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CHARACTERIZATION AND ANALYSIS OF GULLY EROSION IN SOUTHERN BRAZIL WITH THE ASSISTANCE OF UNMANNED AERIAL VEHICLE

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Abstract

The ability to understand the erosive mechanisms of a gully is of great importance for determine its dynamics and the best forms of intervention. Thus, with the assistance of high-resolution data obtained with UAV, this work seeks to characterize and analyse the erosive mechanisms that act in a gully in south Brazil. For this, a survey was carried out using a multirotor UAV, with a flight height of 150m, and an overlaid area of 67ha. The data obtained were processed using the SfM-CMVS (Structure from Motion - Clustering Multi-View Stereo) workflow, generating a Digital Terrain Model with a spatial resolution of 12,6 cm/pixel. However, mass movements proved to be the main lateral and vertical advancement agent of the gully, predominating in the upper portions of the gully. In the lower third of the gully there was a predominance of mass movements and lowering areas related to the contact of sandy rock lenses with more clayey lenses. The products generated in this work provide a database that has the potential to assist in work to be developed, serving as a basis for the study of gully genesis, for the identification of the best mitigation measures, or as an initial framework for the study of evolution of this erosive feature. So, make it necessary more in-depth study of the real impacts of silviculture on erosive mechanisms.

Keywords: Gully Erosion, Structure From Motion–Multi-View Stereo (SfM–MVS), Erosion Mechanisms, Mass Movements.

Resumo / Resumen

CARACTERIZAÇÃO E ANÁLISE DE EROSÃO POR VOÇOROCAMENTO NO SUL DO BRASIL COM O AUXÍLIO DE VEÍCULO AÉREO NÃO TRIPULADO

A capacidade de compreender os mecanismos erosivos de uma voçoroca é de grande importância para determinar a sua dinâmica e as melhores formas de intervenção. Assim, com o auxílio de dados de alta resolução obtidos com VANT, este trabalho busca caracterizar e analisar os mecanismos erosivos que atuam em uma voçoroca no sul do Brasil. Para isso, foi realizado um levantamento com um VANT multirotor, com altura de voo de 150 m cobrindo uma área total de 67 ha. Os dados obtidos foram analisado pelo o algoritmo SfM-CMVS (Structure from Motion - Clustering Multi-View Stereo), gerando um Modelo Digital de Terreno com resolução espacial de 12,6 cm/pixel. No entanto, os movimentos de massa mostraram-se como o principal agente de avanço lateral e vertical da voçoroca, predominando nas porções superiores. No terço inferior da voçoroca predominaram movimentos de massa e rebaixamentos relacionados ao contato de lentes de rocha arenosa com lentes mais argilosas. Os produtos gerados neste trabalho fornecem uma base de dados com potencial para auxiliar nos trabalhos futuros, servindo de base para o estudo da gênese da voçoroca, para a identificação das melhores medidas de mitigação, ou como um ponto de partida para o estudo de evolução desta feição erosiva. Logo, torna necessário um estudo mais aprofundado dos reais impactos da silvicultura nos mecanismos erosivos.

Palavras-chave: Erosão de Ravinas, Estrutura de Motion–Multi-View Stereo (SfM–MVS), Mecanismos de Erosão, Movimentos de Massa.

CARACTERIZACIÓN Y ANÁLISIS DE LA EROSIÓN DE BARRANCO EN EL SUR DE BRASIL CON AYUDA DE VEHÍCULO AÉREO NO TRIPULADO

La capacidad de comprender los mecanismos erosivos de un barranco es de gran importancia para determinar su dinámica y las mejores formas de intervención. Así, con la ayuda de datos de alta resolución obtenidos con UAV, este trabajo busca caracterizar y analizar los mecanismos erosivos que actúan en un barranco en el sur de Brasil. Para ello, se realizó un levantamiento utilizando un UAV multirotor, con una altura de vuelo de 150m, y un área superpuesta de 67ha. Los datos obtenidos se procesaron mediante el flujo de trabajo SfM-CMVS (Structure from Motion - Clustering Multi-View Stereo), generando un Modelo Digital de Terreno con una resolución espacial de 12,6 cm/pixel. Sin embargo, los movimientos de masas demostraron ser el principal agente de avance lateral y vertical del barranco, predominando en las porciones superiores. En el tercio inferior del barranco predominaron los movimientos de masas y áreas de descenso relacionados con el contacto de lentes de roca arenosa con lentes más arcillosos. Los productos generados en este trabajo brindan una base de datos que tiene el potencial de ayudar en el trabajo a desarrollar, sirviendo como base para el estudio de la génesis de barrancos, para la identificación de las mejores medidas de mitigación, o como marco inicial para el estudio de evolución de esta característica erosiva. Luego, hace necesario un estudio más profundo de los impactos reales de la silvicultura sobre los mecanismos erosivos

Palabras-clave: Erosión de Cárcavas, Estructura a Partir del Movimiento: Estéreo Multivista (sfM-MVS), Mecanismos de Erosión, Movimientos en Masa.

INTRODUCTION

Among the forms of erosion, the gully is the one with the greatest destructive power, indicating an advanced stage of soil degradation and an imbalance in the hydric and geomorphological system (ALBUQUERQUE, 2007; MATHIAS, CUNHA AND CARVALHO, 2010). Gullies are features with very complex development and dynamics (VANMAERCKE et al., 2016). Identification of their erosive mechanisms is essential to understand the processes that occur in the landscape (OLIVEIRA, 2005; VANMAERCKE ET AL., 2021). Large erosive features, such as gullies, amplify impacts in the environment, even disturbing large areas of land as observed in New Zealand (BETS ET AL., 2003; PARKNER et al., 2006), Brazil (BACELLAR et al., 2005), and Spain (MARTINEZ CASANOVAS et al., 2009).

In southern Brazil, specifically in the southwest of the state of Rio Grande do Sul, there is a large concentration of gullies associated with very friable sedimentary rocks and has been the subject of several studies related to erosive features (ROBAINA et al., 2002; ROBAINA and TRENTIN, 2004; CABRAL, 2004; CABRAL et al., 2009). Gully erosion is a process of land degradation with globally known impacts with major environmental damage, ecological and economic impacts on a variety of landscape systems (POESEN et al, 2003; BARTLEY et al, 2014; ZAO et al, 2016). Effective management of gully erosion requires high-resolution topographical information that can be used to accurately quantify the spatial distribution and density of gully systems, their morphology and process changes that can alter the dynamics of their morphology and influence their evolution (JACK et al, 2017; KOCI et al, 2019).

In recent years, mostly after 2010, UAVs (Unmanned Aerial Vehicles) and SfM-CMVS (Structure from Motion-Clustering Multi-View Stereo) have frequently been employed for erosion studies (D'OLEIRE-OLTMANNS et al., 2012; STÖCKER et al., 2015; VERDONK, 2015; LIU et al., 2016; GUTIÉRREZ et al., 2018; HOSSEINALIZADEH et al., 2019), allowing new approaches to analyze gullies, especially detailed analysis of these erosive features at low cost (WESTOBY et al., 2012).

Obtaining high-resolution MDTs, which allow the 3D view of the mapped elements through the use of the SfM-CMVS technology, has enabled a variety of detail level studies in gullies focusing on the analysis of very detailed models. The most studied aspects are the volume eroded in different periods of time (KAISER et al., 2014; PETER et al., 2014; GLENDELL et al., 2017; GAFUROV, 2017), headcut retreat rate (GUTIÉRREZ et al., 2014; VANMAERCKE et al., 2016), and morphometry or morphology of erosive features (NOBAJAS et al., 2017; GUTIÉRREZ et al., 2018).

Due to the complexity of the gulling process, several mechanisms act in the formation and development of a gully and are closely related to the action and condition of erosive factors (STARKEL, 2011; VANMAERCKE et al., 2016). Oliveira (2005) indicates that the main mechanisms that act in the gullying process are the transport of soil particles by concentrated flows, erosion by waterfalls, erosion of the hillslope base, liquefaction of soil, mass movements, and particle dragging by concentrated flows in pipes.

The objective of this research is to use SfM-CMVS technology to analyze the distribution and performance of erosion mechanisms in Areal Gully in the municipality of Cacequi. The SfM-CMVS technology allows the 3D modeling of the gully, making possible to identify different mechanisms that can help in the future in the choose of mitigation practices for the advancement of the Areal Gully serving each mechanism individually and distinctly. In this way, it is expected to delimit the most active erosive mechanisms in each portion of the gully, offering a diagnosis of the processes that act in the expansion of the gully today.

METHODOLOGY AND METHODS

STUDY AREA

Areal Gully is located in the municipality of Cacequi (Figure 1) associated with the geomorphological unit of the Sul-rio-grandense Peripheral Depression (CARRARO, 1974), which consists of sandy lithologies of the sedimentary sequence. In the Paraná Basin, these sandy soils occur and have minimal cohesion; thus, they are more susceptible to the erosion process. The studied gully is located near the headcut of the River Areal do Limeira Basin and is approximately 920 meters long and 250 meters wide, covering an area of 6.53 ha.

The area of Areal Gully has an average annual rainfall of around 1,500 to 1,700 mm, with rains well distributed throughout the year (ROSSATO, 2011) and a predominance of frontal rains well distributed spatially with less intensity than convective rains (MONTEIRO, 1963; ROSSATO, 2011).

The surrounding vegetation consists predominantly of eucalyptus plantations for pulp production. The areas chosen for planting this exotic species were those with the greatest environmental fragility, due to their lower price, such as the areas where gullies occur (MARCHIORI and ALVES, 2010; SUERTEGARAY and MORELLI, 2010).

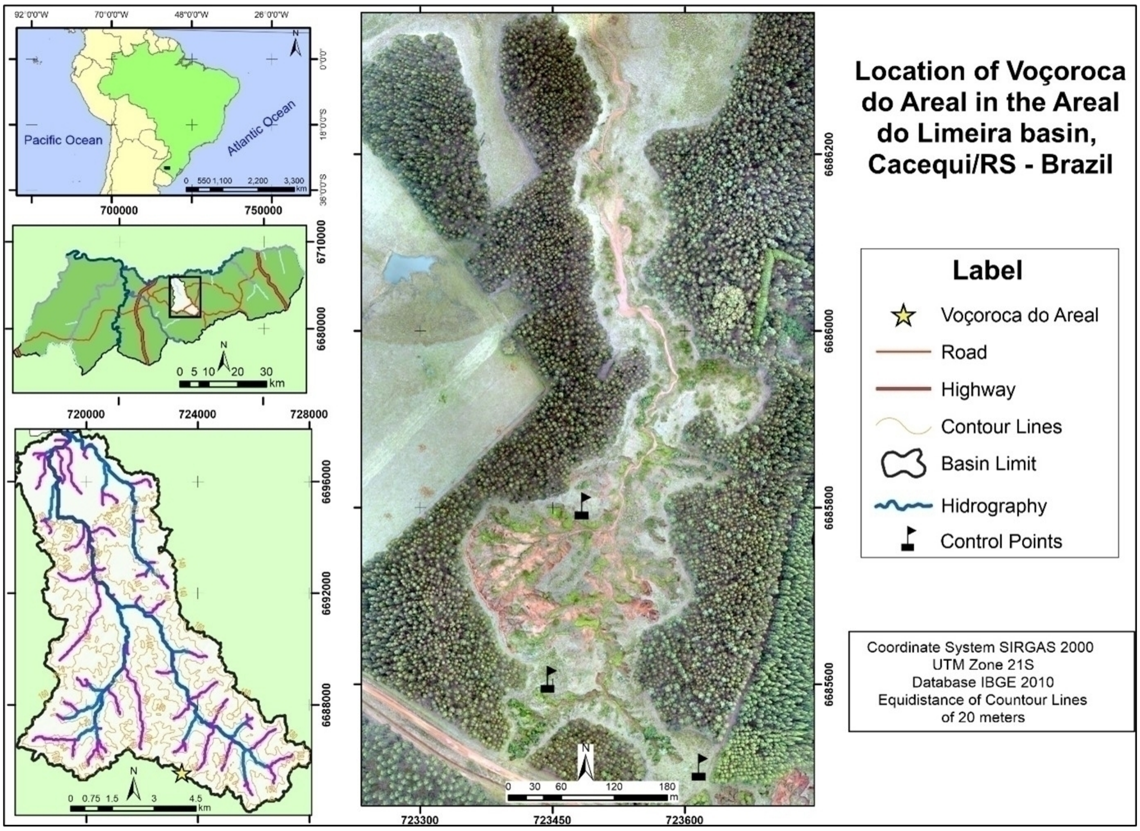

Figure 1 - Localization of Areal Gully

MATERIALS AND METHODS

The multirotor UAV, model Phanton 4, used for the planialtimetric survey was developed by DJI company. A digital camera sensor, model FC330 with RGB spectral resolution, was coupled to the UAV. This camera was developed by the same company and had a focal length of 3.61 mm, an approximate resolution of 12MP, and a GPS C/A code receiver, with approximate accuracy of 5 m.

The survey flight on August 10, 2018 lasted approximately 14 minutes and overlaid a total area of 67 ha, at a flying height of 150 m. The 306 images taken had latitudinal and longitudinal overlap of 85%. The flight height was defined according to the UAV battery capacity and also maintaining a safe height for the equipment due to the large trees in the forestry area beside the gully. To aid data processing, three ground control points were collected, using a geodesic GPS, model Ruide 90 with L1/L2 receiver with centimeter accuracy, using the static relative method, described by Seben et al. (2010), where a 30-minute screening time was used for each point. The demarcation of the GCPs was performed with the use of white ink to draw a target of about 1.5m to be displayed on the image processing software Agisoft Photoscan for correction of subsequent models. The calculated mean squared error of the GCPs points was 72.72 cm with planimetric error of 72.48cm and altimetric error 5,84cm. The area of interest was covered in almost all its extension with more than 9 photographs of the same point and with different views.

Once the images were obtained using the UAV, the digital photogrammetric operations were performed in Agisoft Photoscan, especially the technologies Structure from Motion (SFM) and Clustering View for Multi-view Stereo (CMVS). This set of low-cost technology for high resolution topographic reconstruction allow the creation of 3D models and point cloud from a series of overlapping 2D photos taken from different points of view (FURUKAWA et al., 2010; SCHONBERGER; FRAHM, 2016; TURNER; LUCIEER; WATSON, 2012; WESTOBY et al., 2012).

With the data obtained in the SfM-CMVS process, the interpolation of the point cloud was performed in the same software, creating a triangulated irregular network (TIN), corresponding to the Digital Surface Model of the study area. The procedure resulted in an DSM with a resolution of 12.6 cm/pixel with an average of 63.3 points per square meter.

To generate a Digital Terrain Model (DTM), the Classify Ground Points tool from the Agisoft Photoscan software was used, by classifying the points of the point cloud that correspond to the real surface. In this tool, the parameters of the maximum angle of the terrain were set at 30, the maximum elevation variation at 0.2 m in a determined space of the terrain, and the maximum cell size where no surface points had the value of 60 meters.

To facilitate the understanding of the erosion mechanisms of the Areal gully, it was divided into four different sectors, according to morphometric characteristics and active processes using the software ArcGIS 10.7. The limit of the different sectors was established to integrate within the sectors the main areas of advancement of Areal Gully, presented by Rademann and Trentin (2020), without dividing the same area of advancement into more than one sector.

RESULTS

Due to the large extension of the Areal Gully and the detailed study carried out, four different sectors of the gully were defined considering the different mechanisms of the gully (Figure 2). The sectors were defined as: A - Drainage head; B - Vertical Development; C - Lateral Development and Piping; and D - Drainage stabilization.

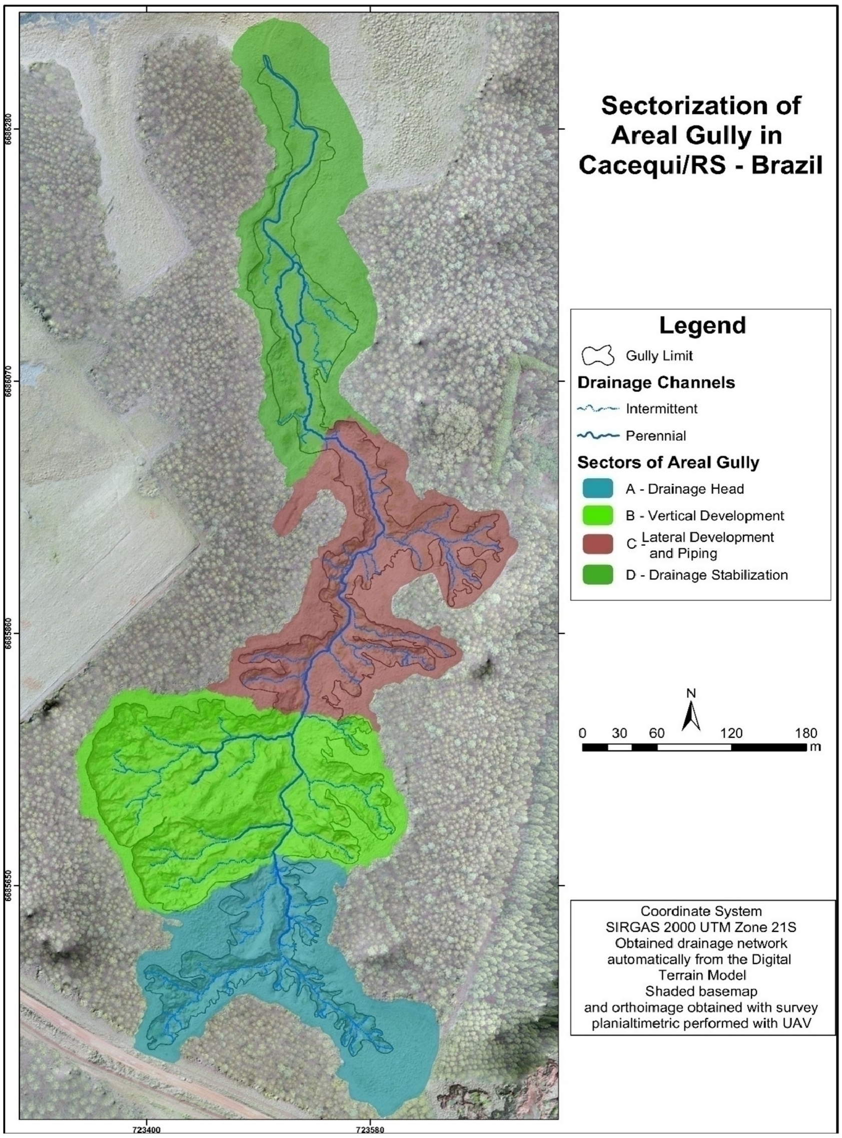

Figure 2 - Sectors of Areal Gully in Southern Brazil.

The headwater drainage sector (Sector A) is located in the upstream portion of the gully, with a predominance of mass movements in the areas of advance and linear erosion in the channel at the base of the gully. An area of resistance to erosion on the west margin of the gully is also highlighted (Figure 3).

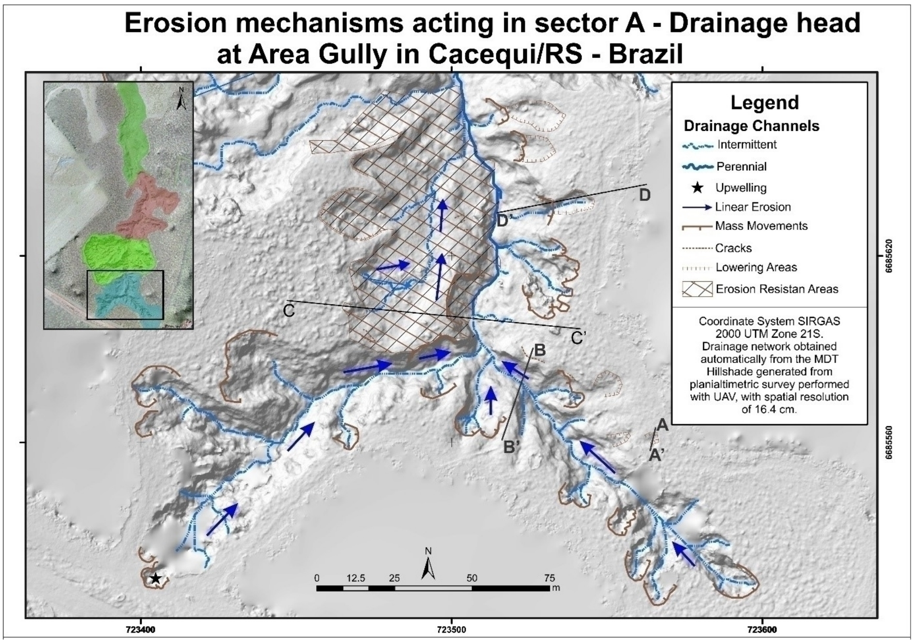

Figure 3 - Map of erosive mechanisms operating in sector A of Areal Gully.

This sector has 23 traces of mass movements, 7 cracks and 9 lowering areas. The sector exhibits two main ramifications, predominance of mass movements as a form of lateral advancement, and in the ramification on the right margin of the gully, as well as the occurrence of lowering areas.

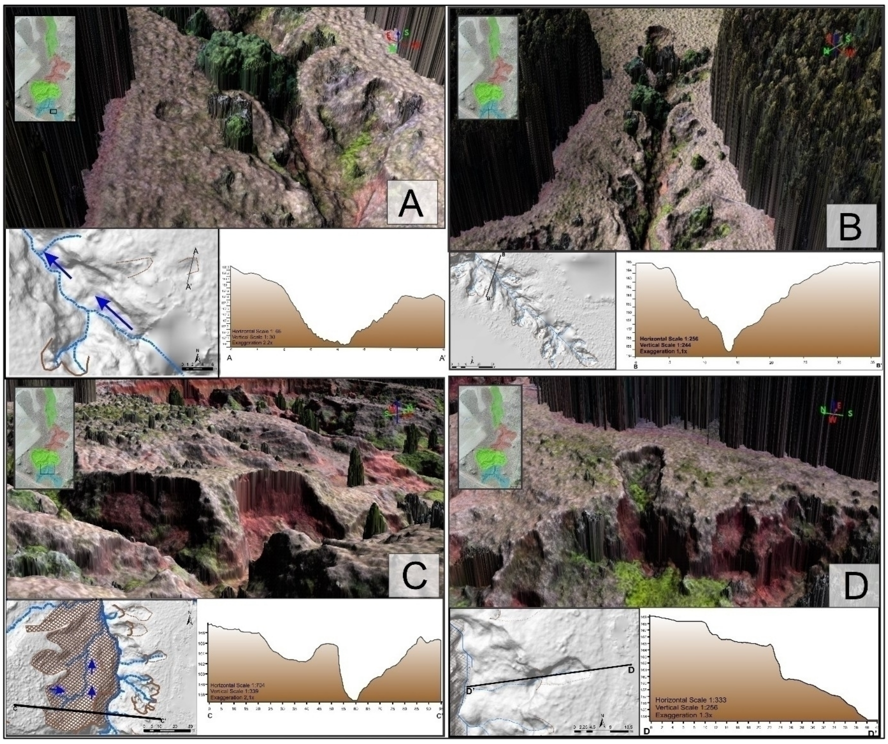

Figure 4 - Schematic representation of the mechanisms acting in sector A (A - Lowering Area; B - Linear Erosion; C - Erosion-resistant portion; D - Lowering followed by mass movement).

The intersection of the two ramifications of the sector includes an area resistant to erosion on the left margin. This area has smoother slopes, a lowering area, and a mass movement area close to the main gully channel. Furthermore, in the ramification on the east margin of the sector, the lowering with a semicircular shape and disconnected from the gulley drainage network can be seen in Figure 4A, represented by the profile A-A'.

The removal of material on the subsurface, called piping, caused the formation of depressions, which can evolve into small dolines and even be associated with mass movements (BERNATEK-JAKIEL; POESEN, 2018). The Areal Gully has a step that is just over one meter deep and indicates the existence of subsurface erosive processes. The feature represented by the profile A-A' indicates an advance of the gully with the action of underground erosion associated with the occurrence of mass movements.

Linear erosion occurs intermittently in this sector, concentrating the flow in the lower areas and carrying the eroded material downstream, represented in the cross section of Figure 4B. Linear erosion in this sector occurs with the formation of V-shaped valleys, with abrupt walls over 10 meters high, following preferential guidance, which suggests structural control in these areas. The vertical walls of this portion of the gulley also facilitate mass movements, evidenced by the occurrence of cracks in the top of the gulley.

The erosion-resistant area (Figure 4C) displays continuity of relief and vegetation in relation to the surrounding area with lower slopes. This feature is more resistant to erosion and has some lower areas in the center, forming converging concave portions, as observed in the topographic profile C-C'. These portions favor surface runoff and flow concentration, increasing both erosion and incision in the hillslope. Close to the main channel of the gully, mass movements with great intensity still form vertical walls over 10 meters high, based on the level of the gully groundwater. Also in sector A, mainly on the right margin of the main channel, areas of lowering followed by mass movement are common, as shown in the diagram in Figure 4D.

Near the gully head, there are semicircular lowerings, with depths of 1 to 3 meters. These downgrades may be associated with textural change in the soil, with an increase in clays on the B horizon. Further down, a new step is formed with the presence of clayey layers in the sedimentary rock and is the basis of mass movements. In general, the erosive process in sector A is quite active, presenting a wide variety of mechanisms, both superficial and subsurface.

Sector B of Areal Gully presents 31 features of mass movements, 3 cracks, and 4 downgrade areas. It is the part of the gully that has the largest eroded volume, with major occurrences of mass movements of great intensity. Due to the large eroded and deposited material at the base, the sector has a large area of reworked deposits. It also has material deposition areas and an area more resistant to erosion in the center of the sector (Figure 5).

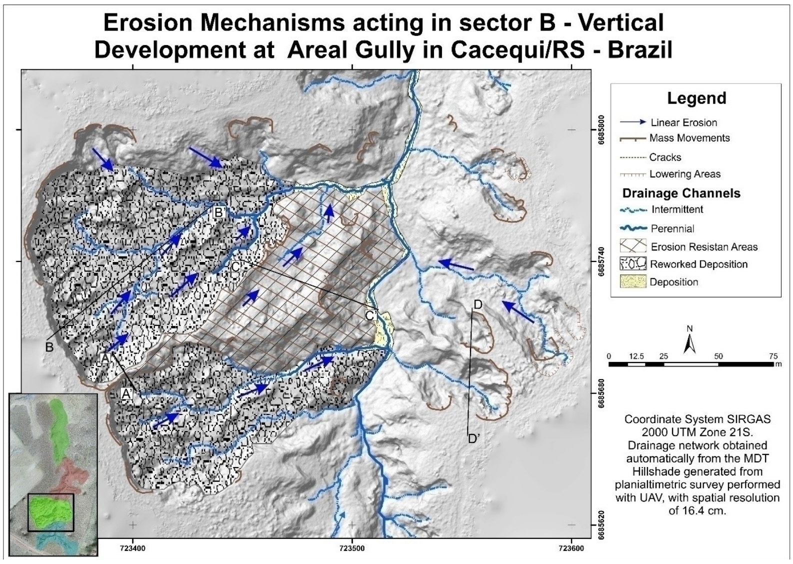

Figure 5 - Map of erosive mechanisms operating in sector B of Areal Gully.

Despite the predominance of erosion mechanisms with vertical development in this sector, there is the occurrence of erosion resistant lines, represented in the scheme of Figure 6A. Form between two large areas of vertical advance, they are over 9 meters high and about 2 meters wide. These features connect the central basement of the sector, which is more resistant to the gully's edge, showing the existence of a less erodible material in some portions of the gully.

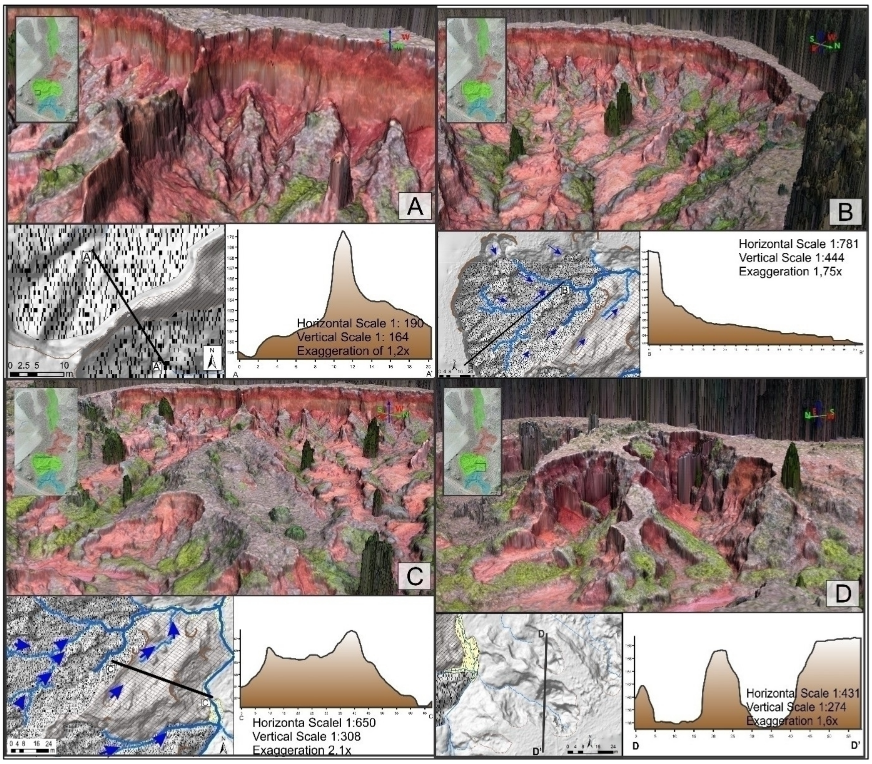

Figure 6 - Schematic representation of the mechanisms acting in sector B (A - Erosion resistant line; B - Vertical development area; C - Erosion resistant area; D - Area of occurrence of intense mass movements).

The main feature of this sector is the vertical development of the gully, with a depth of approximately 25 meters, presenting abrupt very slopped walls, as shown in Figure 6B. These abrupt walls represent a great erosive advance, where the edge of the gully is marked by a sequence of semicircles demonstrating the occurrence of mass movements, resulting in a large volume of eroded material. As a result, at the base of the hillslope, it is possible to observe a large amount of sediments from past mass movements, forming a deposition area.

A portion more resistant to erosion occurs in the center of the gully (Figure 6C). This portion forms a bounce feature in relation to the surroundings due to differential erosion, where less intense processes occur, which is predominantly linear erosion in the central part of the feature, where a small downgrade occurs, forming a converging hillslope. The right margin of the sector has mass movements with great magnitude where the gully is most active, forming small ramifications with slopes of more than 12 meters, with abrupt walls and small intermittent drainage channels at the base, as shown in Figure 6D.

Thus, sector B of the gully presents great altimetric amplitudes, with the erosive mechanisms acting in a marked way resulting in a large volume of eroded material. Part of this material is deposited at the base of the gully forming areas of unconsolidated material that is reworked by linear erosion, surrounded by small pinnacles of more resistant portions of rock. It is a sector where the gully advances, with a characteristic vertical development, forming abrupt walls.

Sector C of the gully, located in the lower third of the gully (Figure 7), has several ramifications and areas of lateral advance, with 19 areas of mass movements, 22 cracks, and 18 downgrade areas. The large number of downgrade areas in relation to the other sectors is an indication of greater action by the piping mechanism responsible for the removal of material on the subsurface and consequently forming downgrade areas.

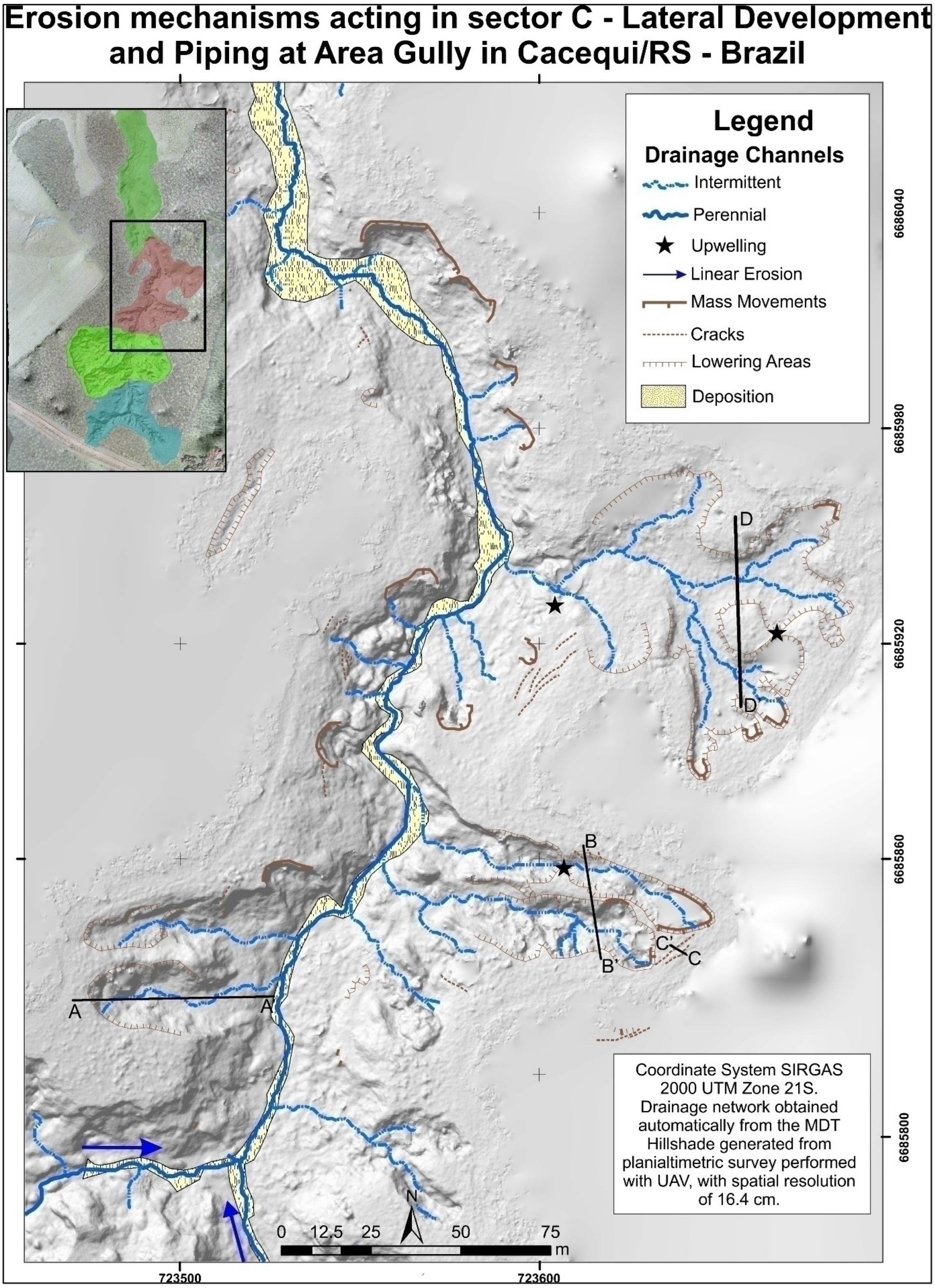

Figure 7 - Map of erosive mechanisms operating in sector C of Areal Gully.

One of the most common erosive mechanisms in this gully sector is the downgrades (Figure 8A), where a large area with a semicircular edge undermines, forming a converging area, with a smoothed profile, without the occurrence of vertical walls, and the establishment of intermittent channels in the center.

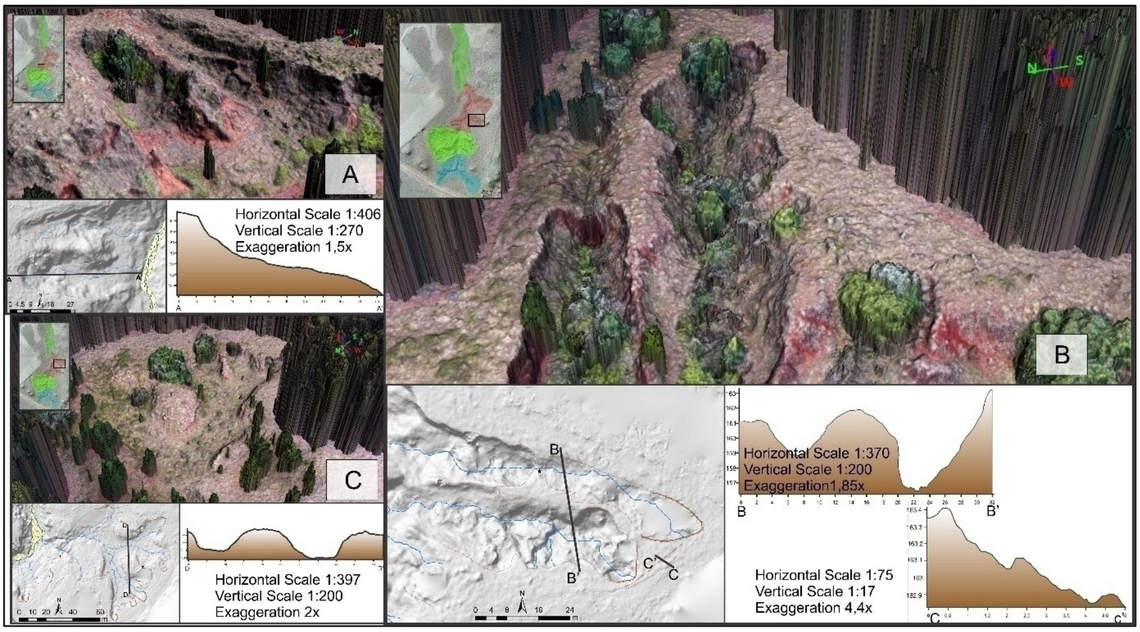

Figure 8 - Schematic representation of the mechanisms acting in sector C (A - Downgrade area; B - Parallel branches associated with the downgrade and crack formation areas; C - Downgrade area).

The occurrence of these lowerings may be associated with the existence of more clayey rock lenses at the base, favoring underground erosion at these points. These lowering points form a converging feature that favors the surface runoff of water, concentrating moisture and making vegetation in these areas more common, as seen in Figure 8A.

The right margin of the sector contains two parallel and linear shaped ramifications (Figure 8B), which are between 3 and 7 meters deep. The two branches are divided by a small strip of land less than 10 meters wide (Profile B-B ', Figure 8B), where water erosion processes and small mass movements occur, contributing to the retreat of this portion of land and a possible joining of the ramifications.

The activity of mass movements in this area is observed in the formation of cracks upstream from the feature, represented in the topographic profile C-C' of Figure 8B. In this portion of the gully sector, the occurrence of upwelling evidences the action of underground erosion.

Further downstream in the gully, ramifications of distinct characteristics are a greater widening of the feature and less depth, reaching about 3 meters in depth, as shown in the topographic profile D-D' of Figure 8C. The base of the gully in this portion has a flat bottom, possibly due to the presence of more clay lithology sheets close to the surface. The headland area also exhibits a small advance of the ramification through small mass movements.

Sector D is located in the most downstream portion of the gully (Figure 9), characterized by the stabilization of the gully, containing only five signs of mass movements, and one of lowering but with a greater occurrence of cracks, adding up to 33. In this sector, the main channel is already well established, with deposition areas close to the channel and the main mechanism is deposition; however, the side walls still exhibit erosion mechanisms.

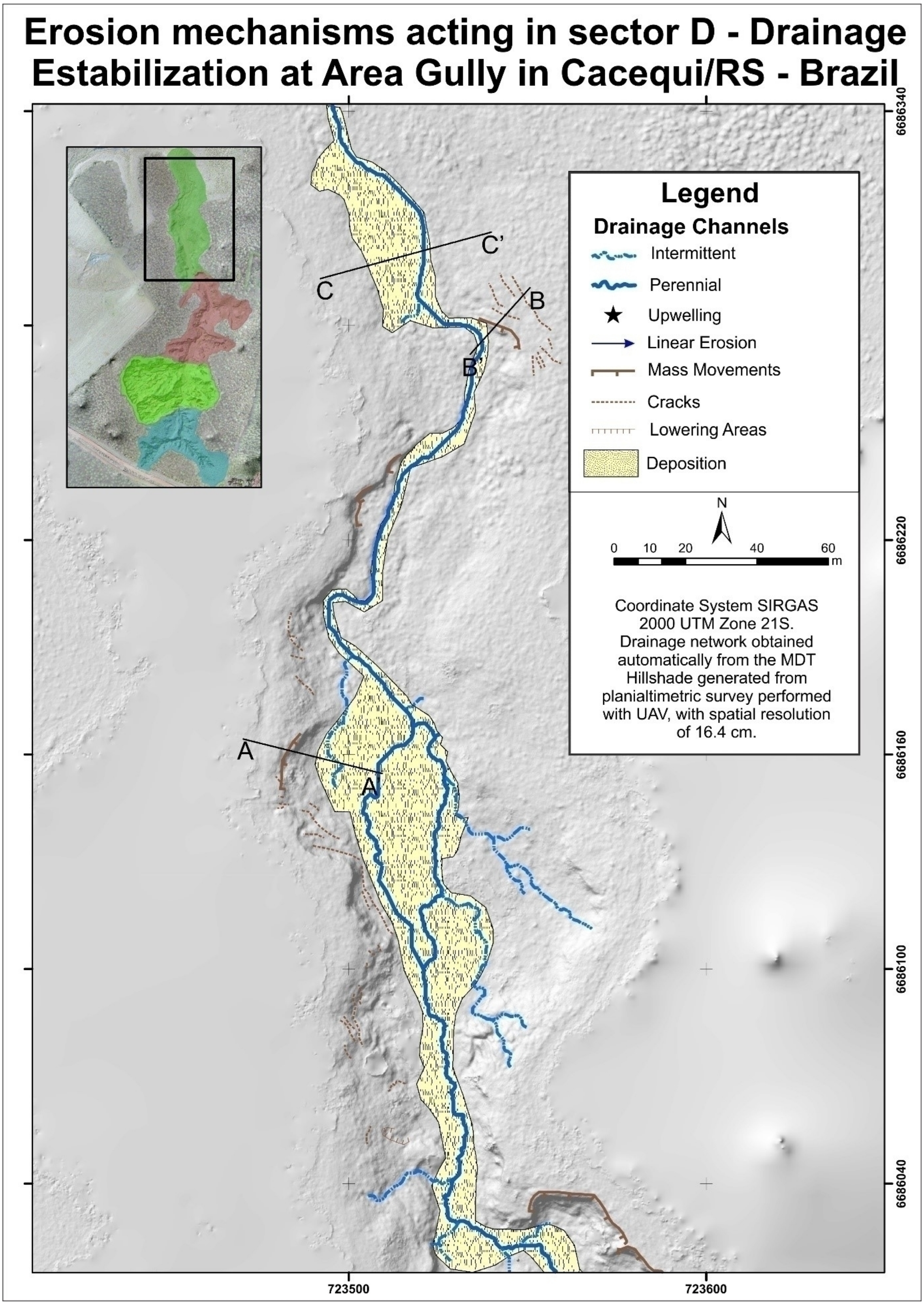

Figure 9 - Map of erosive mechanisms operating in sector D of Areal Gully.

Although the sector is characterized by the stabilization of the gully and is located in the lowest portion, it is still possible to observe the mass movement mechanism acting on the development of the gully. These mass movements occur close to the gully wall, near the main channel, about five meters high (Figure 10A), having at its base a large amount of deposited material resulting from upstream erosion. These are softer mass movements, due to their proximity to the base level, but they contribute to the advancement of the gully. Often these mass movements are associated with undermining the bottom of the hillslope.

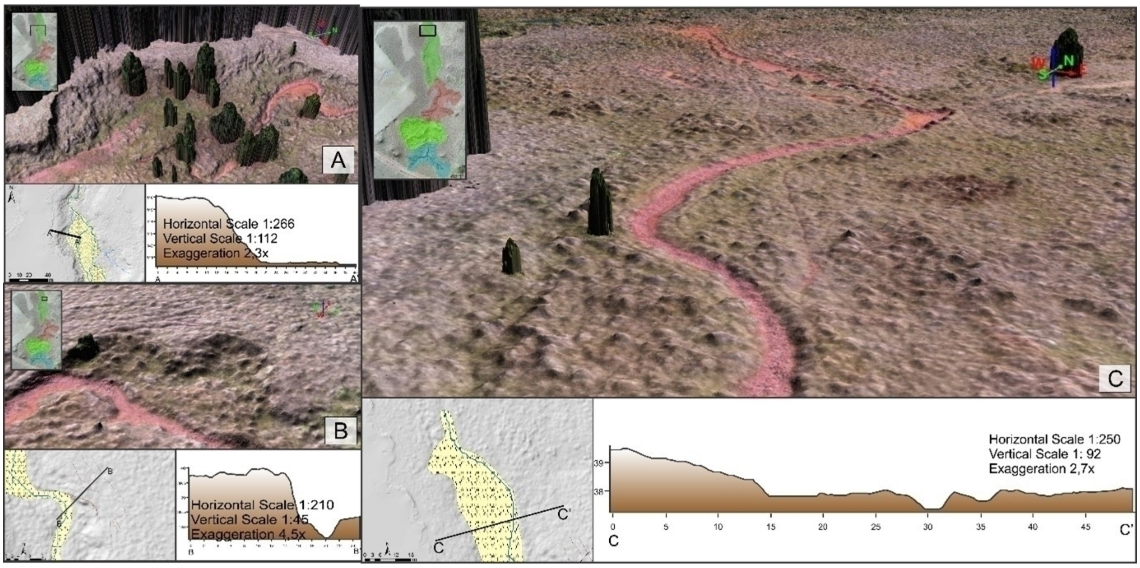

Figure 10 - Schematic representation of the erosive mechanisms acting in sector D (A - Mass movements; B- Small mass movements and associated cracks; C - Flat area).

Further downstream in the sector, small mass movements, approximately two meters high occur, as shown in the profile B-B' in Figure 10B. Along with these mass movements, there are also several cracks and small ridges in the relief, of a few tens of centimeters.

This sector as the lowest in Areal Gully is where the aggradation processes predominate, with the deposition of material and flattening of the relief, as can be seen in Figure 10C. In the final portion of the gully, a perennial drainage channel is established, surrounded by areas of deposition of material and flat areas, without the presence of abrupt walls, characterizing itself as a first order channel and thus being the end of the gullying area. Therefore, sector D of the gully presents smoother mass movements, less expression, and less eroded material, mainly due to its proximity to the base level. The deposition of fine material due to upstream erosion and stabilization of the drainage channel prevails in the sector, connecting with the river network of the hydrographic basin of the Areal do Limeira River.

DISCUSSION

High resolution and refined precision mappings of gullies, such as the models obtained through UAV surveys and the use of SfM techniques to topographic modelling, allow the identification and spatialization of the characteristics of erosive processes. Allowing then the detailing the different types of advances and associated mechanisms to the gully, in this way the main types of evolution can be defined. The predominant erosive mechanisms in the gully are related to mass movements, which are the main controlling agent of the lateral and vertical advance of the gully, especially in the upper portions of the gully. In the lower third portions, mass movements and lowerings related to the contact of sandy rock lenses with more clayey lenses predominated.

A more in-depth analysis of erosion mechanisms within the gully in its different sectors allows for an understanding of the progress of erosive processes and is greatly benefited by the use of high-resolution topographical surveys, as described in this paper, with physical measurements, (depths, widths, volumes). There are several applications and studies that indicate the potential of using high-resolution topographic surveys to analyze erosive mechanisms (PEOESEN, et al, 2003; SMITH et al., 2015; KOCI et al, 2019).

Areal gully has a complex dynamic, with a variety of active erosion mechanisms and with different intensities in different sectors. The mapping and understanding of these mechanisms became possible only by obtaining very high-resolution data, which allow differentiation of small changes in the dynamics of the gully.

The use of UAV and the SfM-CMVS algorithm allowed the identification, mapping, and understanding of the erosive mechanisms in the study area. These analysis tools have great potential to be used for mapping erosion, as a low-cost technique for easy acquisition of data that opens up possibilities for extremely detailed analysis of the phenomena. Specifically pointing to SfM, several are the benefits indicated, such as high resolution ortho-photo mosaics that can be used to assess land cover, physical measurements, evaluation of erosion mechanisms being very valuable for management elements, in addition to lower costs when compared to obtaining these products through other sensors (OUÉDRAOGO et al, 2014; BARTLEY et al 2016; GLENDELL et al 2017).

Despite their potential, these tools still have some limitations and challenges. Highlighting the limitations can be cited the complex structure and pattern of the vegetation present in the mappings, which negatively affects the model's accuracy. The methodological applications are fundamental for the model's accuracy because despite the steps being relatively simple, there are many uncertainties as to the ideal methodology to be applied in each mapping, in each type of landscape or application. The volume of data, captured images, is high, which demands significant storage space and, mainly, a lot of computational processing to generate the products (JAMES & ROBSON, 2012; SMITH et al, 2015; ELTNER et al, 2016; CLAPUYT et al, 2016; MARZOLFF & POESEN, 2009).

In Areal Gully, shrub vegetation is common, and some points, especially in the headwaters that have a higher concentration of humidity, contain large trees that cause interference in the model generated with the SfM-CMVS algorithm, requiring corrections. The vegetation problem, as described by Marzolff & Poesen (2009), is possible to mitigate through the use of a hybrid method of automatic and interactive feature extraction using filters, removing the vegetation pixels, and in areas where there is an intense cloud of vegetation points it is necessary a manually correction which requires careful not to remove the points too much and change the shape of the terrain in the resulting MDT.

Several studies have been developed to correct or adjust these errors and limitations in the use of UAV and the SfM-CMVS algorithm. The main solutions found by the researchers is the accomplishment of more than one flight in which the camera coupled to the UAV has different zenith angles. Or, still, taking photos on the ground with photographic equipment in areas of difficult flight coverage and feeding the software with this information (D'OLEIRE-OLTMANNS et al., 2012; STÖCKER et al., 2015; STUMPF et al., 2015; FRANKL et al., 2015). Further studies of the application of these methods in the study of gullies are still needed.

In addition, shadows often occur near the walls of the gully, depending on the position of the sun, which is a problem that is difficult to solve and causes noise in the model. One way to smooth this error is to make flights at noon, when the incidence of sunlight is closer to zenith.

Sector A is marked by erosive activity, both superficial and subsurface, with the formation of two large advancing ramifications upstream of the hillslope. As noted by (KIRKBY; BRACKEN, 2009) the upper portion of the gully with greater linear erosion helps in expanding the gully, as the material does not deposit in these areas, favoring the advancement through plunge-pools erosion, sidewall erosion and mass movements. The development of the gully is evident to the top of the hillslope and the widening of the ramifications through mass movements.

Sector B exhibits a great erosive advance, where the mass movements are quite active, marking an area of both lateral and vertical advancement. This predominance of mass movements was also observed in New Zealand (BETTS et al., 2003; PARKNER et al., 2006) and Spain (MARTÍNEZ-CASASNOVAS et al., 2009; WIJDENES et al., 1999), where these processes are responsible for up to 90% of the sediment production of a gully (BETTS et al., 2003). As can be seen in Figure 11A, the constant occurrence of mass movements makes it difficult to establish vegetation at the base and walls of the gully. The activities of the erosion mechanisms are also evidenced by the large amount of unconsolidated material at the base. This mechanism is closely related to soil conditions, climate and characteristics of the slope where the gully is located (ABER et al., 2019; ZEGEYE et al., 2020).

Sector C contains more features associated with the subsurface erosion mechanism, and the gully advancement areas do not have such an intense vertical development, forming U-shaped valleys. There is evidence of a more clayey sheet in the lithological substrate relatively close to the surface. In these areas, a contact is formed between lithologies with different textures, the sandiest at the top and just below a clayey sheet, as shown in Figure 11 B.

In the contact areas of the sandiest lithology with the clay lenses, the loss of the reddish color of the rock in the sandiest portion (Figure 11, D) results from the leaching of mineral material in the areas of emergence for a long period of time. In the more clayey portion, the identifiable mottled feature (Figure 11, C) is due to the great water availability in this portion.

Thus, sector C displays major activity of subsurface erosion with the occurrence of the lowering mechanism and evidenced by the upwelling. The lateral development of the gully is greater than the vertical, both due to the location of the lower third of the hillslope, closer to the base level, decreasing the erosive power, and to the existence of more impermeable clay lenses that hinder vertical expansion.

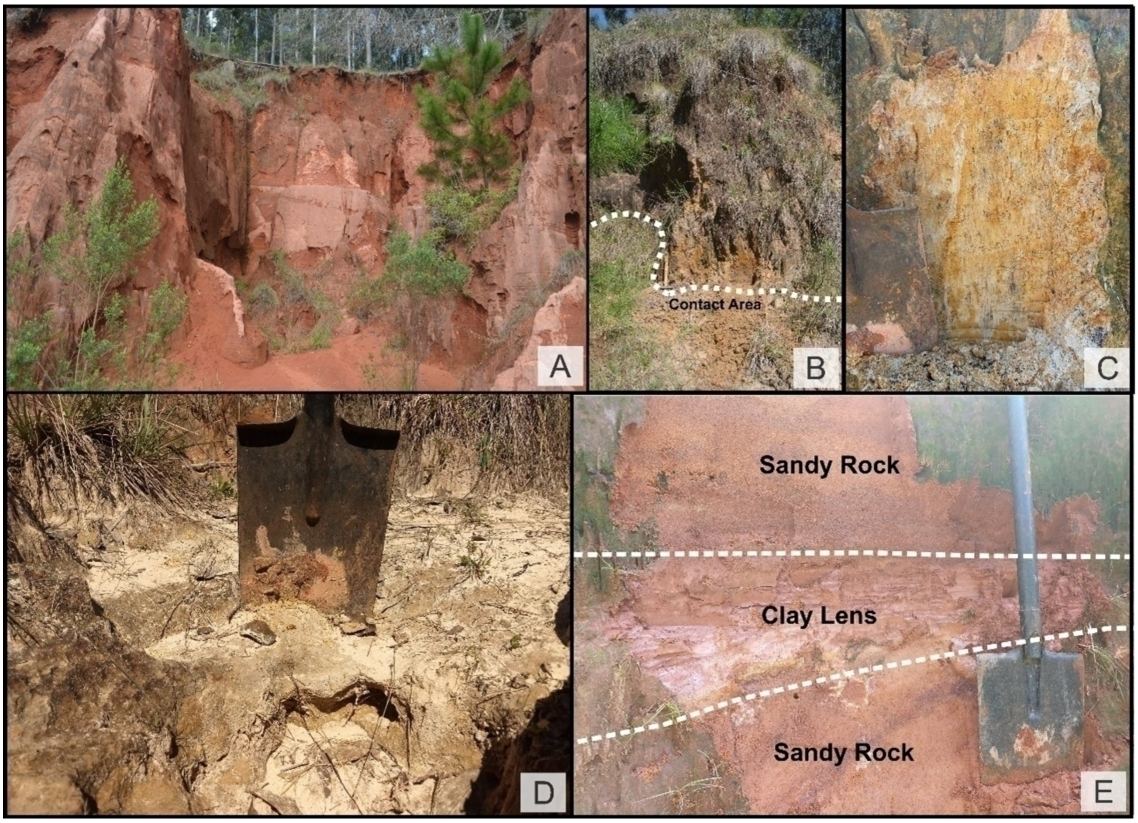

Figure 11 - A - Occurrence of mass movement in sector B of Areal Gully; B - Contact area of the sandiest rock portion with the most clayey portion; C - Mottled aspect of altered clayey rock blade; D - Sandy portion of the slope with loss of color; E – Alternation of rock lenses with different characteristics in Areal Gully.

For a long time, and in several studies, the concept of gully was linked to the performance of hydraulic erosion, with superficial erosion being the main erosive agent of these features (BERGONSE; REIS, 2011). However, recent studies suggest that erosion mechanisms in gullies are more complex, with mass movements as the main agent (MARTINEZ-CASANOVA et al., 2003; BERGONSE; REIS, 2011; BETTS; TRUSTRUM; ROSE, 2003; DE AP BACELLAR; NETTO; LACERDA, 2005; MARDEN et al., 2018).

The work carried out on Areal Gully evidences that the main mechanism of erosion at the present time is the mass movement associated with subsurface erosion and the formation of piping. These mechanisms act in the gully both in the widening of the feature and in the headcut retreat upstream on the hillslope, generating a large volume of eroded material, through huge and unique features similar to the concept of badass geomorphology described by Phillips (2015) and used by Marden et al. (2018) to describe large gullies in New Zealand.

The major occurrence of mass movements and lowering areas in the gully are still not well understood. In different portions of the gully, lenses of more clayey rock amidst sandy lithology (Figure 11E) form discontinuities and are able to trigger different erosive mechanisms. As noted by Wijdenes et al. (1999) in gullies in southwestern Spain, those with soils containing a textural B horizon were more prone to the occurrence of mass movements and regression alcoves, as also found in Areal Gully. Thus, there is evidence of great interference by litopedological factors in the erosion mechanisms of the study area, requiring additional studies for further clarification.

CONCLUSION

Several studies have been developed to correct or adjust these errors and limitations in the use of UAV and the SfM-CMVS algorithm. The main solutions found by researchers is the accomplishment of more than one flight providing the camera coupled to the UAV different zenith angles. Photos can also be taken on the ground with photographic equipment in areas of difficult flight coverage and this information also feed into the software (D'OLEIRE-OLTMANNS et al., 2012; STÖCKER et al., 2015; STUMPF et al., 2015; FRANKL et al., 2015). Further studies about the application of these methods in the study of gullies are still needed.

Nevertheless, the tools provided sufficient quality data to study the erosive mechanisms of Areal Gully that made the sectorization of the gully possible. The mapping and identification of erosive mechanisms provide data for future studies of genesis and mitigation of the gullying process that occurs at the site.

It is important to highlight the existence of a planted eucalyptus forest around Areal Gully. This vegetation cover has impacts on the dynamics of the gully, decreasing the runoff and increasing the infiltration of water in the soil. However, a more in-depth study of the real impacts of silviculture on erosive mechanisms is necessary.

The work done makes it evident that the action of erosive mechanisms in a gully is complex. The different sectors have several factors that influence the mechanisms that act on erosion, as well as their intensity. The mapping of erosive mechanisms in Areal Gully made use of new technologies for mapping erosion, opening opportunities for several studies and approaches on the subject with a new methodological perspective, still little explored.

The products generated in this work provide a database that has the potential to assist in work to be developed, serving as a basis for the study of gully genesis, for the identification of the best mitigation measures, or as an initial framework to study the evolution of this erosive feature.

Considering that each erosive mechanism has a determined form for its containment, the delimitation of these mechanisms in an extremely detailed level can facilitate a management plan for the Areal Gully considering these peculiarities of the gully. With proper management, most of the economic and environmental problems caused by a gully of this size could be mitigated.

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