been supported by the FAPESP Foundation, Proc. No. 2013/18073-4, and the Pro-Rectory of Research of the University of São Paulo.

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