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Controlling factors of gullying in the Maracujá Catchment, Southeastern Brazil

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Abstract

Hundreds of gullies ('voçorocas') of huge dimensions (up to 400–500 m long, 150 m wide and 50 m deep) are very common in the small Maracujá Catchment in southeastern Brazil. These erosional features, which occur with an uneven intensity throughout the area, started due to bad soil management practices at the beginning of European settlement, at the end of the 17th century, and nowadays are still evolving, but at a slower rate. As surface soils are usually very resistant to erosion, the outcrop of the more erodible basement saprolites seems to be an essential condition for their beginning. An analysis of well known erosion controlling factors was performed, aiming to explain the beginning and evolution of these gullies and to understand the reasons for their spatial distribution. Data shows that geology and, mainly, geomorphology are the main controlling factors, since gullies tend to be concentrated in basement rock areas with lower relief (domain 2) of Maracujá Catchment, mainly at the fringes of broad and flat interfluves. At the detailed scale (1:10 000), gullies are more common in amphitheatre-like headwater hollows that frequently represent upper Quaternary gullies (paleogullies), which demonstrate the recurrence of channel erosion. So, gullies occur in areas of thicker saprolites (domain 2), in places with a natural concentration of surface and underground water (hollows). Saprolites of the preserved, non-eroded hollows are usually pressurized (confined aquifer) due to a thick seal of Quaternary clay layer, in a similar configuration to the ones found in hollows of mass movement (mudflow) sites in southeastern Brazil. Therefore, the erosion of the resistant soils by human activities, such as road cuts and trenches ('valos'), or their mobilization by mudflow movements, seem to be likely mechanisms of gullying initiation. Afterwards, gullies evolve by a combination of surface and underground processes, such as wash and tunnel erosion and falls and slumps of gully walls.

Keywords: **gullying; erosion; human impacts; geomorphologic controls; catchment**

Introduction

Gullies are considered one of the worst environmental problems in crystalline basement rock areas of tropical regions, where they are frequent and can reach large dimensions (Wells and Andriamihaja, 1993; Xu, 1996; Coelho Netto, 1997). In these areas, gully erosion is responsible for several environmental impacts, such as soil losses, destruction of properties and natural habitats, silting of reservoirs and groundwater drawdown (Lal, 1990; Xu, 1996; Bacellar, 2000). Gullies usually appear as a consequence of bad land management practices, but some studies have shown that there is not always a clear relation between land use and gully intensity, since other factors, such as relief, seem to control their spatial distribution (Dietrich and Dunne, 1993; Coelho Netto, 1997; Poesen *et al*., 2003). Although it is not yet possible to predict gully development, there are some attempts to relate gully location to controlling factors, such as some relief attributes, such as drainage area and slope gradient and form (see, e.g., Dietrich and Dunne, 1993; Poesen *et al*., 2003). Gullies can develop by different erosional processes and mechanisms, such as overland flow erosion and subsurface flow erosion (tunnel and seepage erosion) as well as several kinds of mass movement (see, e.g., Lal, 1990; Selby, 1990; Dietrich and Dunne, 1993; Oliveira, 1997; Coelho Netto, 1997). These mechanisms should be known

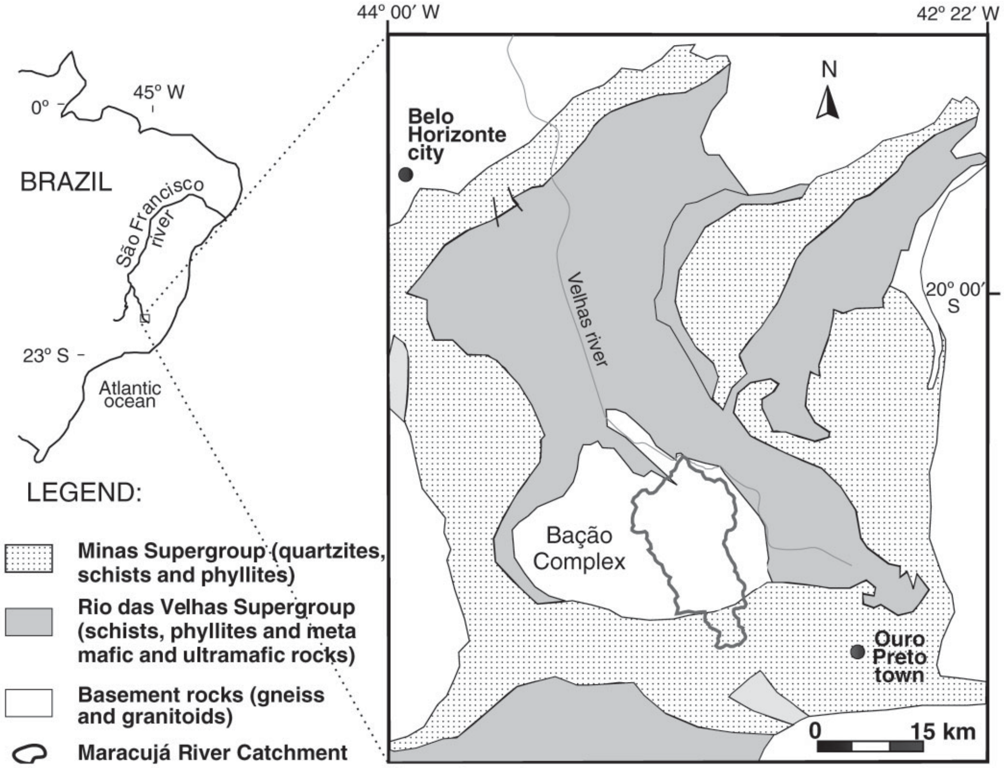

Figure 1. Location of the Maracujá River Catchment.

when gully prevention and control measures have to be taken. Here, we try to determine the controlling factors and the evolving mechanisms of gullying in Maracujá Catchment in order to explain its heterogeneous concentration. We hope that this knowledge will improve future land management practices in this catchment and in other areas with similar environmental conditions.

Study Area

The Maracujá Catchment, 140 km^2 in area, is located in Minas Gerais state, in southeast Brazil (Figure 1), inside a famous Brazilian geomorphic landscape, the Ferriferous Quadrangle (Door, 1969). This river is a sixth order (Strahler classification) tributary of the Velhas River, which, in turn, is one of the main tributaries of the São Francisco River, the third largest in South America (Figure 1). Maracujá Catchment shows a diversified set of lithologies and landscapes and an uneven distribution of gullies.

Geology

Four geological units can be found in the Maracujá Catchment: crystalline basement, Minas and Rio das Velhas Supergroups and Quaternary sediments. The crystalline basement rocks (Arquean) outcrop in a structural window, with a domic form (Bação Complex, Door, 1969; Hippert, 1994), cut in Minas and Rio das Velhas Supergroup rocks (Figure 1). The Bação Complex is composed of tonalitic, trondhjemitic or granodioritic gneisses, with some intrusions of granodioritic and granitic granitoids (see, e.g., Hippert, 1994; Endo, 1997). The gneisses frequently show a well developed compositional banding, with dark micaceous bands alternating with clear quartz–feldspatic ones. In a recent detailed mapping (Franco, unpublished geological report; Graça, unpublished report; Lopes, unpublished report; Martins, unpublished report; Salaroli, unpublished geological report; Vilela, unpublished report) three main bodies of gneisses were mapped (Funil, Amarantina and Praia, Figure 2) – with very slight compositional and textural differences among them.

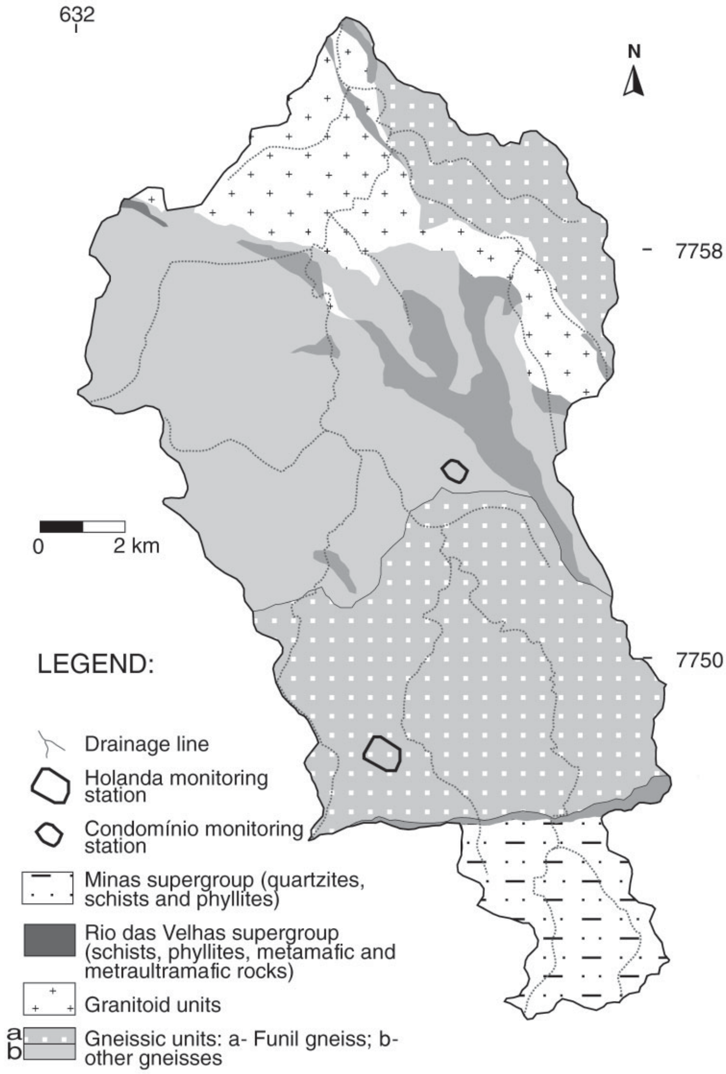

Figure 2. Geologic map of the Maracujá Catchment (modified from Johnson, 1962; Franco, unpublished report; Graça, unpublished report; Lopes, unpublished report; Martins, unpublished report; Salaroli, unpublished geological report; Vilela, unpublished report).

Rio das Velhas Supergroup unit (Arquean) is composed in the area by schists, metamafic and metaultramafic rocks (Endo, 1997). This unit overlies basement rocks, outcropping around the Bação Complex and also inside it, in the form of long rock slabs, probably placed by shear zones (Figures 1 and 2). Minas Supergroup rocks (Proterozoic) overlie the previous units (Figure 1). They outcrop on Maracujá Catchment headwaters (Figure 2), in a region of higher altitudes ('Upper Compartment', see below), where they are composed of schists, phyllites and, secondarily, by quartzites and ferriferous formations (Door, 1969). Some of these quartzites are hard, but there are certain thin veins of ferruginous quartzite that are very soft and friable. Finally, this region is covered by unconsolidated colluvial and alluvial sediments (Quaternary), poorly described until now.

The geotectonic evolution of the area is complex, due to the superimposition of several tectonic events from Arquean to Upper Proterozoic age (Endo, 1997), which resulted in the formation of shear zones, folds and foliations (schistosity and compositional bandings). Recently, strong evidence has been found of brittle tectonic events during Tertiary and Quaternary periods that gave origin in certain places to brittle structures (joints and faults) in the correlative sediments (Saadi, 1991). As these neotectonic phases are not completely understood yet, more studies are currently being made in order to understand their characteristics and relative chronology.

Weather and vegetation

Mean annual precipitation in the area ranges from 1024 to 1744 mm, with a maximum between October and March (Bacellar, 2000). Weather is colder and more humid (CWb, in Köppen classification) on the Upper Compartment (Minas rocks) than on the lower one, which is hotter and more seasonal (CWa).

Vegetation varies in a similar way, with a dominance of tropical forest on the Upper Compartment and a savannah type ('campos cerrados') over great part of the Lower Compartment, especially on flatter areas, with a predominance of oxisols, poor in nutrients. However, even in this compartment there are scattered pockets of riparian tropical forest along rivers and headwaters hollows or over areas of more fertile soil, as on Rio das Velhas Supergroup areas inside the Bação Complex (Figure 2).

Historical background and land use

Brazilian native people already occupied this region at least 10 000 years B.P. and the European settlement only began at the end of the 17th century, as a consequence of a huge gold rush nearby (Burton, 1869; Gutersohn, 1945). Gold did not occur in the Maracujá Catchment, but this area was a supply centre of cattle and agricultural products for the neighbouring mining towns (Ouro Preto and Sabará), some kilometres away, at that time economically very active (Gutersohn, 1945). In fact, compared with its neighbouring regions, the Bação basement window was preferentially settled because of its relatively lower relief. Land occupation by man has been increasing in the area since the 1970s. Nowadays, most of the primary vegetation has been cut and the main economic activity is cattle grazing on mis-managed and overstocked pastures.

Methods

Geomorphology was characterized at 1:25 000 scale, through the integration of the following maps: hypsometric, slope and relief compartment, the last done following the methodology of Meis *et al*. (1982). At a larger scale, the relief was described following Hack and Goodlet (1960).

Quaternary sediments were characterized through an approach adapted to study Quaternary continental sediments of mountainous regions, the morphostratigraphic approach, initially proposed by Frye and Willman (1962), and further modified by Meis and Moura (1984) and Mello (1997) in order to couple the morphological description of geomorphic surfaces with allostratigraphy (NACSN, 1983). A detailed stratigraphic survey was completed on exposures along road cuttings and gully walls, supported by additional subsurface information (auger boring and GPR data), in order to identify sedimentary bodies and regional disconformities. Ten representative geological cross-sections were made across specific areas, mainly at headwaters hollows. This information was always tied to good morphological classification of colluvial ramp and alluvial terrace surfaces. This involved comparisons of top surface levelling and form reshaping by either erosional processes (sheet, splash and rill erosion) or colluvial or alluvial deposition through Upper Quaternary (Bacellar, 2000). Thus, in the recently incised channel valleys typical of this region, the older the ramp or terrace surface the higher and the rounder it usually is, because their primary form tends to be gradually reshaped by these geomorphic processes (Martin *et al*., 1998). Regional correlation and some 14C datings of organic clay layers and correlated paleosols, as was done by Dietrich *et al*. (1990), completed this analysis and permitted the chronological distinction of morphostratigraphic units in the catchment.

Historical recordings (e.g. Burton, 1869) and two sets of aerial photographs (from 1948 and 1996) allowed the identification of the disturbance caused by humans and the evolution rate, morphology and spatial frequency of gullies (Figure 3). Finally, gullying controlling factors were analysed, comparing simultaneously several layers of essential attributes with a gullying distribution map.

Soil erodibility analysis was carried out through field estimates and laboratory tests. Field estimates are based on the visual inspection of the relative intensity and frequency of erosional features (rills and plunge pools alcoves) on soil exposures (see, e.g., Alcântara, 1997). Then, soils are classified as of low, intermediate and high erodibility. Moreover, the following commonly used laboratory tests (Bryan, 1976, 2000; Head, 1986; Lal, 1990) were also evaluated as erodibility indexes.

- Silt–clay ratio (SCR) – this consists of the ratio of silt to clay content, both obtained with grain size tests. It is a variation of the Boyoucos ratio (Selby, 1990).
- Crumb test (Sherard *et al*., 1976).
- Penetrometer test, which uses a drop-cone penetrometer (Head, 1986), according to the methodology of Alcântara (1997). It consists of measurements of the penetration depth of soil at natural moisture content and also in the

Figure 3. Gullies of the Maracujá Catchment.

water-saturated state. According to Alcântara (1997), the difference of cone penetration depth (DP) between the water-saturated sample (Psat) and natural moisture content sample (Pnat) is proportional to the erodibility of tropical soils.

- Aggregate stability, following Yoder (1936) and Kemper and Roseneau (1986).

Maracujá Catchment Characteristics

Geomorphology

The relief varies widely throughout this catchment. Field data, aerial photography interpretation and the superposition of three maps derived from topography maps (hypsometric, slope and relief compartment) allowed the characterization of four homogeneous geomorphologic domains in the catchment (Figure 4).

Domain 1 is located on the catchment headwaters ('Upper Compartment'), on the Minas supergroup rocks. Altitudes are higher than 1140 metres and the hills are steep, with relief amplitudes between 70 and 140 metres. Hillcrests are sharp and follow rock foliation, forming a trellis drainage pattern. It is separated from other downstream domains by some waterfalls (bedrock steps that act as local base levels).

The other domains (2, 3 and 4), located in the medium and low Maracujá River ('Lower Compartment'), between 1140 and 900 metres in altitude, are composed of basement and minor proportions of Rio das Velhas rocks (Figure 2). They exhibit an angular-dendritic drainage pattern.

Domain 2, which occurs in three separated areas (2a, 2b and 2c, Figure 4), shows gently sloping hills (<30 per cemt) and amplitudes lower than 70 metres. On the other hand, a steeper relief, with amplitudes higher than 140 metres, characterizes domain 3. Finally, domain 4 presents an intermediate pattern between domains 2 and 3.

As the lithology of the Lower Compartment domains is similar, the flatter relief in domain 2 is probably due to the more effective action of local base levels at their channel outlets (Figure 4). These base levels have apparently prevented deeper river incision during recent geologic time, favouring lateral channel erosion over channel scouring and allowing wider and thinner Quaternary sedimentation (see below). Deprived of effective local base level control at their channel outlets, domains 3 and 4 show more incised valleys and narrower Quaternary sedimentation. Studies are

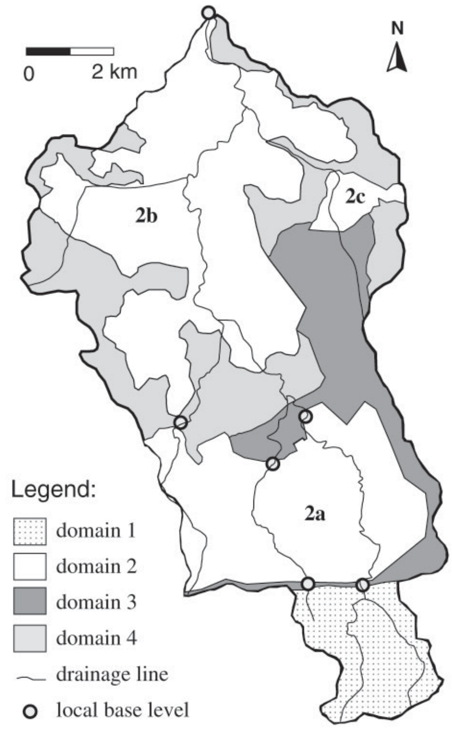

Figure 4. Geomorphologic domains of the Maracujá Catchment.

being performed in order to understand whether local base levels are of tectonic origin. In fact, the alignment of domain 2a base levels (knick points along a ENE direction, Figure 4) is a good indication of their tectonic origin.

Thicker and well developed soils (oxisols) prevail in the basin, especially on flatter areas (domain 2), while less developed ones (inceptisols and ultisols) are more common in the steep terrains, mainly in domains 1, 3 and 4. Entisols are restricted to some areas of domains 1 and 3, over resistant rocks, such as quartzites, schists and some granitoids.

Quaternary sediments

Unconsolidated sediments of Quaternary age occur throughout the catchment as colluvial ramps or fluvial terraces, up to 20 metres thick. Such sediments were studied through a morphostratigraphic approach (Frye and Willman, 1962; Meis and Moura, 1984; Mello, 1997), which allowed the chronological distinction of three main Upper Quaternary morphostratigraphic bodies in the catchment (Figure 5), very similar to the ones found nearby (Mello, 1997).

T3–R3 sediments. These represent the older alluvial (T3) and colluvial (R3) sediments of the area, occurring with very well rounded topographic forms, totally reshaped by erosional processes and colluvial or alluvial deposition (Figure 5). They occur locally on side slopes of the main valleys, usually several metres above the current floodplain. They are harder and more quartzose than younger sediments and present light grey tones, with reddish and yellowish mottles (plyntite). Neotectonic joints and faults are very common in some outcrops (Bacellar, 2000).

T2–R2 sediments. Recognized elsewhere in the catchment, they usually lie on valley bottoms, some metres above the current floodplain. According to some 14C datings on organic clays and paleosols, they are 31 340–7490 years B.P. and occur discordantly over basement or T3–R3 sediments. The alluvial sediments (T2), composed of pebbly or clayey sands and organic clays, represent fluvial terraces, which outcrop along low-order channels and in their unchannelled amphitheatre-like headwaters (hollows), where they frequently fill partially ancient erosional features (paleogullies; see below). These terraces are partially or totally overlain by reddish-brown, cohesive, massive, sandy-clay sediments, generally with a well developed soil profile (usually oxisols). Stratigraphic and geomorphologic evidence allow us to interpret them as colluvial ramps (R2), which originated from eroded lateral slopes, provoking a partial reshaping of T2 terraces (ramped terraces, Figure 5). Joints and strike-slip faults frequently affect these sediments.

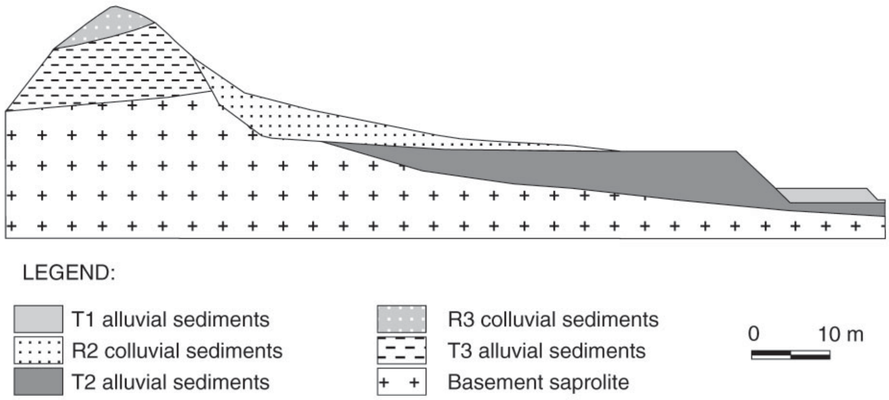

Figure 5. Idealized geological cross-section depicting the relationship among quaternary sedimentary units of the Maracujá Catchment. The older the unit the more reshaped it is by subsequent erosional and depositional processes (see the text).

Figure 6. Northward view of typical gullies of Maracuja Catchment. The dotted white line represent the top of the gneiss saprolite. These gullies (A and B) are located in Holanda monitoring station (see Figure 2).

T1 sediments. There are found as fluvial terraces (T1), incised on T2 and up to 2 metres above the current floodplains (Figure 5). They are up to 3 metres thick and are composed of sandy clays and also organic clays, but younger (<5300 years BP) and softer than T2 clays. Because of their younger age, these sediments were not overlaid by significant colluvial ramps, and their top surface is, therefore, plain (Figure 5). There is no evidence of tectonic deformation in these sediments.

Erosion

As in other parts of southeastern Brazil, post-settlement bad soil management practices have caused severe sheet and rill erosion in this region, especially on soils on steep slopes from basement areas, which nowadays are frequently deprived of the surface organic (A) soil horizons. These kinds of erosion caused progressive reduction of soil fertility leading to a gradual economic impoverishment of the whole region (Gutersohn, 1945).

Nevertheless, the most astonishing erosional features of the area are the 385 gullies, easily identified by aerial photography interpretation (Figure 3). They occur with a heterogeneous distribution throughout the catchment, in some places eroding more than 40 per cent of the ground, as in some parts of geomorphologic domain 2, while they can be almost absent on other places, as in domain 3 (compare Figures 3 and 4). These gullies are always graded to the drainage system and are very large (Figure 6), frequently reaching 400 to 500 metres long, 150 metres wide and 50 metres deep. According to historical recordings (Burton, 1869), gullies started due to bad agricultural soil practices at the beginning of European settlement. The old age of such gullies makes determination of their controlling factors and starting mechanisms difficult, but their current evolution clearly occurs by several mechanisms (discussed below), notably slumping, favoured by the headcut undermining and by the high hydraulic gradients in the characteristically steep gully walls. Nowadays, aerial photography interpretation shows that in the last 50 years few gullies have appeared and most of the old ones are now totally stabilized or evolving at slow rates (Sobreira, 1998), as many of them have already reached the interfluves in their headward retreat. This precludes any correlation with the evolution model of gullying of Oliveira (1997).

Soil erodibility

As is well known, it is very difficult to measure erodibility, because of the great number of intervening factors (pedologic, geologic, geomorphologic, anthropic, biologic and climatic) and the variety of erosional mechanisms (see, e.g., Lal, 1990; Bryan, 2000). As there is not yet a universal method to quantify this property, soil erodibility was first estimated in the field by visual inspection (VI) of road cuts and gully walls, since the magnitude of rills and plunge-pools alcoves (Dietrich & Dunne, 1993) on the exposures can be crudely correlated with this property. Based on the intensity and frequency of these erosional features the soils were classified as of low, intermediate and high erodibility. Granulometry tests carried out on several samples showed that low and high erodibility soils classified by visual inspection have silt–clay ratio (SCR) lower than 0·66 and greater than 1·44, respectively. This information confirms that among tropical soils, usually deprived of swelling minerals, the higher the clay content the bigger the cohesion and aggregation and, consequently, the lower its erodibility (Barthès and Roose, 2002).

Thus, soils derived from Minas and Rio das Velhas rocks usually show low erodibility throughout their profiles, due to their higher content of non-swelling clays (SCR lower than 0·66). The only exceptions are the soils from some thin quartzite veins from the Minas group (ferruginous quartzites), which outcrop on catchment headwaters (domain 1), that produce friable soils and saprolites, with a fine silty texture and SCR > 1·70, which are very susceptible to gully erosion.

Conversely, basement soil profiles in the Maracujá catchment are usually very heterogeneous, with low erodibility soils (VI low and SCR < 0·66) above more erodible saprolites. Indeed, the erodibility of these saprolites apparently can vary widely, as shown by the VI (intermediate and high erodibility) and by the SCR, which ranges from 2·00 to 6·00 (Bacellar, 2000). However, VI and SCR indices could not separate the subtle erodibility differences found amongst basement saprolites.

In order to determine erodibility more precisely, some traditional geotechnical and agronomical laboratory tests were carried out on 13 selected samples of Funil gneiss saprolites (Table I), which is the geologic unit most prone to gully erosion in the Maracujá Catchment. Two samples of soils (oxisol B horizon) were tested as well, to calibrate the test results (Table I).

Although there is not good agreement with SCR, the VI data indicate two main classes of erodibility among these Funil gneiss saprolites: intermediate and high (Table I). The first test performed was the crumb desegregation test (Sherard *et al*., 1976), which shows poor replicability and no correlation with SCR and VI.

Then, grain size tests without chemical dispersant and strong mechanical agitation were carried out, in order to obtain some dispersion index through the SCS test (Sherard *et al*., 1976). However, these samples do not exhibit particles smaller than 0·005 mm with the test procedures (SCS = 0), confirming that these saprolites are not dispersive.

Afterwards, an erodibility test with a drop-cone penetrometer (Head, 1986) was used, following the methodology of Alcântara (1997). According to this author, the difference of cone penetration (DP) between the saturated sample (Psat) and natural moisture state sample (Pnat) would be proportional to soil erodibility. The DP results of the selected samples showed good correlation with visual erodibility, but when low erodibility soil samples were evaluated, this

Table I. Erodibility data from selected Funil gneiss saprolites and soils (oxisol B horizon)

	Sample	Visual inspection (VI)	Silt–clay ratio (SCR)	DP (%)	Psat (mm)	MWD (mm)
Soil	1	low	0,28	80	8,8	2,08
	2	low	0,44	121	6,2	2,2
Saprolite	9	intermediate	4,11	–	–	–
	9b	intermediate	2,50	28	6,2	0,7
	151	intermediate	3,50	15	4,8	1,26
	212–7	intermediate	2,54	30	6,0	0,87
	212–8	intermediate	2,27	–	–	–
	151m	high	5,35	143	13,0	0,33
	212–1	high	–	–	–	–
	212–2	high	6,00	158	16,3	0,22
	212–3	high	4,18	137	18,3	0,16
	212–4	high	4,45	82	18,0	0,17
	212–5	high	6,18	93	12,2	0,13
	212–6	high	3,91	158	14,0	0,17
	212–10	high	3,64	121	15,0	0,25

– No results.

index failed (Table I). Better agreement can be found when VI for saprolites and soils is compared with the amount of saturated penetration (Psat, Table I), supporting the idea that there could be some relationship between strength and erodibility (Bryan, 2000).

The best results were found with the aggregate stability test, measured by the mean weight diameter (MWD index, following Yoder (1936) and Kemper and Rosenau (1986), which allowed distinction of slight erodibility differences, confirming previous studies in this area (Parzanese, 1991; Silva, 2000) and elsewhere (Bryan, 1976, 2000; Barthès and Roose, 2002). Funil gneiss saprolites with MWD > 0·70 mm and <0·33 mm have low and medium (VI) erodibilities, respectively (Table I). It is important to say that this test was equally efficient in evaluating erodibility among Funil gneiss soils (oxisols), which exhibit coarser water-stable aggregates (MWD > 2·08 mm), due to the iron oxides and hydroxides as natural cements.

Scan microscope data provided by Morais (2003) showed that Funil gneiss saprolites with intermediate erodibility (Table I) have either an abnormal particle aggregation, due to some inherited characteristics of the parent rock, usually coarser and more quartzose (commented on below), or some kind of cement deposition (iron oxides and hydroxides) during further weathering processes.

Gullying Controlling Factors

As commented previously, gully concentration varies enormously throughout the catchment (Figure 3). In order to understand the reasons, the usual erosion controlling factors (see, e.g., Xu, 1996) were analysed separately.

Pedologic controls

There is no evident relationship between pedology and channel erosion in Maracujá Catchment, because soils are systematically less erodible than the saprolites, especially on flatter basement areas, with predominance of oxisols, where gullies are more frequent. Santos (2001) performed a year-round experiment on field plots, showing that the sheet erosion rate over local oxisols is very slow under the current volumes of overland flow. Therefore, the exposure of saprolites seems to be an essential condition for gully initiation, confirming previous studies in this area (Parzanese, 1991).

Anthropogenic controls

Human activities, such as deforestation and the construction of fences, paths, trenches and roads, are usually mentioned as responsible for the concentration of overland flow and, consequently, for gully initiation in Brazil (see, e.g., Parzanese, 1991). About 70 per cent of Maracujá Catchment's gullies are directly associated with human activities (Bacellar, 2000), mainly the boundary ditches ('valos'), which are trenches hundreds of metres long and 2 to 3 metres depth, dug in the soil by the first settlers to separate properties, instead of fences or walls.

Erodibility tests with the Inderbitzen apparatus (Inderbitzen, 1961) on similar oxisols of southeastern Brazil have shown that shallow overland flows with velocities > 1·64 m/s are able to erode them easily (Rego, 1978). Field observations have showed that during storms some ditches could concentrate torrents up to 3 metres deep. Bacellar (2000) performed some analytic simulations with the Manning empirical equation for channel flows (Selby, 1990) in order to estimate the range of flow velocities inside these ditches. Bacellar (2000) has proved that even relatively shallower flows (30 cm deep) in ditches with a rugosity factor of 0·033 and a slope gradient of 20 per cent have enough erosional power (estimated flow velocity = 5·6 m/s) to cut the less erodible oxisols (A and B horizon) and reach the saprolites. It is important to note that Bacellar (2000) adopted conservative parameters in these simulations. Therefore, basement rock soils are resistant to erosion under the usual conditions of overland flow (Santos, 2001), but not under conditions of concentrated flow in the ditches. It is important to note that these ancient ditches are frequent in other parts of Brazil, usually associated with gullying (Furlani, 1980; Augustin, 1994).

However, anthropogenic factors cannot explain by themselves the uneven concentration of gullies, since they are rare in some parts of the catchment, intensely affected by man, while in other relatively less disturbed parts they are abundant (Bacellar, 2000). Therefore, although human disturbance is very important, other factors also interfere in gully propagation.

Geologic controls

Geology plays a fundamental part in gully development, since it directly controls soil profile development and influences its physical properties, such as erodibility. Gullies, characteristically huge in this catchment, are relatively

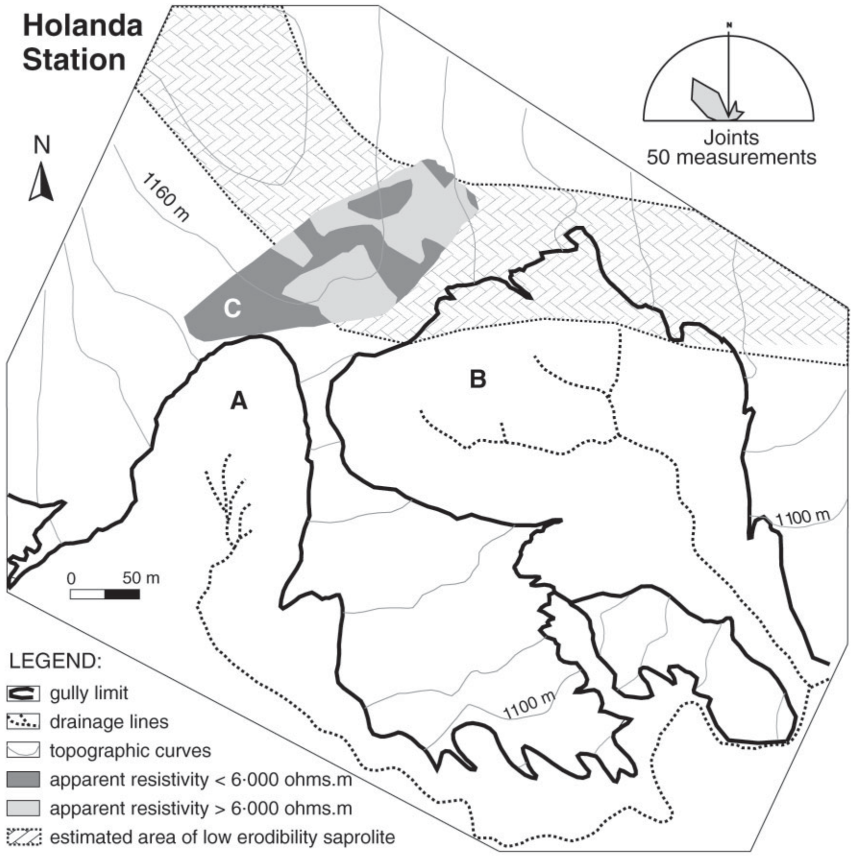

Figure 7. Map depicting the two gullies (A and B) of Holanda monitoring station (see Figures 2 and 6), with representation of an apparent resistivity pseudo-section at 45 m deep. Note the area of low apparent resistivity around C. Inset: joint measurements made at this station. The joint main orientation (NW) coincides with a strong electrical alignment detected by the electroresitivity survey.

rare in Minas and Rio das Velhas supergroup rocks, as a consequence of their thin and loamy regolith. The only exception is the friable quartzites (Minas supergroup), from the Upper Compartment, which are characterized by a thick weathering mantle, composed of silts and fine sands without aggregation.

On the other hand, the basement rock regolith is usually well developed, with thick saprolites of silty or fine sandy texture, which are very prone to gully erosion. Despite the great variability of weathering and pedological processes, a good relationship was found between basement rock composition and its saprolite erodibility. As shown by aggregate stability tests, fine texture and feldspatic gneisses and granitoids from the area produce more erodible saprolites than coarser and more quartzose varieties.

Thus, basement lithology, with typical abrupt lateral variations (e.g. igneous intrusions and dikes), intensely affects gully propagation. Lithologic contacts, dikes or even thick compositional bands of gneisses are enough to prevent or to divert the headward retreat of a gully due to natural differences of their saprolite erodibility (Bacellar, 2000).

A good example of this phenomenon can be observed at the two gullies that occur near Holland creek (Holland monitoring station, Figures 6 and 7). The eastern gully of this station shows an anomalous pattern of retreat, since it began to evolve following the local slope gradient (northwest direction), but at a certain moment it shifted abruptly to a west growing direction (Figure 7), discordant with the slope gradient. Overland erosion processes cannot explain this behaviour. Detailed field surveys have demonstrated that a W/NW trending ductile shear zone affects the gneiss, which outcrops in the toe of this gully's north sidewall. The resultant rocks (mylonites) produce thinner and much less erodible saprolites (Figure 7), because of its aggregates, coarser (with MWD > 0·7, see above) and more quartzose than the other ones nearby (with MWD < 0·33). This contrasting low erodibility explains why the eastern gully has stopped retreating northwestward, but it is still impossible to understand why it has continued to evolve with an apparent anomalous pattern, discordant with the slope gradient (westward). Electroresistivity surveys (with an adapted

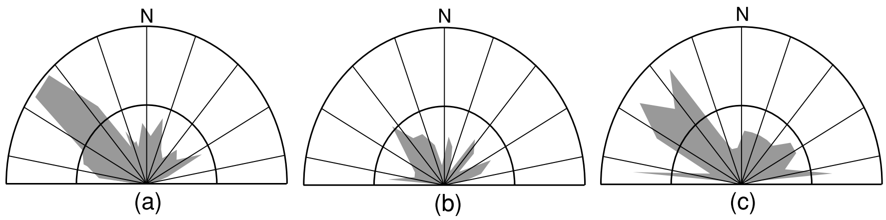

Figure 8. Rose-diagrams of the west part of the Maracujá Catchment representing the directions of: (a) geologic brittle structures (joints and faults); (b) gully channels; (c) headwater hollows.

3D-dipole–dipole method, after Nery and Aranha, 1995) showed that its evolution has followed a zone of great groundwater influx (zone of low apparent resistivity), which occurs just above the head of both gullies (area around point C, Figure 7). Field structural data suggest that northwest-trending joints (inset of Figure 7), which are common in this area, possibly explain the low apparent resistivity zones. This relationship between groundwater flow and NW discontinuities, well known in the region by hydrogeologists (Fernandes, unpublished report), may explain why there is a statistically good relationship between these structures and gully channels and headwater hollows (see below) throughout the Maracujá Catchment (Figure 8). So, geology plays either an active role (groundwater preferential influx by discontinuities) or a passive role (erodibility anisotropy) in gully evolution.

However, lithology cannot explain by itself the uneven concentration of these erosional features, because gullies can be abundant or not on the same lithology, as, for instance, on Funil gneiss (compare Figures 2 and 3).

Geomorphologic controls

According to the threshold concept, there exists for a given slope gradient a critical drainage area necessary to cause gully erosion (Poesen *et al*., 2003). It is almost impossible to determine these topographic parameters in Maracujá Catchment, because its 385 gullies are usually very large (up to 150 metres wide) and most of them have already reached the drainage divide. Therefore, they are now in a stable situation or are evolving very slowly (Sobreira, 1998). So, it is necessary to analyse other topographic parameters in order to explain gully concentration in this catchment.

Gullies are clearly concentrated in geomorphologic domain 2 (Figures 3 and 4), which is the flattest area of the catchment, with slope gradients < 30 per cent. In fact, domain 2 has 3·7 gullies/km^2, while the other domains in the basement rocks (domains 3 and 4) have fewer than 1·6 gullies/km^2. When areas of gently sloping interfluves (watercourse interfluves with average slope gradient < 15 per cent, graphically obtained from the slope map) are placed over the geomorphologic domains (Figure 4), it can be verified that about 70 per cent of the gullies tend to group mainly at the border of such interfluves (Figure 9), generally on the flatter ones in domain 2. Gullies are rare on areas of this domain with steeper interfluves as well as on the other domains, even on the surrounding areas of these kinds of interfluve. Therefore, gullies are more common in the flattest domain, specially on the borders of flat and broad interfluves. Some field permeability data (Bacellar, 2000) and preliminary hydrological balance of headwater catchments have shown that these interfluves are probably the best groundwater recharge places of Maracujá Catchment, due to its smoother relief, with well developed, permeable, porous and deep soils (oxisols). So, the preservation of thick soil profiles (with erodible saprolites up to 50 metres deep) as well as the larger groundwater availability in these flatter interfluves seem to be an important control factor of gully distribution in this area.

Gully occurrence is uneven even on a detailed scale (Bacellar, 2000), as they are more frequent inside headwater topographic hollows (64·3 per cent) than in noses (13·7 per cent) and side slopes (22·0 per cent). This preferential concentration, described by other researchers in southeastern Brazil (Coelho Netto, 1997) and elsewhere (Montgomery and Dietrich, 1989; Dunne, 1990), can be explained by the natural convergence of surface and underground water towards hollows (Hack and Goodlet, 1960).

The geometry of some headwater hollows of Maracujá Catchment support the idea that many of them may represent old gullies ('paleogullies', Figure 10) that were partially filled by sediments deposited in further depositional events. These paleogullies are certainly pre-European settlement, as they do not cut historical constructions. They could have been formed as a consequence of some Upper Quaternary climatic shifts (see, e.g., Suguio, 1999; Bacellar, 2000), as described by Coelho Netto (1997).

It is not always easy to identify these paleogullies, since their primary forms, with scarped walls, have been gradually reshaped to smoother and flatter ones by a combination of exogenetic processes (mainly by creep, slump and surface wash) during the Upper Quaternary. Although local factors can affect the current form of paleogullies, as a

Figure 9. Map of the Maracujá Catchment depicting the geomorphologic domains and the gently sloping interfluves (<15%). Most gullies occur in the fringes of these interfluves, mainly in domain 2. Only the larger gullies are represented for better visualization.

general rule it can be assumed that the greater their reshaping the older they are, which makes it possible to establish their relative ages. As we can see below, this assumption was further confirmed in the field, because the most easily identified paleogullies are that ones partially filled by the younger sediments of Maracujá catchment (T2–R2 and T1–R1 sediments, Figure 10). As current gullies are more frequent in headwater hollows, which usually represent paleogullies, this phenomenon is clearly recurrent, confirming previous studies in Brazil (Oliveira, 1989; Moreira, 1992; Augustin, 1994; Coelho Netto, 1997) and elsewhere (Smith, 1982; Bothaa *et al*., 1994). As soon as the saprolites are reached, usually by concentrated flow in ditches, gullies tend to follow previous routes of gully retreat, due to rock discontinuities or saprolite erodibility anisotropies. As previously commented, discontinuities guide preferentially the underground flow (fractured aquifers) and the erodibility variations are able to shift or prevent gully retreat towards certain directions.

An important question remains unanswered: why are some headwater hollows cut by gullies and others are totally preserved from erosion? As geological processes can be recorded in sediments, a good way to answer this question is to study Upper Quaternary stratigraphy. As commented before, a morphostratigraphic approach was chosen to study Quaternary sediments that occur in the Maracujá Catchment from valley bottoms up to headwaters hollows. This analysis showed that hollow sediments occur with a relatively uniform stratigraphy throughout Maracujá Catchment, being composed of T2–R2 and minor amounts of T1–R1 Quaternary sediments (Bacellar, 2000). A typical sequence consists of alluvial layers, covered up by colluvial sediments (Figures 10, 11 and 12). The alluvial layers comprise white pebbly or clayey sand, at the base, overlain by black organic clay (T2 clay), which is composed, essentially, of kaolinite, quartz and organic matter. This 2–6 metres thick clay layer is soft (N_{SPT} varies between 1/45 and 4), plastic (liquid limit = 47 and plastic limit = 30) and shows an average sensitivity = 6·0 (Lambe and Whitman, 1969). Seven 14C datings of headwater hollow samples revealed ages between 31 340 and 7490 years B.P., a relatively long time span, which precludes any correlation with other erosional events identified in southeastern Brazil (Dietrich *et al*., 1990; Augustin, 1994; Suguio, 1999).

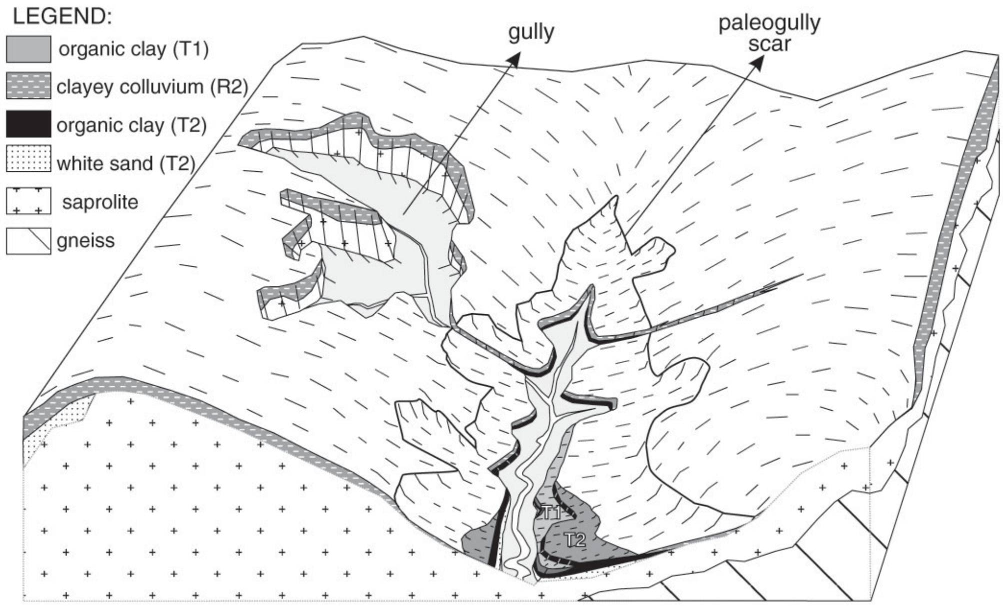

Figure 10. Schematic diagram of typical headwater hollow, which represents a paleogully, filled up by upper Quaternary sediments (T2/R2 and T1). The channel incision cuts the less erodible sediments (organic clays and colluvial soils) and reaches the more erodible gneiss saprolite. The further natural convergence of underground and surface water towards the hollows leads to the development of a new gully. Where the saprolite is thinner (right), deep gullies do not develop.

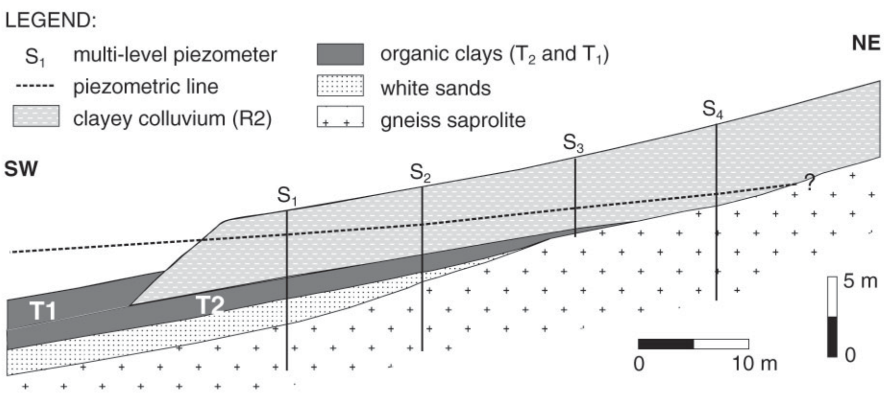

Figure 11. Geologic cross-section through a preserved headwater hollow valley (Condominio station, see Figure 2). Note the soft organic clay (T2) layer under colluvium (R2), both dipping towards the valley bottom. T2 clay is overlain by a younger and softer organic clay (T1) of Holocene age. Water under T2 clay is pressurized (with artesianism), as can be seen by the piezometric line.

This alluvial package was overlain by red brown sandy clay, up to 6 metres thick (Figures 11 and 12), composed basically of quartz, kaolinite and Al or Fe oxides and hydroxides. It shows very good aggregation, with resistant blocky aggregates with pebbly or coarse sand texture, typical of Brazilian oxisols (Parzanese, 1991). These sediments were interpreted as pedogenized (oxisol) colluvial ramps, based on local geomorphologic and stratigraphic evidences (Bacellar, 2000).

The organic clay (T2), with low permeability ($k = 5{\cdot}6 \times 10^{-7}$ cm/s), seals an underlying confined aquifer, including the (pebbly) sand and the top of the gneiss saprolite. Piezometer (Casagrande type, Lambe and Whitman, 1969) readings in a typical unchannelled amphitheatre-like hollow, preserved from current gully erosion (Condomínio station, Figure 11), revealed high pore pressures in this aquifer, enough to cause an artesian condition in the hollow bottom in the rainy season.

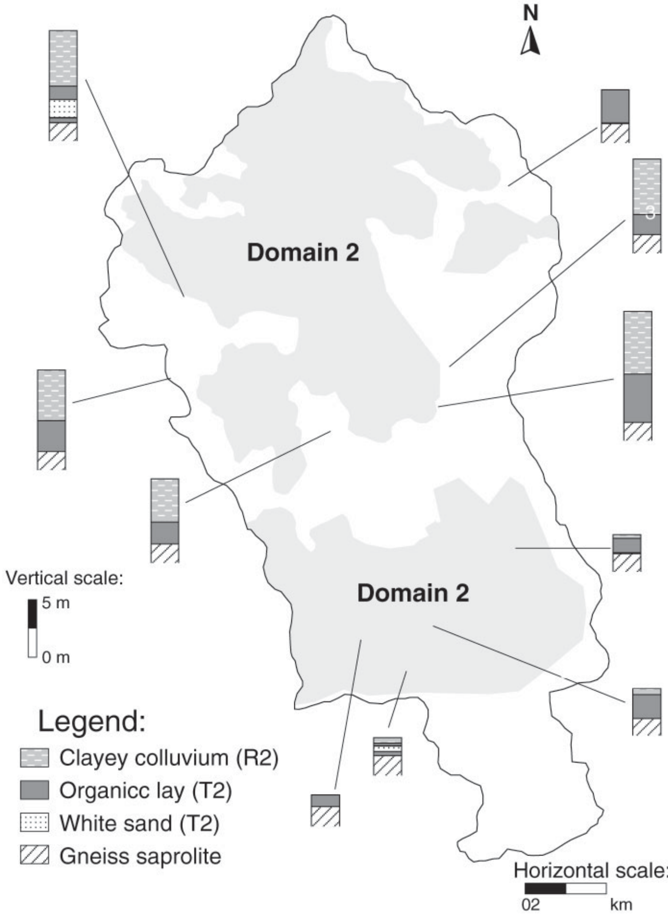

Figure 12. Some stratigraphic profiles of Quaternary sediments (R2–T2 units) throughout the Maracujá Catchment. In the geomorphologic domain 2, whose river incision is hampered by local base levels, the sediment thickness is thinner than in the other domains, apparently deprived of effective local base level control. The thicker sedimentary cover of the other domains probably difficult channel incision and a widespread gully development in these areas.

Pinhole erodibility tests (Sherard *et al*., 1976) performed by Silva (2000) and Morais (2003) have shown that the saprolites of Funil gneiss (Figure 2) are very prone to tunnel erosion (Dunne, 1990). Morais (2003) has demonstrated through physical modelling that these saprolites are very susceptible to slumping, even under small hydraulic gradients. As these saprolites are under artesian pressure inside the preserved headwater hollows, slumping and tunnel erosion by natural discontinuities (joints or animal cavities) seem to be very likely triggering mechanisms of saprolite erosion, as soon as the cover of less erodible soil (A and B oxisoil horizons) is removed by, for example, concentrated flow in boundary ditches.

Preliminary studies have demonstrated that the morphology and stratigraphy of headwater hollows of Maracujá Catchment are very similar to those from basement rock areas of southeastern Brazil (Oliveira, 1989; CETEC, 1992; Moreira, 1992; Augustin, 1994; Coelho Netto, 1997; Bacellar *et al*., 2004). Two of these hollows (Vila Albertina and Vila Barraginha) are very well known in the Brazilian geotechnical literature (CETEC, 1992; Bacellar *et al*., 2004), because they were sites of huge, catastrophic mass movements (mudflow type). Both sites are characterized by a colluvium-buried layer of soft and plastic organic clay, located inside unchannelled headwater hollows, sealing an underlying confined aquifer, in a situation very similar to the Maracujá hollows (Bacellar *et al*., 2004). Both accidents were explained by placement of poorly constructed embankments over these meta-stable hollows. Laboratory data indicate that the organic clay (T2) of Maracujá Catchment exhibits shear strength (UU type test, Lambe and Whitman, 1969) and sensitivity similar to Vila Barraginha's (Bacellar *et al*., 2004). This suggests that many Maracujá headwater hollows, which are not cut by current gullies, could be in a meta-stable situation as well, very prone to mudflow movements. Some Maracujá Catchment gullies seem to be associated with clay rich valley bottoms, with hummocky forms, a common inherited feature of sites affected by mudflow movements. So, the erosion of upper soil horizons by concentrated surface flows (conditioned mainly by boundary ditches), and, to a minor degree, by mudflow movements seem to be the likely triggering mechanisms of gully erosion in this catchment. Both can expose the more erodible saprolite, leading to further gully development by a combination of secondary mechanisms, mainly falls and slumps (due to headcut undermining and the high hydraulic gradient), tunnel erosion and wash and rill erosion on the collapsed or gully wall soils (Bacellar, 2000). These mechanisms (mainly slumps and tunnel erosion) are probably more effective in the fringes of gently sloping interfluves, where the regolith thickness and groundwater availability are probably bigger.

The stratigraphy of these headwater hollow sediments varies according to the geomorphologic domains. In domain 2, controlled by bedrock steps, which act as local base levels (Figure 4), the geologically recent fluvial incision was probably less intense, provoking stronger lateral channel erosion, hampering relief incision and favouring alluvial over colluvial sedimentation from lateral slopes (colluvial ramps). This explains why in headwater hollows of this domain the alluvial sediments (T2) are found in shallower deposits, covered by thin colluvial ramps, that thicken up towards lateral slopes, as shown by several geological profiles (Figures 11 and 12). As a consequence, it is easier to cut the protective cover of less erodible organic clay and colluvial sediments in this domain and reach the pebbly sands and saprolites underneath, which show lower erodibility and are under artesian pressure. The opposite occurs in the headwater hollows of the other geomorphologic domains of basement rock area (domains 3 and 4), which are deprived of effective local base levels. This situation results in narrower and deeper valley bottoms, with alluvial sediments (less erodible than the ones from domain 2, due to their coarser grain size) covered by thick layers of colluvial sediments (Figure 12), which are more available in these steeper relief domains, producing a configuration less prone to river incision and gully initiation. However, as commented previously, the headwater hollows of these domains could not be considered stable at all, because they can have the same unstable inner configuration (soft organic clay layers confining saprolites), which can be destabilized by any process that can cause local channel incision, as showed by Brierley and Fryirs (1999).

Conclusions

Very large gullies are natural phenomena in the Maracujá Catchment, as indicated by the great frequency of old erosional features (paleogullies). Current gullying began with the European settlement at the end of the 17th century, as a consequence of inappropriate land use practices, especially digging of boundary ditches (‘valos’). Although triggered by man, gullies grow intensely only in favourable places, dictated by lithology and, mainly, geomorphology. In fact, large gullies are rare in Minas and Rio das Velhas supergroup areas, as a consequence of the low erodibility and small thickness of their loamy saprolites. On the other hand, in basement rocks the situation is more favourable for their development, because of the greater erodibility of its saprolites, specially those consisting of silty or fine sandy aggregates (Bryan, 1976, 2000; Parzanese, 1991; Silva, 2000). However, lithology does not explain the uneven concentration of gullying, because its incidence is variable in geologically similar areas. Actually, gullies are more common on low relief areas (geomorphologic domain 2, with slope gradients < 30 per cent) and, especially, at the fringes of broad and flat interfluves. The concentration is also uneven at a detailed scale, with gullies growing mainly in amphitheatre-like headwater topographical hollows. As can be easily seen by aerial photography analysis, the geometry of many headwater hollows supports the idea that they represent old erosional features (paleogullies), very similar to the ones identified by Oliveira (1989). Field data have shown that these paleogullies were partially filled by Upper Quaternary sediments, including layers of organic clay and of colluvial sediments. This clay is soft, plastic and with low permeability, working as a seal of a confined aquifer on underlying saprolite and alluvial sediments.

So, the erosion of soils by human activities, such as boundary ditches (‘valos’), or the soil mobilization by mass movements involving the unstable organic clay layer (mudflows) in the hollows, are likely triggering mechanisms for gullying. When the underlying saprolite is exposed, secondary mechanisms began to operate in gully retreat, such as wash and tunnel of collapsed or gully wall soils and falls and slumps of gully walls. However, many more studies are necessary to establish with precision the natural sequence of these primary and secondary mechanisms.

The uneven distribution of gullying in this and in other areas of basement rocks should be considered in future land planning or engineering works. More vulnerable areas, such as headwater hollows, should always be well investigated in order to prevent the possibility of accidents, as mudflows and gullies.

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